

Investigation into the generation of electricity via electrostatic induction

J H Jooste



orcid.org/**0000-0003-4159-1786**

Thesis accepted for the degree *Philosophiae Doctor in Engineering with Mechanical Engineering* at the North-West University

Supervisor: Prof JH Wichers

Co-supervisor: Prof JJ Walker

Graduation: May 2020

Student number: 27124339

PREFACE

My sincere thanks and acknowledgement to:

- God – Giver of all good gifts and Creator and Ruler of Nature.
- My wife, Zani, co-researcher and supervisor on site, and our children. Thank you for all the discussions and ideas and putting up with a laboratory throughout your home for many years.
- Prof Harry Wichers for the opportunity and management insight and courage!!!!
- Prof Jerry Walker for access to very rare resources and welcoming me into your factory.
- Prof Dawid Serfontein and Mr Barend Visser for discussions at critical junctions.
- Mr Heinrich van der Merwe for helping me at critical junctions.
- Mr Riaan Greeff for co-researching and access to the Faraday Cage laboratory.
- Mme Alta van Niekerk for tremendous support in editing this thesis!
- The team of examiners, for academic integrity and courage and vital contributions.
- Mme Ilse Botha and team at the NWU Examinations Office for a marking miracle.

ABSTRACT

The present research investigated electricity generation via the electrostatic induction charging of capacitors, for two primary reasons:

- Mankind needs energy to live and survive; but
- Present technologies have at least contributed to mankind now being left with essentially no time to address various ecological tipping points that might make certain parts of Earth uninhabitable (Lenton *et al.*, 2019).

Prior research highlighted the possibility that capacitors might be part of a new energy solution. Present research took four years and reviewed more than 6 000 literature sources. More than hundred and twenty sources are cited in the formal literature review, and a selection of over a hundred experiments is reported on.

By Grace, it can be reported that:

- No reasons could be established in physics that would prevent electrostatic induction from being used as an electricity generation methodology.
- Despite extensive search, no indication could be found that there is any energy requirement for the propagation of the electric fields that initiate electrostatic induction. Similar to gravity fields, electric fields might just propagate to infinity.
- Various technological guidelines have been formulated that might be used as the building blocks of a technology underpinning electricity generation via electrostatic induction charging of capacitors.
- A specific concept has been developed that might culminate in a specific and sustainable solution, using β -radiation from radioactive carbon-14 to electrostatically charge capacitor stacks. Initial estimates indicate that 1 kg of carbon-14 might generate over 400 Watts continuously for the next 5 730 years (half-life of ^{14}C).

Research also assisted in contributing towards the two capacitor paradox, which highlights the complexity of conduction current charging of capacitors.

Key terms

“ β -radiation”, capacitor, “electrostatic induction”, “electricity generation”, energy, “two capacitor paradox”.

OPSOMMING

Die huidige navorsing is toegespits op die ondersoek na die opwekking van elektrisiteit via die laai van kapasitore deur elektrostatische induksie, vir twee primêre redes:

- Die mensdom benodig energie om te leef en te oorleef; maar
- Huidige tegnologie het minstens daartoe bygedra dat die mensdom nou by verskeie ekologiese kantelpunte staan. Daar is in wese geen tyd oor om te voorkom dat bepaalde dele van die Aarde onleefbaar word nie (Lenton *et al.*, 2019).

Vooraf navorsing het uitgewys dat kapasitore dalk deel van 'n nuwe energie-oplossing mag wees. Die huidige navorsing het vier jaar geneem, in die loop waarvan oor die 6 000 literatuurbronne ondersoek is. Hiervan is meer dan honderd en twintig bronne opgeneem in die formele literatuuroorsig. Meer as 'n honderd eksperimente is uitgevoer.

Genadiglik kan vermeld word dat:

- Geen beginsel kon in die fisika gevind word wat sou voorkom dat elektrostatische induksie aangewend word as deel van elektrisiteitsopwekking nie.
- Nieteenstaande 'n uitgebreide soektog kon geen aanduiding gevind word wat meebring dat enige energie-inset benodig word vir die voortplanting van elektriese velde nie. Hierdie velde veroorsaak elektrostatische induksie. Net soos swaartekragvelde sal elektriese velde waarskynlik voortplant tot in oneindigheid.
- Verskeie riglyne is geskep om die boublokke te vorm vir die tegnologie wat opwekking van elektrisiteit via elektrostatische induksie van kapasitore moontlik maak.
- 'n Spesifieke konsep is geskep wat mag uitloop op 'n volhoubare oplossing deur gebruik te maak van β -straling vanuit radio-aktiewe koolstof-14 om kapasitorstapels te laai via elektrostatische induksie. Aanvanklike ramings toon dat 1 kg koolstof-14 moontlik meer as 400 Watt kontinu sal opwek oor die volgende 5 730 jaar (halflewe van ^{14}C).

Navorsing het ook 'n bydrae gelewer tot die sogenaamde twee-kapasitor-paradoks. Die paradoks beklemtoon hoe ingewikkeld die laai van 'n kapasitor via 'n geleidingstroom is.

Sleuteltermen

“ β -straling”, “elektrostatiese induksie”, energie, kapasitor, “opwekking van elektrisiteit”, “twee-kapasitor-paradoks”.

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CHAPTER 1 INTRODUCTION

1.1 Introduction: a research journey

The researcher's journey started with the development of a dual voltage section insulator, intended to separate the overhead electrical infrastructure for electric trains between adjacent feed-in substations. The component had to be applicable in both the older 3 000 V direct current and the newer 25 000 V alternating current regimes.



Figure 1-1: An old Mark I 3 000 V DC section insulator.

The section insulator had to address both mechanical and electrical requirements. Specifically, the development intent with the dual voltage section insulator was to meet the electrical needs on differing arc gaps for the different voltages through a mechanical solution employing two adjacent arc gaps. For further discussion, it is important to recognise that a section insulator is a form of switch. The locomotive's pantograph constitutes a dynamic part of the switch.

The serial arc gaps stimulated a competitive feature planned for the section insulator, replacing a single switch with a set of serially connected switches. The generic concept was that it is difficult to maintain an arc over multiple connected gaps. During the development, the section insulator project was selected as one of the final entries submitted to investors in Switzerland as part of the Swiss South African Venture Leaders. Interaction with investors highlighted that the switch technology is potentially much more valuable than the section insulator.

Development then pivoted to develop a switch that will prevent arc generation at opening. The project progressed well until a prior art development was encountered: "Dynamically opening

contact mechanism for current limiting circuit breakers” (In German: “Dynamisch öffnender kontaktmechanismus für strombegrenzende leistungsschalter”) (Otto, 1971):

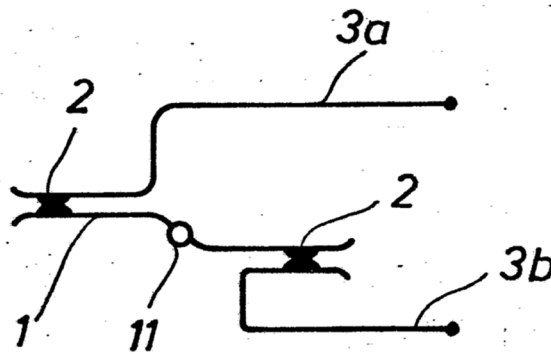


Figure 1-2: Figure 4 from DE 2157927 (Otto, 1971: 10).

A double opening switch had been known since 1971 – and this destroyed the possibility of successfully patenting a switch with, for example, six or more gaps.

Once again the research project had to pivot.

Another competitive feature planned for the section insulator was to feed a counter current through the switch at the moment of opening. The potential differences of the conventional and counter currents had to be equal and opposite – ensuring no current flow, and thus reducing the likelihood of an arc at opening. Alternating current systems could use transformers to generate the counter current. Direct current systems could use capacitors to generate counter current.

This research - on the physics of capacitors towards the section insulator application – showed that electrostatic induction offers interesting possibilities for energy generation.

1.2 Introduction: a world in need of energy

Mankind uses tremendous amounts of energy. In 2018 world consumption was 13 864,9 MTOE (million tonne oil equivalent), equivalent to 161 248 787 GWh (BP staff, 2019). For the 7 713 468 100 people possibly on Earth by the end of 2018 (Staff, 2019); the consumption might be 20 905 kWh per person per year, or 57 kWh per person per day. This data compared closely with World Bank data at effectively 61 kWh per person per day – and is thus approximately equivalent (World Bank staff, 2014). This figure seems high – which perhaps indicates very high energy consumption in richer parts of the world.

“Energy is vital to civilization. In fact, all of human history can be viewed through the lens of energy.” (Kaku, 2008: 259). “Energy is the ‘capacity to do work’, it facilitates all other economic activity.” (Institute for Energy Research, 2010).

Energy accounts for approximately 8% of the world gross domestic product (Institute for Energy Research, 2010), (King *et al.*, 2015). The 2015 world gross domestic product was \$74 188 701 million (World Bank, 2016). In 2015 around \$6 000 billion was thus spent towards energy.

Energy production and use has substantial impact on the environment. The International Energy Agency (2015) estimates that two thirds of greenhouse gas is produced during the production and use of energy.

The Intergovernmental Panel on Climate Change released the special report “Global Warming of 1,5°C” on 8 October 2018 – indicating the following:

- Severe climatic consequences will result if global warming is not kept within 1,5°C from pre-industrial levels, over the next 12 years.
- Even a 0,5°C increase from 1,5°C to 2°C global warming increase, will significantly exacerbate the climatic consequences.
- The 0,5°C prevention might spare 50% more people from water stress, accompanied by food scarcity and climate-induced poverty.
- The primary mitigation strategy is to reduce greenhouse gas emissions, so that the level of greenhouse gas in the atmosphere will stabilise and over time be naturally removed.

Which industry segments emit greenhouse gas? Edenhofer *et al.* (2014) indicates the following sectors as prime greenhouse gas emitters:

Greenhouse Gas Emissions by Economic Sectors

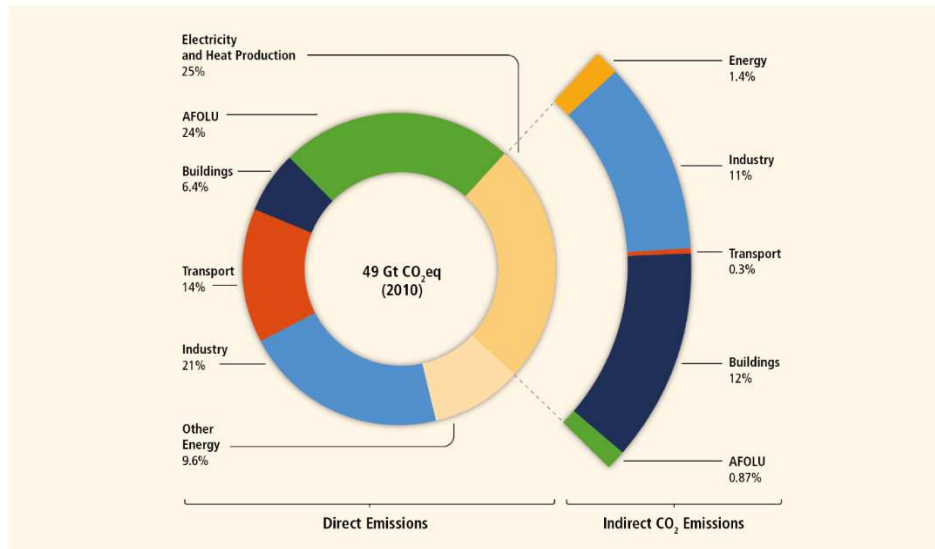


Figure 1-3: Prime greenhouse emitting sectors (Edenhofer *et al.*, 2014).

It appears that the prime reasons for greenhouse gas emissions reside on the human needs for electricity, transport (personal and freight mobility as well as materials handling in industry, agriculture and forestry) and heating.

There is little political appetite to take the leadership required to stabilise greenhouse gas emissions. Australia, for example, already indicated that it is but a small player, and that its coal industry should not be impacted. Ward (2018) indicated that the IPCC report also indicates climate change as a “threat multiplier” where climate-induced population shifts might even lead to war. There is also a discussion on various tipping points – where climate impacts might be exacerbated from certain levels.

Civilization and mankind need energy, but in such a form that it would mitigate the various disasters warned against by the IPCC.

1.3 Introduction: a possible technological solution

The research into capacitors and thus electrostatics highlighted that electrostatic induction might be used to electrostatically charge capacitors; for instance in the Wimshurst influence machine (Thompson, 1888) and in Faraday’s nested ice pails (Faraday, 1843b). The opportunity is that, while energy is required as an input to generate an electrostatic source, no further energy input is required to propagate the electrostatic induction through even an infinite

number of capacitors; given that the capacitors are in a format and layout that will allow electrostatic induction to occur.

This is reminiscent of a breakeven situation. Some fixed setup energy is required to prepare for a harvest of energy. As more capacitors are added, the variable yield of energy would increase. At some level of capacitors (thus determining the total capacitance), the yield of energy would match the setup energy – which would constitute the breakeven point. Beyond breakeven, nett energy would be created, which might constitute an alternative source of energy without all the harm described in the previous section.

Chapter 2 will describe electrostatic induction, the Wimshurst influence machine and Faraday's ice pail experiments as well as the rationale to using a stack of capacitors rather than a single capacitor of equivalent capacitance.

1.4 Research question

Could electrostatic induction provide a pathway towards electricity generation at a scale larger than currently utilised in TENG and MEMS (refer paragraph 2.8 on page 65), in order to power houses, cars and industries?

Various sub-questions will assist in answering the prime question:

- What is the microscopic level physics of electrostatic induction? How does it actually work?
- Does electrostatic induction of capacitors correlate with Maxwell's basic equations of electrodynamics?
- Compare conduction current charging of a capacitor with electrostatic induction charging thereof with particular reference to the two capacitor paradox.
- Various capacitor topological modalities exist. Could any of these be charged via electrostatic induction and also then in such a way that internal losses be minimised?
- What is the impact of and mitigation for fringing of electrostatic fields? What is the significant difference in performance, if any, between a stack of serially connected capacitors and one equivalent capacitor?
- What is a feasible holding mechanism for capacitor stacks, especially to mitigate charge decay?
- How could a capacitor stack be energised?
- How could energy be harvested from a capacitor stack?

- What is the energy balance and the efficiency of electrostatic induction as a pathway to electricity generation?

1.5 Knowledge gap to be closed

It appears at this stage of the research as if it is self-evident that energy must be able to be generated via electrostatics. The probability is that around 80% of the information used in the final solution has been known for a long time – and that perhaps a missing 20% must be created now. An interesting but perhaps trivial piece of information would be the insight as to why electrostatics has been overlooked for so long. This insight might assist in promoting the technology to a wider community. However, this insight is not relevant for the current research but for future commercialisation if, God willing, feasible technology may be developed.

Initial research indicated certain uncertainties in current electrostatic theory. It must be recognised that knowledge is not neutral with respect to the objective. Research towards a specific objective adds relevance to knowledge, and may also deepen the insight, but it may also highlight uncertainties. These may be uncertainties primarily with respect to the objective, and not an indication that the body of knowledge is incomplete. Research into electrostatics with a view to attain utility scale electricity generation would hopefully generate new insights, even possibly from the same prior knowledge.

The first three sub-questions deal with the physics of electrostatic induction charging of capacitors. There is yet uncertainty and gaps in the literature, as evidenced more than fifty articles each on Maxwell's displacement current and on the two capacitor paradox. Addressing these issues will also build knowledge in the researcher, enabling effective research.

The remainder of the sub-questions deal with the mechanical building blocks of an electrostatic induction charging technology. They are essential in order to present guidance on the technology.

1.6 Contribution of this research

Table 1-1 summarises the research sub-questions and the contribution achieved in this research:

Table 1-1: Guide to sub question sections in literature survey	
Sub-questions	Contribution achieved
Describe the microscopic level physics of electrostatic induction.	No clarity could be attained. A summary of what could be established is provided, primarily to encourage further research.
Does electrostatic induction charging of capacitors fit in with Maxwell's basic equations?	Definitely. Electrostatic induction charging allowed Maxwell's displacement current to be verified, isolated from conduction current. Further research has been proposed, in conjunction with a radioisotope source, implying a total lack of current.
Compare conduction current charging of capacitors with electrostatic induction charging of capacitors. Note the two capacitor paradox.	Electrostatic induction charging outperforms conduction current charging when capacitors are used as an energy storage medium. A substantial contribution may have been made to the two capacitor paradox by highlighting the inherent energy and exergy aspects. The two capacitor paradox also highlights the multiple complexities associated with conduction current charging of capacitors.
What is the optimal capacitor topology for electrostatic induction charging?	Parallel plate capacitors.
What is the impact of and mitigation for fringing of electrostatic fields?	Increase the surface area of electrodes and reduce the gap between electrodes, and ensure symmetry in fabrication. Future research, with proper instruments, should investigate lessons emanating from a conformal map compiled by James Clerk Maxwell. Maxwell showed the electric field lines and equipotential lines at the edges of a parallel plate capacitor, and indicated immense symmetry.
What is a feasible holding mechanism for capacitor stacks?	Increase path lengths for tracking. This work must be continued with proper instruments as high voltage electrostatic charges are difficult to contain.
How could a capacitor stack be energised?	Various options are described, but the most feasible solution seems to be nuclear radiation from a β -radiation source. Carbon-14, a waste material from nuclear power plants, will emit only electrons that can travel maximum about 242 mm in air. The ^{14}C decays nitrogen-14, a stable atom.
How could energy be harvested from a capacitor stack?	This is a standard electrical engineering problem, to retrieve energy from capacitors. Two options emerged: • A composite wave may be crafted that will

	best fit the use. If a Z-wave will outperform a sinusoidal wave, it can be generated. • The multiple capacitors offer the advantage of dealing with multiple lower potential differences, as opposed to one large difference.
What is the energy balance and the efficiency of electrostatic induction as a pathway towards electricity generation?	Discussed below.

As the research progressed, various other contributions were generated via serendipity and Grace:

- The possibility of electrostatic induction charging of capacitors via nuclear radiation.
- The possibility of electrostatic induction charging of a single plate capacitor.
- The possibility of electrostatic induction charging of super- and ultra-capacitors.
- Charge polarity reversal was encountered in three serially connected capacitors.
- It was realised that a capacitor stack likely functions as an antenna, and should be treated as such to improve functioning.
- When charge is brought into and removed from a hollow conductor, energy can be generated at entry and at exit. This resonates with Faraday's law of electromagnetic induction. Maybe a Faraday's law of electrostatic induction should be formulated.

1.6.1 Energy balance considerations

It has been highlighted that James Wimshurst used electrostatic induction since at least 1881 to charge parallel plate capacitors (Thompson, 1888: 611). This application is thus not new. What is new, are the following insights:

- The use of multiple serially connected parallel plate capacitors would negate the charge decay due to fringing effects where electrodes are spaced too far apart.
- Electrostatic induction is seemingly propagated throughout an entire stack of capacitors without any energy cost associated with the propagation itself.

The combined impact of these insights is that electrostatic induction charging of parallel plate capacitors offers a pathway towards the efficient creation of electrical energy as:

- The input energy would be the energy required to create the initial source of electrostatic charge. This is a fixed and determinate amount of energy for a fixed and determinate amount of charge.
- This charge then electrostatically induces energy in a stack of parallel plate capacitors as it is being propagated throughout the stack. There is no apparent additional energy cost associated with the propagation.
- The output energy would be the energy harvested from the stack of parallel plate capacitors. This output is linearly related to the number of individual capacitors in the stack. The number would be increased until the output of energy reaches the level of the input of energy (breakeven). Further increases in the number of individual capacitors would enable the nett generation of energy.

The efficiency of electricity generation is an inevitable consequence of the interplay between a fixed energy input to generate electrostatic charge and the linearly increasing energy yield from additional parallel plate capacitors. The breakeven point is at the intersection of the curves for the energy cost of generation versus the energy yielded from that number of capacitors. Beyond this breakeven point, energy may be produced. Figure 1-4 visualises this discussion:

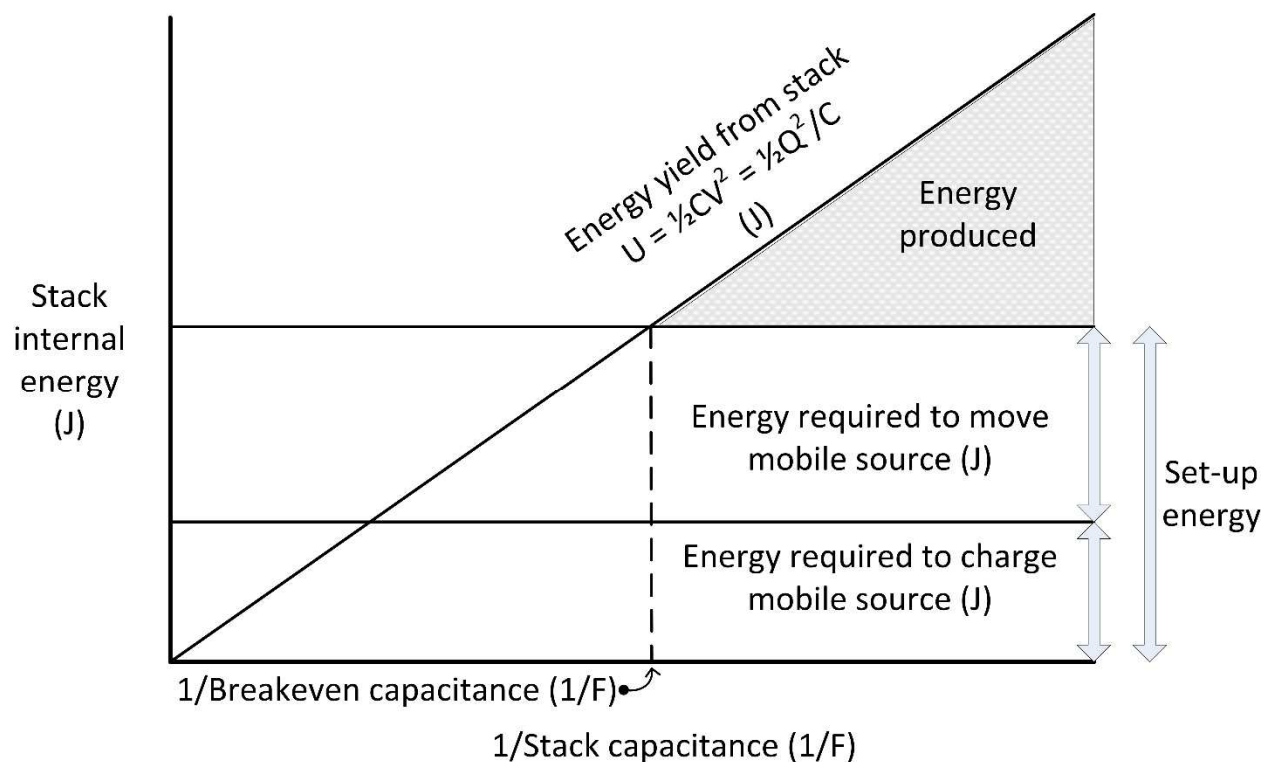


Figure 1-4: Possible breakeven perspective.

Current research highlighted the fit between β -radiation and electrostatic induction charging of capacitor stacks. This might offer access to energy without harming the environment – neither in production nor in consumption.

1.7 Limitations

The research focus seems to be impossible, making it difficult to attract research funding. Research must thus be conducted primarily with own instruments, including a Van de Graaff Generator and an electroscope – as well as various self-built models.

At a laboratory of a co-supervisor, a 50 000 V DC generator is available as well as an electrostatic voltmeter. It is unfortunately analogue and limited to 2 000 V maximum exposure.

An overarching problem seems to be that electrostatics is not part of a general research focus, at least in South Africa. Various attempts have been made to initiate collaboration with international experts, typically physicists; unfortunately to no avail. It also appears as if a range of instruments available for purchase is not available today.

Research funds are thus primarily limited to own funds.

1.8 Research methodology

On an overall strategic level, it is intended that this research should substantiate that there might be an element of truth in the basic research question – and that the research will then enable sufficient research funds to be granted for next stage research.

The research constitutes a search for an answer to whether and how electrostatics might be applied in order to generate nett energy. It appears that this might be found through an iterative process of the following:

- Conducting a literature survey and reflecting upon it from the perspective of the research question;
- Conceptualising and preparing experiments;
- Conducting the experiments;
- Reflecting on the contribution of the experiments to the problem-specific body of knowledge; and

- Repeating the process, while hopefully iteratively approaching closer to the objective.

Design science research has been identified as a valid research methodology that will guide the development of the technology whilst maintaining scientific rigour, allowing attainment of the academic objectives. A three cycle design science research process has been proposed (Hevner, 2007):

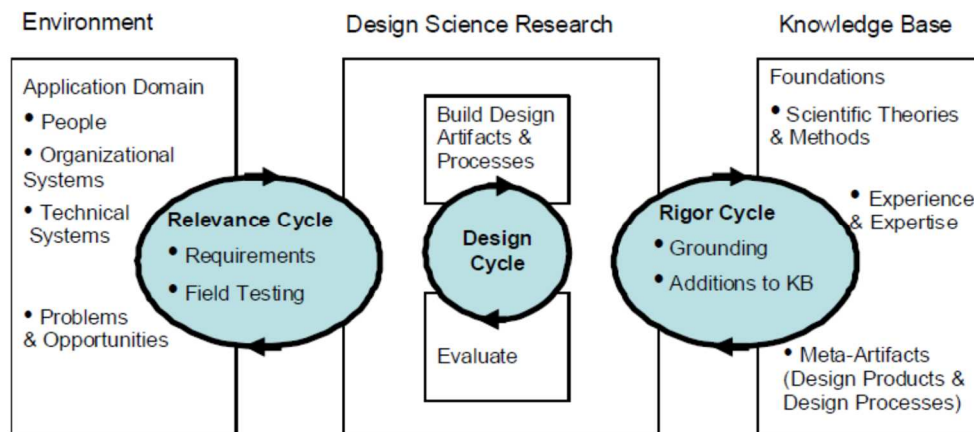


Figure 1-5: Design science research cycles (Hevner, 2007: 88).

This research process mandates radical innovation, as opposed to the incremental innovation which may be expected from normal professional design. Note, however, that the current research is searching for an appropriate technology – it is not aimed at developing a product exploiting that technology towards a solution. Thus only certain relevant aspects of design science research will be utilised. The design science research methodology was used more as a sensitisation, especially as the research technology output must yet pass the physics proof-of-concept. There is not at the moment any value in the relevance cycle, as an example.

1.9 Thesis outline

It is envisaged that the thesis will contain:

- this introduction;
- a literature review, specifically also covering the sub-questions and new questions emanating from experiments;
- a review of relevant research methodologies;

- a section on experimental work, and reflection and planning for follow-up experimental work;
- findings; and
- conclusions, including delineation of future research.

CHAPTER 2 LITERATURE REVIEW

2.1 Introduction to literature review

Paragraph 1.4 on page 5 defined the research question as well as the sub questions. For ease of reference, Table 2-1 contains a reference to the relevant section in the literature review, dealing with each sub question:

Table 2-1: Guide to sub-question sections in literature survey	
Sub-question	Literature survey
Microscopic level physics of electrostatic induction	Paragraph 2.3 on page 20
Fit with Maxwell's basic equations	Paragraph 2.7 on page 59
Compare conduction current charging of capacitors with electrostatic induction charging of capacitors. Note the two capacitor paradox.	Paragraph 2.9 on page 66 For two capacitor paradox, refer to paragraph 2.9.2.2 on page 82
Preferred capacitor topological modality	Paragraph 2.10 on page 105
Fringing of electrostatic fields	Paragraph 2.12.4 on page 121
Holding mechanism for capacitor stacks	Paragraph 2.12.7 on page 127
Energisation of capacitor stacks	Paragraph 2.12.10 on page 131
Energy harvesting from capacitor stacks	Paragraph 2.12.11 on page 133
Energy balance	Paragraph 2.12.12 on page 134

The sub-questions deal with the building blocks of the desired electricity generation technology. These are in some ways the apex of a structure supported by the literature survey and subsequent empirical work. The literature survey must thus ensure that the research is empowered to answer the sub-questions, and will cover a wider field.

Chapter 2 records some of the literature consulted during this research. As will hopefully become visible to the reader, prior work is considered to be of vital importance, offering many clues to the solution of current problems. The literature study is thus supplemented at each moment, where relevant, by an interrogation and a reasoned expansion of the knowledge base towards solving the research problems.

Literature review is considered to be part and parcel of research – not just the foundation on which research will be conducted. The intention is nowhere to just validate the existence of the research problem. It is taken as a given that mankind needs energy and especially ecologically neutral energy. The chapter is organised as follows:

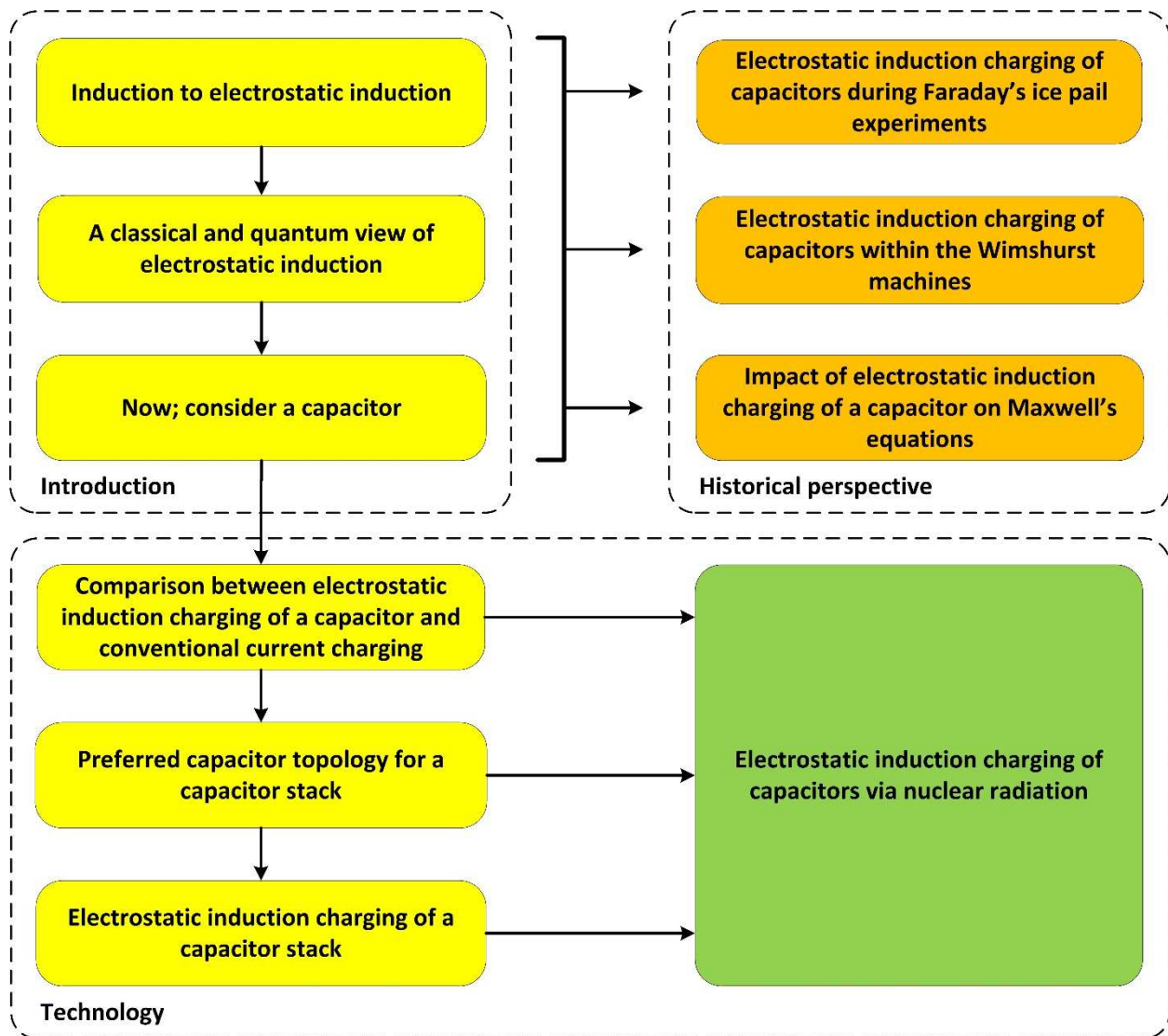


Figure 2-1: Layout of the literature review.

The strategic intent for including these sections are as follows:

INTRODUCTION

- Induction to electrostatic induction. Bring the reader and the researcher on the same knowledge baseline with respect to electrostatic induction. Electrostatic induction seems to be an overlooked topic.
- A classical and quantum view of electrostatic induction. Prior research indicated the absence of a generally accepted theory on how electrostatic induction operates on a microscopic level. Such a theory is vital for the present research, as it would answer questions on the speed of electrostatic induction propagation, losses to be expected as well as the energy source powering electrostatic induction.

- Now, consider a capacitor. Bring the reader and the researcher on the same knowledge baseline with respect to a capacitor. All should be familiar with capacitors, as Earth and the atmosphere and the ionosphere together constitute a capacitor. Mankind lives in a capacitor.

HISTORICAL PERSPECTIVE

- Electrostatic induction charging of capacitors during Faraday's ice pail experiments. Historical overview, both to learn from it but also to exhibit that electrostatic induction charging is a well-known practice.
- Electrostatic induction charging of capacitors within the Wimshurst machines. Historical overview, both to learn from it but also to exhibit that electrostatic induction charging is a well-known practice.
- Impact of electrostatic induction charging of a capacitor on Maxwell's equations. Maxwell formulated the foundational equations for classical electrodynamics. The capacitor played a crucial role there-in. The concept of electrostatic induction charging of the capacitor may bring new insights, particularly to the displacement current which has been a matter of contention since its formulation in the 1860s.

TECHNOLOGY

- Comparison between electrostatic induction charging of a capacitor and conventional conduction current charging. This section provides a comprehensive overview of the two charging approaches, as this is vital for the present research.
- Preferred capacitor topology for a capacitor stack. Various capacitor topology modalities are compared and a best modality for electrostatic induction charging is selected.
- Electrostatic induction charging of a capacitor stack. Various considerations relevant for electrostatic induction charging of a stack of capacitors are dealt with here, including the aspect of fringing of electric fields.
- Electrostatic induction charging of capacitors via nuclear radiation. Introducing a new concept that should constitute the answer to the research question.

The literature review is approached as a valuable part of research. This methodology is based on a concept of reflective writing. Driscoll (1994) adapted the three stem questions by Borton (1970) to create the Driscoll Borton framework of reflection (Dabell, 2018; Frameworks for

Reflective Writing, 2019). The Driscoll Borton framework has now been adapted for literature survey research:

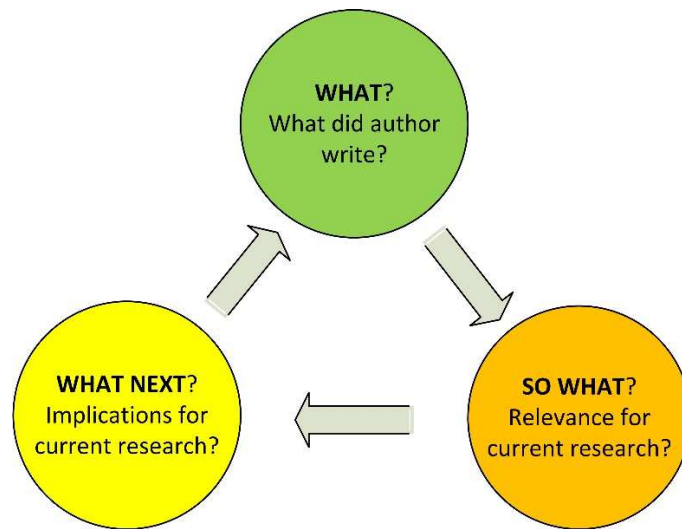


Figure 2-2: Driscoll Borton framework adapted for literature survey research.

Each new piece of information is then interrogated according to the three aspects. It was not written as per such subheadings, as that would have resulted in disjointed writing which is difficult to follow.

Walker (1985) described reflective writing for internalisation of experiences during events. His statements are equally applicable to pieces of information from authors:

- “The use of writing also captures the initial event in a way that enables it to be the basis of continuing and more developed reflection.” (Walker, 1985: 63)
- “The experience is also preserved in such a way that the learner can return to it when further knowledge has been gained which might help to interpret it more fully.” (Walker, 1985: 63)
- “Another significant element in reflection is the association of ideas: the bringing together of new and old in a way that can be the basis of working to integrate them.” (Walker, 1985: 64)
- “The portfolio helped participants to integrate existing and new knowledge.” (Walker, 1985: 65)
- “It can prevent the situation arising where new knowledge lies on top of old knowledge, without integration taking place.” (Walker, 1985: 65)

2.2 Induction to electrostatic induction

According to Thompson (1888: 569): “Electrical influence, or the effect which an electrified body exerts upon a body brought into its neighbourhood” was discovered by John Canton in 1753. Electrostatic induction occurs when an electrostatically charged source is brought in proximity to another object (target); not in contact. In the case of contact, charge is distributed via conduction. An important difference between conduction and induction is:

- When **conduction** occurs, charge is moved – say from one conducting body to another.
- When **induction** occurs, charge is retained on the original conducting bodies. Charge is thus still available for further electrostatic induction.

In a non-contact (proximity) situation, the electrostatic field will induce separation of charges if the second object is conductive (or polarization in a non-conductive object). Opposing charges will move closer to the source object while similar charges will move away from the source object. Most introductory physics textbooks contain corresponding illustrative diagrams (OpenStax College, 2011):

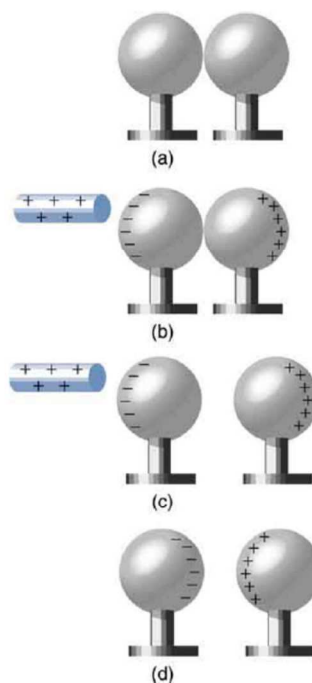


Figure 18.13 Charging by induction. (a) Two uncharged or neutral metal spheres are in contact with each other but insulated from the rest of the world. (b) A positively charged glass rod is brought near the sphere on the left, attracting negative charge and leaving the other sphere positively charged. (c) The spheres are separated before the rod is removed, thus separating negative and positive charge. (d) The spheres retain net charges after the inducing rod is removed—without ever having been touched by a charged object.

Figure 2-3: Example of electrostatic induction from a physics text book (OpenStax College, 2012: 634).

The positively charged source thus induced separation of charges in the initially connected spheres (part a), such that negative charges moved closer to the source and positive charges moved away from the source (part b). Figure 2-3 shows that this separation might be entrapped by separating the spheres whilst the source is still proximate (part c). Once the source is removed, the charges will migrate closer to each other, while remaining on their respective spheres (part d).

Now, if electrostatic induction operates in a certain way for the first two spheres, it would operate in the same way for many more spheres – given that the original dimensions and gaps are maintained, even if spheres are spaced around the Earth. First consider isolated conducting spheres; placed in relatively close proximity – equidistant around the Earth:

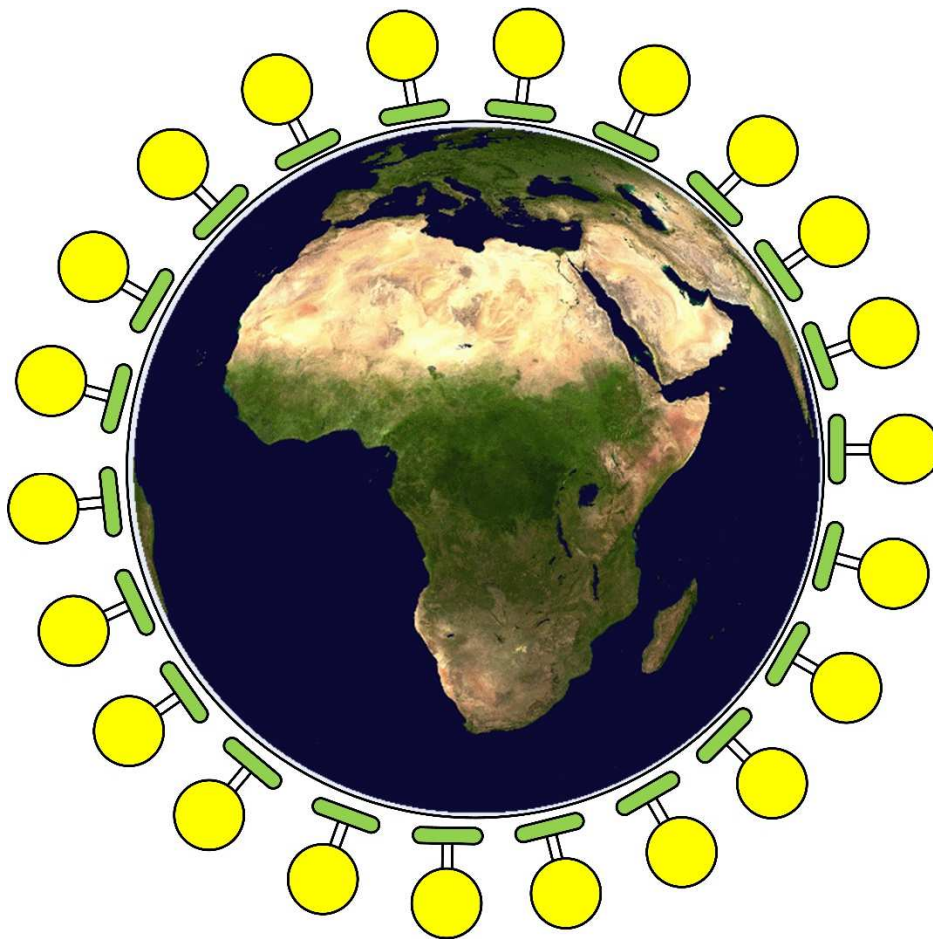


Figure 2-4: Isolated conducting spheres could circle the Earth.

Now induce a charge on a first sphere. The charge would immediately electrostatically induce charges on all other spheres, circling the Earth:

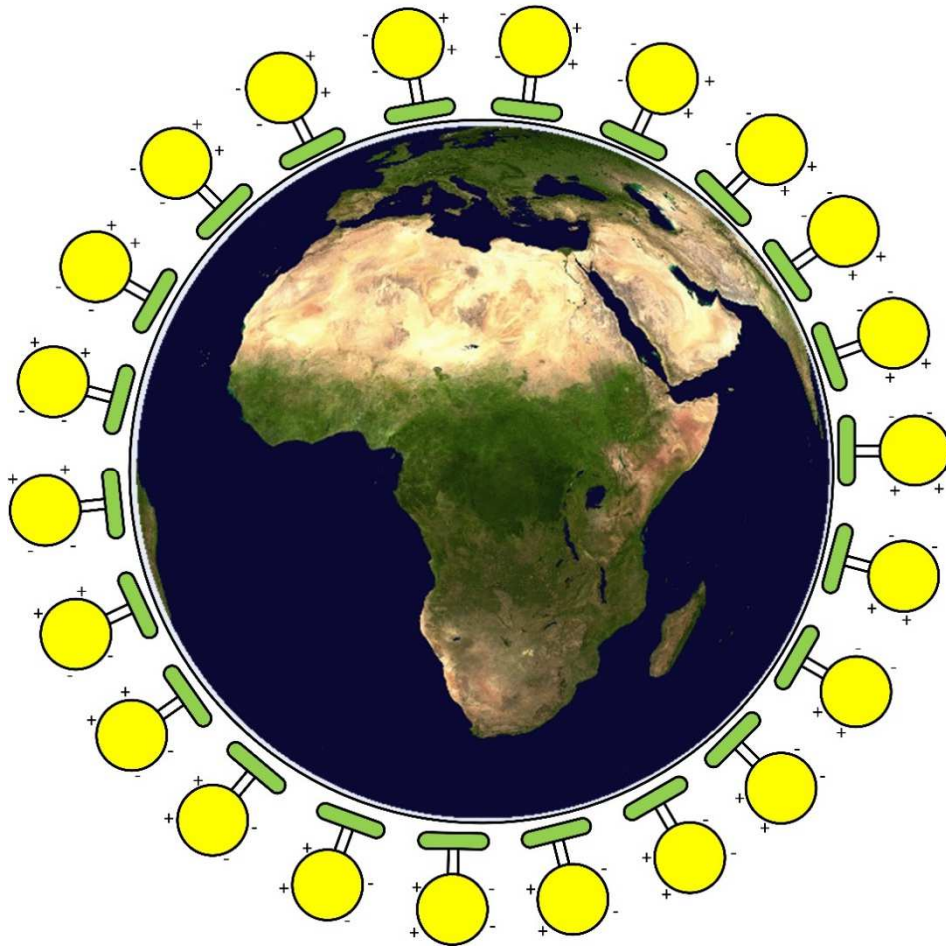


Figure 2-5: Electrostatic induction could circle the Earth.

The example raises three points, which will be discussed shortly:

- At what **speed** does electrostatic induction occur?
- What are the **losses** associated with electrostatic induction?
- What is the **energy source** for electrostatic induction? Energy is used to create the initial electrostatic source and also to move it close enough to the first conducting sphere. What is the energy source for electrostatic induction from that point onward? Are there limits to this energy source – or can an array of spheres span the Universe across 14 billion light years? Will an initial charge be inductively propagated across the Universe?

2.3 A classical and quantum view of electrostatic induction

The answers to the above questions would reside in the actual operation of electrostatic induction. Furthermore, even as certain rules have been established and apparently validated on the level of classical electromagnetics, the quantum equivalents must be identified and validated and synchronised with the classical versions. The HOW must be established, as that would indicate the speed of electrostatic induction, the losses incurred as well as its energy requirements and source. The HOW is also important when designing a technology that is primarily based on electrostatic induction, as that would indicate specific opportunities and threats.

For this research, due to time constraints, only the effect of electrostatic induction on conductive objects will be considered. The impact of polarization on dielectrics, including vacuum, cannot be ignored, but must be dealt with separately. The polarization mechanism is vital, as it likely establishes the energy storage mechanism in a dielectric. There are questions, though, as to the functioning of this mechanism in vacuum. Zangwill (2012: 46) holds the following on vacuum polarization, which might be the most complex dielectric:

Maxwell's theory is the classical limit of quantum electrodynamics (QED), a theory where charged particles and electromagnetic fields are treated on an equal footing as quantum objects. It is the most accurate theory of Nature we possess. Second quantization produces electrodynamic effects which cannot be described by any classical theory. An example is *vacuum polarization*, which is the virtual excitation of electron-positron pairs in the presence of an external electromagnetic field. If the external field is produced by a static point charge q , this relativistic quantum effect modifies Coulomb's law at distances less than the Compton wavelength of the electron, $\lambda_c = h/mc$.

To appreciate the scale involved, the Compton wavelength of an electron is 0,0243 Angstrom, which is $2,43 \times 10^{-12}$ m.

It is common cause that when an electrostatically charged object is brought closer to a conductor, electrostatic induction will cause opposite polarity charges to appear closer to the object and similar polarity charges to appear away from the object. All the time, apparently, charges will obey the Coulomb forces that will ensure a certain distribution. These diagrams, such as Figure 2-3: Example of electrostatic induction from a physics text book (OpenStax College, 2012: 634), appear frequently in physics text books.

It is no wonder there is no clarity on the detail mechanism of electrostatic induction, as there is no clarity even on the electric field which causes electrostatic induction. Consider Griffiths (1999: 61):

What exactly is an electric field? I have deliberately begun with what you might call the 'minimal' interpretation of E, as an intermediate step in the calculation of electric forces. But I encourage you to think of the field as a 'real' physical entity, filling the space around electric charges. Maxwell himself came to believe that electric and magnetic fields are stresses and strains in an invisible primordial jellylike 'ether'. Special relativity has forced us to abandon the notion of ether, and with it Maxwell's mechanical interpretation of electromagnetic fields. (It is even possible, though cumbersome, to formulate classical electrodynamics as an 'action-at-a-distance' theory, and dispense with the field concept altogether.) I can't tell you, then, what a field is—only how to calculate it and what it can do for you once you've got it.

Electrostatic induction occurs as a solution between two conflicting realities:

- In an electric field, there is a **unique electric potential allocated to every position**, relative to the source of the field. This relationship is expressed as:

$$E = V/d$$

where:

E – electric field strength (V/m)

V – electric potential (V)

d – distance between position and the source (m)

or, from Coulomb attraction, first principles (Popović & Popović, 2000: 31):

$$\mathbf{E} = \frac{1}{4\pi\epsilon_0} \frac{Q}{r^2} \mathbf{u}_r \quad \left[\frac{V}{m}\right]$$

where:

E – electric field strength (V/m)

ϵ_0 – permittivity in vacuum

Q – charge of source (C)

r – distance from the source (m)

u – direction between measuring point and source

- It is **not possible for potential differences to exist within a conductor**, as it would immediately lead to an internal current which would eliminate the potential difference. Conductors will throughout have the same electric potential. Tipler and Mosca (2003: 697) recognises the “momentary electric current” phenomenon. Oughstun (2015: 15) agreed: “If an ideal conductor is placed in an external electrostatic field, the charges flow temporarily within it (this has now temporarily become a non-static arrangement) so as to set up a surface charge distribution which produces an additional electric field that, when added to the initial external electrostatic field, results in a zero field inside the conductor once static conditions are re-established.”

These two conflicting realities are resolved by the total absence of electric field within the conductor. Thus the whole conductor is at the same potential.

Electrostatic induction would then, according to the classical view, cause the appearance of charges at the extremities of the conductor – such that the counter field would negate the original electric field. The consequence is that there is no electric field within the conductor – which is intuitively correct. However, for the final “no electric field within a conductor” state to manifest; the counter field had to appear, and in fact be maintained as long as the conductor is within an external electric field.

Based on this discussion, Figure 2-6 shows conductors in an electric field and also how electrostatic induction would distribute charges:

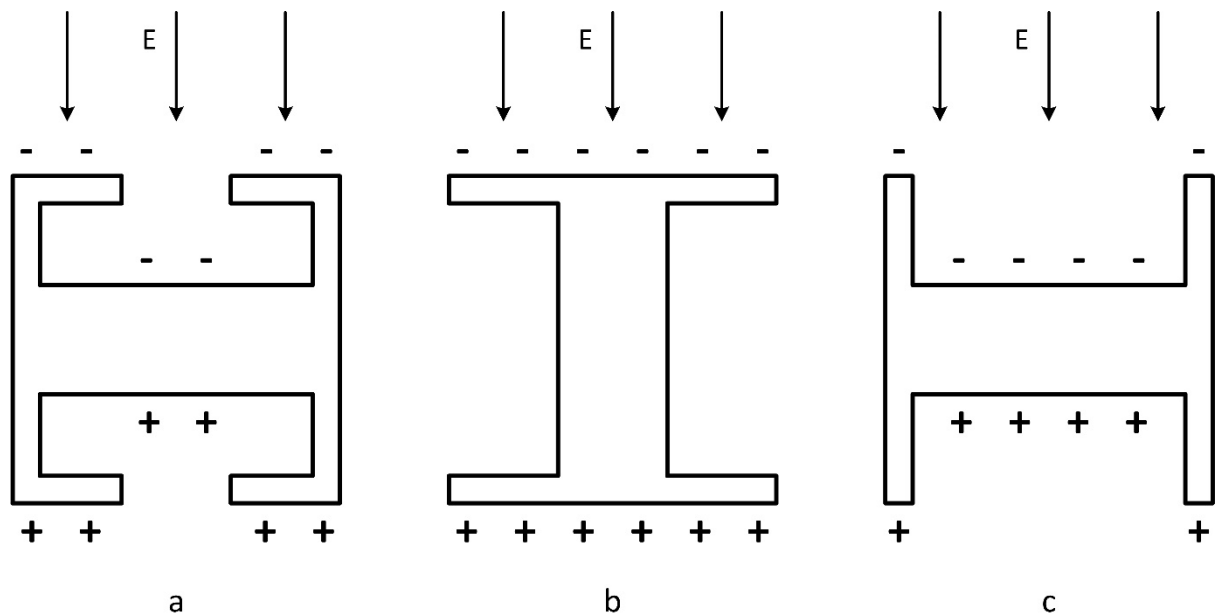


Figure 2-6: Conductors in electric field.

“Migration” of and appearance of charges on the extremities to ensure an effective null electric field within the conductor correlates with Gauss’s Law (Popović & Popović, 2000: 57). A closed Gaussian surface just below the surface of the conductor would contain no charges (unless specifically located therein) and would then experience no electric field flux through the Gaussian surface.

However, how does it happen that the charges appear? There appears to be two hypotheses:

- Electrostatic induction involves the physical movement of **charged entities** (electrons, ions, electron vacancies or electron holes) through matter. This hypothesis might be associated with a classical view.
- Electrostatic induction involves the **perturbation** the electromagnetic waves associated with charged entities (electrons, ions, electron vacancies or electron holes) – throughout matter. This hypothesis might be associated with a quantum view.

These hypotheses will now be discussed in terms of four considerations:

- What moves?
- Participation
- Speed
- Energy source

The following framework will guide the discussion:

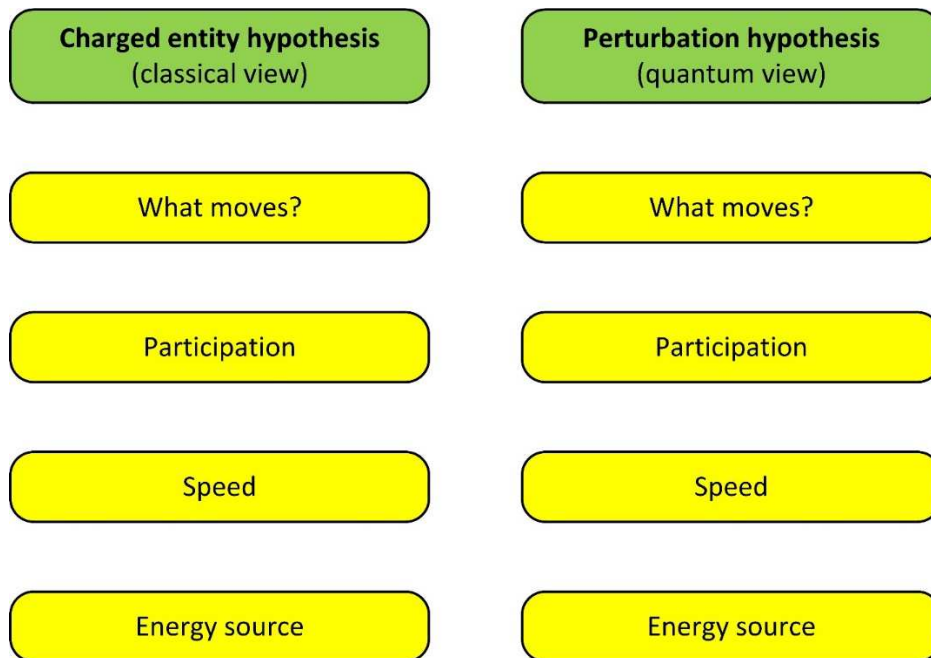


Figure 2-7: Framework for electrostatic induction hypotheses.

The following discussion will be structured according to the eight cells in the framework. Some evaluation will occur at the relevant cell – and it is done this way for effective discussion, and not due to personal bias to short circuit review.

2.3.1 Charged entity hypothesis: what moves?

How would electrostatic induction take place according to the charged entity hypothesis?

Popović and Popović (2000: 66) describe electrostatic induction as the migration of initially “free positive and negative charges in equal number”. This involves movement of mass which involves energy – and could not be correct. Purcell and Morin (2013: 128) agrees with Popović and Popović through “Positive ions are drawn in one direction by the field, negative ions in the opposite direction.” and “They can go no farther than the surface of the conductor. Piling up there, they begin themselves to create an electric field inside the body which tends to cancel the original field. And in fact the movement goes on until that original field is precisely cancelled.”

Tipler and Mosca (2003: 697) holds the electron movement view: “Two uncharged metal spheres touch each other. When a positively charged rod (Figure 21-3a) is brought near one of the spheres, **conduction electrons flow from one sphere to the other**, toward the positively charged rod.” Then: “A conductor contains an enormous amount of mobile charge that can move freely within the conductor. If there is an electric field within a conductor, there will be a net force on this charge causing a momentary electric current (electric currents are discussed in Chapter 25). However, unless there is a source of energy to maintain this current, the **free charge in a conductor will merely redistribute itself** to create an electric field that cancels the external field within the conductor. The conductor is then said to be in electrostatic equilibrium. Thus, in electrostatic equilibrium, the electric field inside a conductor is zero everywhere. The time taken to reach equilibrium depends on the conductor. For copper and other metal conductors, the time is so small that in most cases electrostatic equilibrium is reached in a few nanoseconds.” (Tipler & Mosca, 2003: 702).

However, Tipler and Mosca (2004: 1228) also recognised the failings of the classical view of conduction: “Thus, the classical theory fails to adequately describe the resistivity of metals. Furthermore, the classical theory says nothing about the most striking property of solids, namely that some materials are conductors, others are insulators, and still others are semiconductors, which are materials whose resistivity falls between that of conductors and insulators.” There is an explanation for this failing: “The classical theory of conduction fails because electrons are not classical particles. The wave nature of the electrons must be considered.” (Tipler & Mosca, 2004: 1236). Then, in conclusion: “the free-electron model of metals gives a good account of electrical conduction if the classical mean speed v_{av} is replaced by the Fermi speed u_F and if the collisions between electrons and the lattice ions are interpreted in terms of the scattering of electron waves, for which only deviations from a perfectly ordered lattice are important” (Tipler & Mosca, 2004: 1244).

2.3.2 Charged entity hypothesis: participation

Which entities would participate in electrostatic induction: a selected few or all? Multiple authors indicate that the charged entity hypothesis would involve the selection and movement of only a small fraction of the available entities – corresponding with the charge requirements in terms of the electric field and conductor geometry.

Electron movement versus positive entity movement. There are multiple free electrons in metal – approximately at the level of one free electron per atom. It is also accepted that electrons drift

and the electron drift velocity may be calculated. What then would be the drift velocity of the atoms with the electron vacancies or ions? Also, such atoms might be locked into lattices. Would the atom then move to satisfy the movement of positive charge or would the electron vacancy somehow be passed on from atom to atom?

Local intelligence. It is significant to acknowledge, especially in an era where artificial intelligence is becoming more vital, that redistribution of specific electrostatic charges would have had to be powered by some natural intelligence – instantaneously and over the most complex shapes and with participation by multiple entities. Furthermore, the working and location of this natural intelligence is seemingly unknown. However, if the redistribution occurs as an inherent reaction by all electrostatically charged entities to the electric field, then there is no need for a local intelligence to select the specific entities to participate in a specific exposure.

Continuous, realtime updating. The achievement of this natural charge redistribution intelligence is even more of a miracle, considering that electrons are not stationary. They are continuously revolving in atoms at significant speeds around probabilistic orbits.

Information storage. A lot is known about electrons and atomic particles, including spin and colour. Nevertheless, where would the relevant information for electrostatic charge redistribution be stored? This question is informed by the perception that only an insignificant fraction of the electrons in an electrode would participate in the electrostatic redistribution of charge. The electrons are considered here as proxy for the negative charges – where the same argument must hold for positive charges.

Gauss's Law teaches that the charge must reside on the surface (Tipler & Mosca, 2003: 703); but in what way is electrons participating in the electrostatic charge redistribution differentiated from other, non-participating electrons? Appreciate that due to the continuous spin of electrons, such redistribution would also occur continuously, even when there is no change to the overall electrostatic charge or the macro orientation and position of the entity. The PARTICIPATE or NOT command is possibly issued as a form of tag – similar to the playground game where players are tagged to become "it"; thus to be the designated charges in terms of the momentary redistribution of charge.

Fraction participating. The core assumption of the charged entity hypothesis is that all charged entities in a conductor will be sorted into three categories:

- Those participating and moving towards the source of the electric field.
- Those participating and moving away from the source of the electric field.
- Those not participating.

Table 2-2 illustrates the small fraction of electrons present in a typical electrode that would actually participate in electrostatic charge distribution:

Table 2-2: Electrostatic activation of electrons			
Criteria	Symbol	Value	Unit
Electrode area	A	1	m ²
Electrode thickness	D	0.001	M
Electrode volume	V	0.001	m ³
Density of copper	P	8 960	kg/m ³
Electrode mass	M	8.96	G
Atomic mass unit for copper	AMU	63.546	U
Avogadro's number		6.02E+23	-
Atoms in electrode		8.49E+22	atoms
Charge present	Q	0.005	C
Number electrons per Coulomb	n/C	6.24E+18	electrons
Electrostatically relevant electrons		3.12E+16	electrons
Fraction of electrostatic activation (One free electron per atom in copper)		3.68E-07	
Inverse of fraction		2 720 613	groups

Table 2-2 indicates that for a charge of 0,005 C on a 1 m² copper electrode of 1 mm thick – the total number of electrons present will be 2 720 613 times the number of electrostatically active electrons. Each copper atom contains one free electron. Only a very small fraction of electrons will participate in electrostatic charge redistribution – only one electron per 2 720 613 possible electrons. How would this occur? How does the decision occur? How is the decision communicated? Is one electron fully activated – or are 2 720 613 electrons partially activated in some gradient according to their positions? Remember that the positions are continuously changing.

2.3.3 Charged entity hypothesis: speed

No literature could be sourced supplying definitive evidence-based information on the speed of electrostatic induction. Tipler and Mosca (2003: 702) indicated: “The time taken to reach equilibrium depends on the conductor. For copper and other metal conductors, the time is so

small that in most cases electrostatic equilibrium is reached in a few nanoseconds.” Electric conduction may be taken as a guide to establish the speed of action, and it is a close relative to electrostatic induction as both are initiated by electric fields and both, for now, are occurring in metallic objects. Then, there are three speeds that might be considered:

- The electron drift speed (“Typical drift speeds are of the order of a few hundredths of a millimeter per second, quite small by macroscopic standards.” (Tipler & Mosca, 2004: 789)).
- The Fermi speed, which would be $1,56 \times 10^6$ m/s for copper.
- The speed of propagation of the electromagnetic wave through a conductor, which would be less than the speed of light in a vacuum, at 3×10^8 m/s. A switch that is closed must trigger an event almost immediately depending on the speed of light and the distance to complete the circuit. It would be interesting to determine which distance is the effective distance for event triggering: the full distance of the circuit or half the circuit distance. Interestingly, the telegraphers’ equations developed by Oliver Heaviside to resolve his transmission line model, uses half the circuit distance.

As the speed of propagation of the electromagnetic wave approaches the speed of light, this same speed might also be applied to the propagation of electrostatic induction, given all the other similarities.

It is obvious, when considering the calculation in Table 2-3, that electrostatic induction according to the charged entity hypothesis, cannot occur near the speed of light. In fact, on energy considerations, it is doubtful that it can occur at all. Tipler and Mosca (2003), and other authors, might be mistaken in assuming a very fast redistribution of charge within the charged entity hypothesis.

2.3.4 Charged entity hypothesis: energy source

Electrons have mass. Movement of mass requires energy. Their initial movement requires acceleration and deceleration and thus energy, irrespective what fraction of charged entities are involved or how far the entities must move. Movement back to original positions would require a new injection of energy. It is thus not as if energy is borrowed to reflect the new distribution of charge according to the electric field, and then returned when the electric field is terminated. Where would the energy for electron movement, in both directions, come from?

If the perception is that electrostatic induction must occur at a speed near the speed of light, enormous amounts of energy would be required even to move just one electron through the thickness of an electrode. In fact, an infinite amount of energy would be required to accelerate any mass to the speed of light, and no mass can move at the speed of light. The relativistic kinetic energy associated with one electron moving at 99,9% of the speed of light, would be $8,741 \times 10^{-13}$ J. Work of 27 280 J would be required to move 0,005 Coulomb charge at 99,9% of the speed of light. To attain this speed within 10^{-15} seconds, which would be an essential starting point to attempt overall redistribution at near the speed of light, would require an energy supply of $2,728 \times 10^{19}$ W, which is totally unfeasible for 0,005 Coulomb of charge. Table 2-3 illustrates the calculation:

Table 2-3: Relativistic kinetic energy for electron movement			
Criteria	Symbol	Value	Unit
Mass	m	9.109E-31	Kg
Speed of light	c	300 000 000	m/s
Speed target	-	0.999	%c
Lorentz factor	γ	22.37	
Kinetic energy per electron	KE_{rel}	8.741E-13	J
Charge present	Q	0.005	C
Number electrons per Coulomb	n	6.242E+18	
Kinetic energy per charge	KE_{rel}	27 280	J
Time for charge redistribution	t	1.000E-15	S
Power required for redistribution	P	2.728E+19	W

Movement of any mass requires energy, and movement nearer the speed of light requires immense amounts of energy. The absence of an obvious source questions the feasibility of this hypothesis.

2.3.5 Perturbation hypothesis: what moves?

Zangwill (2012: 127) explains (current author's emphasis):

Electrostatic induction in a real metal does not involve any long-range displacement of charge. Equilibrium is re-established by tiny perturbations of the conduction electron wave functions at every point in the conductor.

When summed over all occupied states, the corresponding perturbed charge density Lorentz averages to zero at all interior points. This is the meaning of (5.1). At all surface points, the perturbed charge density amounts to tiny excesses or deficits of electronic charge which Lorentz average to the macroscopic surface charge density $\sigma(\mathbf{r}_s)$.

The “(5.1)” of Zangwill in the quotation refers to the equation stating for a perfect conductor: “both the macroscopic electric field and the macroscopic charge density vanish everywhere inside its volume V :

$$\mathbf{E}(\mathbf{r}) = \rho(\mathbf{r}) = 0 \quad \mathbf{r} \in V \quad (\text{Zangwill, 2012: 126})$$

Tipler and Mosca (2004: 1228) recognised the failings of the classical view of conduction: “Thus, the classical theory fails to adequately describe the resistivity of metals. Furthermore, the classical theory says nothing about the most striking property of solids, namely that some materials are conductors, others are insulators, and still others are semiconductors, which are materials whose resistivity falls between that of conductors and insulators.” There is an explanation for this failing: “The classical theory of conduction fails because electrons are not classical particles. The wave nature of the electrons must be considered.” (Tipler & Mosca, 2004: 1236). Then, in conclusion: “the free-electron model of metals gives a good account of electrical conduction if the classical mean speed v_{av} is replaced by the Fermi speed u_F and if the collisions between electrons and the lattice ions are interpreted in terms of the scattering of electron waves, for which only deviations from a perfectly ordered lattice are important” (Tipler & Mosca, 2004: 1244).

Tipler and Mosca thus approaches Zangwill’s view of electrostatic induction involving “perturbations of the conduction electron wave functions at every point in the conductor” (Zangwill, 2012: 127). Note that Tipler and Mosca were not discussing electrostatic induction at quantum level – but electrical conduction. A discussion of induction might have brought them to Zangwill’s hypothesis. It is important to note that both electric conduction and electrostatic induction are caused by electric fields. There should thus be similarities, especially also when both are observed in metallic solids. However, electrical conduction is based on current flow – which does not occur in electrostatic induction, apart from a possible initial “momentary electric current” inside the conductor (Tipler & Mosca, 2003: 697). The current associated with electrical conduction implies a relationship between resistivity and temperature, while no mention could be found of a relationship between electrostatic induction and temperature.

Hoddeson *et al.* (1987) traced the development of the “quantum-mechanical electron theory of metals”. Olsen and Vignale (2010) described the phenomenon of electrical conduction from a quantum mechanics perspective. Adhikari (2014: 34) compares classic electron and quantum

mechanical approaches towards electrical conduction: “The first approach and formulation in equation (9) assumes that all the free electrons in a material drift in the presence of external electric field and all they contribute to the electrical conduction whereas in quantum mechanical approach, in equation (20), only specific electrons drift with a high speed nearly the Fermi velocity v_F have supposed to contribute to the electrical conductivity, σ .”

It is evident that although a lot of research went into conductivity, magnetism and superconductivity, research into electrostatics, and specifically electrostatic induction, lagged. This matter is incredibly complex and a deep understanding of quantum mechanics is necessary to break new ground. It appears that such detailed research of electrostatic induction from a quantum mechanics perspective would add insight to both quantum mechanics as well as to electrostatics. None of multiple authors refer to the perturbation of the conduction electron wave function in relation to electrostatics.

Gaspari *et al.* (1964) investigated the interaction between core electrons and unpaired valence electrons, subsequent to a perturbation of the wave functions. This might add valuable insight into the HOW of electrostatic induction.

However, despite these partial contributions, no direct exposition of HOW the perturbation approach might work, could be found. Professor Zangwill was thus contacted at Georgia Tech, and by Grace he replied: “I am pretty sure no one has studied the dynamics of electrostatic induction microscopically. However, electrostatic induction is just the phenomenon of electric polarization for the special case of a metal.” (Zangwill, 2019). Electrostatic induction at a microscopic level in metal is seemingly too specialised for the research community. No relevant additional material could be sourced.

Electrostatic induction at a microscopic level does pose special challenges:

- The theory must distinguish between conductor, semi-conductor and isolators. This is achieved successfully in current approaches, but must be incorporated into the new theory – especially as it will be used to resolve metal-isolator-metal applications.
- The theory must interface seamlessly between macroscopic and microscopic levels.
- Some benchmark cases of electric field propagation, this is not an exhaustive listing:

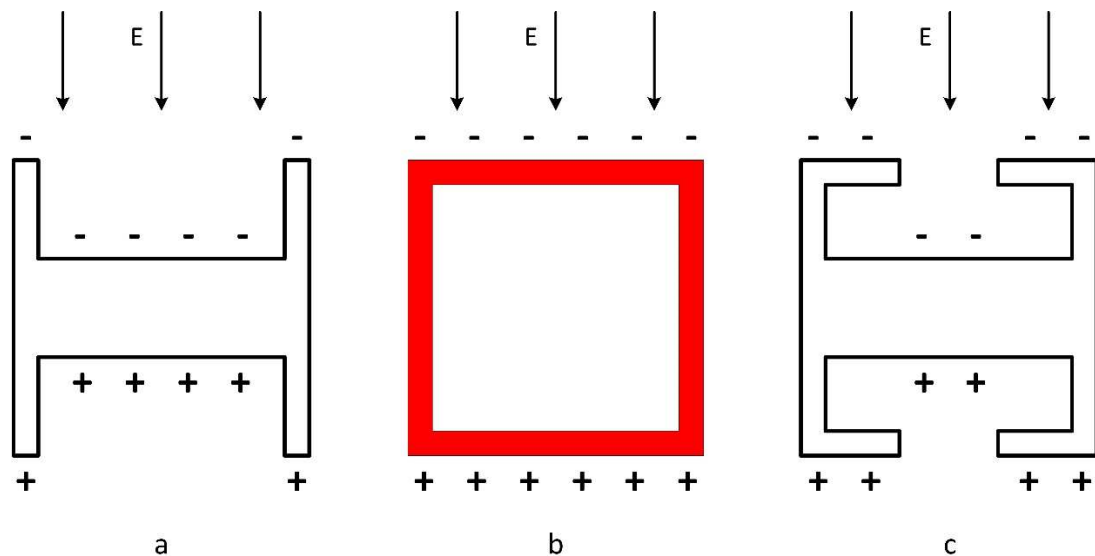


Figure 2-8: Benchmark tests for microscopic electrostatic induction theory.

Case a is standard, but might also be used to test local charge density concentrations correlating with the local radii of curvature. Case b is a Faraday cage. Would the perturbations propagate through the metal and the enclosed space? A Faraday cage might even be a challenge for the classical view to explain. Case c is similar to case a; but where-as in cases a and b the perturbations might perhaps be allowed to transport on the surface, from the front to the rear end of the conductor, as viewed in the direction of the electric field – in case c there are undercuts which might inhibit such transport.

- A hollow electrode constitutes another benchmark. It is the inverse of case b above. From first principles, what drives the outward migration of charge? Does this process really continue until all charge has migrated, or will the last unit of charge remain behind?
- Problems such as these are frequently solved by specifying the relevant boundary conditions up front, a priori. Could a microscopic theory of electrostatic induction arrive at the boundary conditions from first principles?
- The theory will have to incorporate a determination of what is inside and outside. Gagnon (2019) calculated that the hydrogen atom is 99.9999999999996% empty space. What is then inside or outside?
- The classical view prescribes that once a conductor is placed in an electric field, a counter field must be established inside the conductor such that no field must remain inside the conductor. The classical view also holds that charge will radiate an electric field, perpendicular to the surface where it resides. There can be no tangential electric

field component, as that will cause continued movement of charge. What will now happen if the conductor is skew with respect to the electric field:

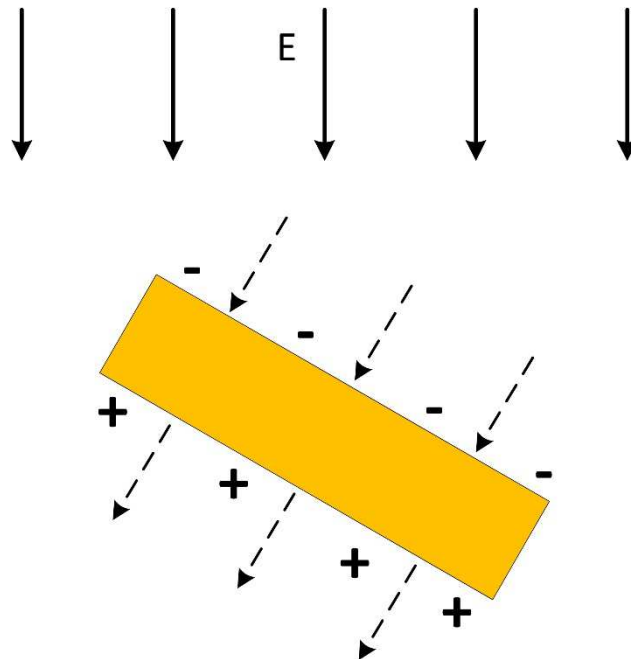


Figure 2-9: A skew conductor in an electric field.

The solid line denotes the original electric field, while the dashed line shows the secondary field, due to charges electrostatically induced on the surface of the conductor. The question is: Will the original electric field propagate beyond the skew conductor, especially if posited that the conductor is infinitely wide? If the conductor is smaller, and in scale parity with the electric field, what would drive further propagation of the electric field? Fringe effects?

This layout and reasoning likely underpin the bending of electric field lines to ensure that force lines enter and exit a surface as a normal. In the visualisation discussed below, Figure 2-9 should show, for example, the field lines from the source curving in to enter the surface co-linear with the dashed lines.

By Grace this question could be resolved experimentally by setting up the field and target conductor in an electric field observation chamber. The suspended seeds or particles in oil will then show the effective electric field lines. The developed theory could then be verified against the observed pattern. A single electrostatic source would be better than a capacitor configuration with two sources. In the capacitor configuration, the

downside source might induce its own effects on the away side of the conductor – clouding the issue.

- Ideally it should be possible to provide answers from first principle physics on the relevant forces when inserting and removing conducting electrodes or dielectric slabs from charged capacitors. Conventionally this problem is approached from the assumption that total energy will remain constant. It will be good to be able to verify results from another approach.

2.3.5.1 What might the microscopic view of electrostatic induction look like?

A perturbation is normally seen as an impulse disturbing the equilibrium of a system, such as the series of masses and springs below:

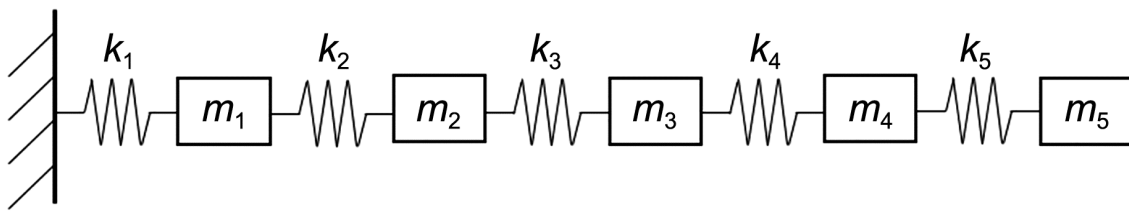


Figure 2-10: A system ready to receive a perturbation (Qiu & Jiang, 2016: 3403).

An electrostatic source would emit an electric field which would act as a perturbation to the conduction wave electron functions throughout space and the conductors (Zangwill, 2012).

2.3.5.2 The devil is in the details

A valid theory will resolve ambiguity and provide a solid foundation for progress.

In 1987 Luryi (1988: 501) could still believe: “It is well known that a grounded metal plate completely shields the quasistatic electric fields emanating from charges on one side of the plate from penetrating into the other side.” By 2014: “By abandoning the notion that metal electrodes perfectly screen the electric field, both first-principles calculations and fundamental quantum theory offer an explanation that the diminishing capacitance of nano capacitors is in part due to the existence of the atomically thin two-dimensional charge layers between metal-dielectric interfaces.” (Hanlummyuang & Sharma, 2014: 660) Better insight into the quantum-level

physics allowed identification of and use of quantum capacitance and even negative quantum capacitance. Such insight is vital and valuable. It allowed researchers at the University of California, Santa Barbara, to improve the inductor, using kinetic inductance and intercalated graphene. This might empower entry into the IoT market of \$2,7 to 6,2 trillion per year by 2025.

The exact functioning of capacitors at nano-scale is also important as Zangwill (1988) used serially connected stacks of capacitors to model the electrostatic potential in insulator solids:

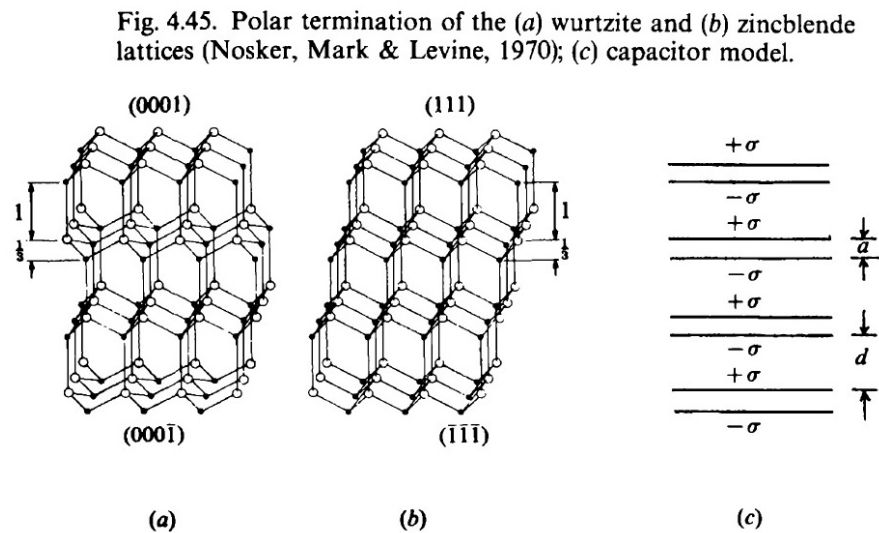


Figure 2-11: Capacitor stack to model an insulator (Zangwill, 1988: 105).

2.3.5.3 Immediate way forward

However, for the present research it appears that a working hypothesis would be that an electric field would create a perturbation of the electron wave functions throughout the conductor. This perturbation must likely be extended to all charged entities in the conductor.

Researchers must be co-opted to develop the microscopic theory of electrostatic induction.

2.3.6 Perturbation hypothesis: participation

Zangwill (2012: 127) indicates that electrostatic induction will involve perturbation of electron waves “at every point in the conductor”. Thus – all charged entities are involved.

Local intelligence. It is significant to acknowledge, especially in an era where artificial intelligence is becoming more recognised, that redistribution of specific electrostatic charges or even specific electromagnetic signals (customised signals per entity according to position) would have had to be powered by natural intelligence – instantaneously and over the most complex shapes and with participation by multiple entities. Furthermore, the working and location of this natural intelligence, is seemingly unknown. However, if the redistribution occurs as an inherent reaction by all electrostatically charged entities to the electric field – then there is no need for a local intelligence to select the specific entities to participate in a specific exposure.

The participation of all charged entities would correspond to the analogy of a beam subjected to a load. All molecules in the beam would participate to withstand the load:

- Some molecules would experience tensile stress, with maximum deflection at the extremity reducing to nil deflection at the neutral axis.
- The molecules on the neutral axis would not experience any stress.
- The molecules on the other side of the neutral axis would experience compressive stress, with the maximum deflection at the extremity.

The analogy refers to a mechanical situation, where there is no reference to some intelligence designating specific molecules to participate. All participate and the force at each point communicates the expectations.

The mechanical stress analogy leads to the following possibility for electrostatic induction:

- None of the entities inside the conductor participate.
- All of the entities on the surfaces, towards and away from the electric field, participate.

Participation must establish:

- A perceived total charge on the faces away from and towards the electric field, as required by the magnitude of the field and the cross-sectional area of the conductor, as radiated by the electric field.
- Local charge densities must correspond to the local radius of curvature of the conductor. Sharper parts will attract a higher charge density.

2.3.7 Perturbation hypothesis: speed

Thomson's theorem holds that the redistribution of electrostatic charge ensures that the energy will attain a minimum (Stratton, 1941: 114), (Fiolhais *et al.*, 2016), (Grinfeld & Grinfeld, 2015).

Zangwill (2012: 128) describes it as: “All physical systems in mechanical equilibrium arrange their charge density to minimize their total energy.” After redistribution, the distribution of electrostatic would not contain a reserve of energy that will allow further redistribution of charges. This implies that redistribution must occur essentially instantaneously, which would imply action at the speed of light.

The discussion on correspondence between electric conduction and electrostatic induction led to the assumption that propagation would occur at the speed of light. Also, if the Zangwill explanation is accepted, it is obvious that propagation must be at the speed of light. There is simply no other speed than the speed of light at which an electric field could interact with the electron waves in a conductor.

By Grace, Turtur (2007: 2) described the Hertzian dipole emitter, and makes the case that, as the opposite polarity particles oscillate:

- Electric waves and field is transmitted;
- Magnetic waves and field is transmitted; and
- Electromagnetic waves and field is transmitted, as the Maxwellian interaction between electric and magnetic waves and fields.

There is no indication that the electric fields and waves are retarded relative to the magnetic fields and waves. It may thus be assumed that all move at the same speed and phase. As electromagnetic waves move at the speed of light, the constituent waves must thus move at the same speed which is the speed of light.

2.3.8 Perturbation hypothesis: energy source

What energy source drives redistribution of electrostatic charge? Could electrostatic induction perhaps be the only natural process that occurs without requiring energy? In this hypothesis, where an electric field would interact with the electron waves in a conductor, there is no need for an energy source to fuel propagation. The electric field propagates to infinity without needing an energy source, in the same way that gravity would similarly propagate without an energy source. This hypothesis thus needs no energy source to succeed.

The energy source is related to losses, and then specifically charge loss. Faraday (1843a: 177) conducted his ice pail experiments (see paragraph on 2.5 page 43) and concluded: “I have

given you this experiment for the purpose of showing, that whatever the amount of power which I may put into this complicated arrangement, the same amount would appear outside. I have stated before, theoretically, what I now prove by experiment, that if there were a thousand cells of metal, exactly the same amount of power put on the centre cell, would appear on the outer cell.” When Faraday referred to power, he meant charge.

2.3.9 Conclusion regarding the hypotheses on electrostatic induction

The previous discussion may now be summarised as:

Table 2-4: Different hypotheses on electrostatic induction		
Consideration	Hypothesis	
	Charged entity	Perturbation
What moves?	Electrons, ions, electron vacancies or holes, Dirac or Majorana fermions (University of California - Irvine, 2017).	The electric field propagates through matter, towards: “Equilibrium is re-established by tiny perturbations of the conduction electron wave functions at every point in the conductor” (Zangwill, 2012: 127).
Participation	Some of the entities, corresponding to the calculated charge.	All entities in the object.
Speed	No certainty. Literature silent. Any speed would require a source of energy, which would be depleted as the amount of interactions increase. No evidence yet of such a depletion.	The speed of propagation of the electric field, which should approach the speed of light.
Energy source		None required for propagation of the electric field, and the resultant interaction with local electron wave functions.

In the present analysis, and with full recognition that present knowledge is actually woefully inadequate to reliably resolve the question of how electrostatic induction occurs, it appears as if the classic approach is not consistent in all four of the identified considerations, whereas the quantum mechanics approach appears to be logically consistent. This hypothesis is thus accepted as the working hypothesis for the current research, even though more work is required to detail it.

2.3.10 The future

New developments in femtosecond lasers (Gaumnitz, Jain *et al.*, 2017, Wong, Winchester *et al.*, 2018), based on research on chirped pulse amplification recognised in the 2018 Nobel Prize for Physics (NobelPrize.org 2018), might be used to video the behaviour of electrons under the influence of electrostatic impulses. Specifically, Liang, Zhu and Wang (2018) developed “single-shot 10-trillion-frame-per-second compressed ultrafast photography (T-CUP), which passively captures dynamic events with 100-fs frame intervals in a single camera exposure”. A review indicates that two current technologies (LIF – DH “digital light-in-flight recording by holography” (Kakue, Tosa *et al.*, 2012) as well as trillion-frame-per-second compressed ultrafast photography (T-CUP) (Zhu, Chen *et al.*, 2016) may image faster than 10 trillion (10^{12}) frames per second (Liang and Wang, 2018).

New insights are possible when electron behaviour might be observed. Also, what does the behaviour of the positive charges signify? What happens there?

Filming the behaviour of electrons might also at last establish the health of Schrödinger's cat. Consecutive establishment of the position of electrons (and thus also establishing their speed) might warrant revisiting the Copenhagen interpretation of quantum superposition.

The University of California – Irvine, has a fibre-optic Sagnac interferometer microscope: “It's the most accurate way to optically measure magnetism in a material” (University of California - Irvine, 2017). As the instruments improve, our insights will advance, especially if the optic measure of magnetism could be modified to measure the electric field or electrostatic charge.

Researchers must be co-opted to develop the microscopic theory of electrostatic induction.

2.3.11 Experiment to establish speed of electrostatic induction

Empiric evidence towards the speed of electrostatic induction would provide clues towards the detailed physics thereof. There are two primary domains involved in electrostatic induction:

- Propagation through a conductor
- Propagation through a dielectric

Research would gain more credibility to initially establish the speeds in each domain, and then perhaps for a range of materials in each. Once propagation models have been constructed, they may be validated against tests of propagation through stacks of capacitors, representing interleaved conductors and dielectrics.

Speed tests might involve:

- generating a signal and the time of generation;
- directing the signal simultaneously along a shorter and a longer route;
- recording the time of arrival;
- calculating the speeds attained.

Electromagnetic waves, including the electrostatic induction signals, generate a spectrum of harmonics which may obscure the intended results. Initial pulse generation might thus rather be a cyclic signal than a pulse signal. It would be imperative to consult radio frequency experts to design the test protocol, as that can yield additional credibility.

The present research does not have time available to conduct this task, nor are the laboratory resources available. It must thus be done in future research, and a contribution of the present research would be to highlight the need for such experiments.

2.4 Now consider a capacitor

Capacitors are standard circuit elements and are thus widely discussed in literature. One example is by Serway and Jewett (2014: 778) illustrating a capacitor:

Figure 26.1 A capacitor consists of two conductors.

When the capacitor is charged, the conductors carry charges of equal magnitude and opposite sign.

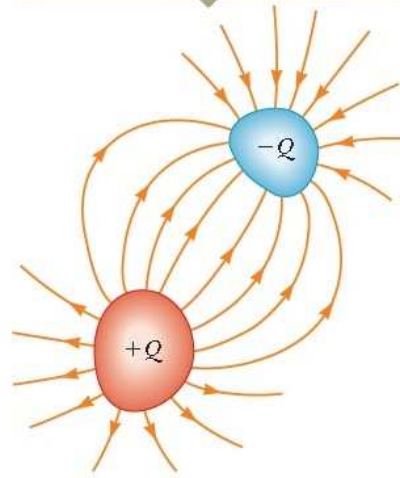


Figure 2-12: A capacitor (Serway & Jewett, 2014: 778).

Serway and Jewett (2014: 777) refer to Figure 2-12 to define a capacitor as: “Consider two conductors as shown in Figure 2-12. Such a combination of two conductors is called a capacitor. The conductors are called plates. If the conductors carry charges of equal magnitude and opposite sign, a potential difference ΔV exists between them.”

As an aside – this definition really applies to mutual capacitance, involving two or more conductors, in contrast to self-capacitance, involving one conductor only. Purcell and Morin (2013) start the discussion of capacitance with a single conductor and calculate its capacitance for a sphere and a disk:

$$C_{sphere} = 4\pi\epsilon_0 R$$

$$C_{disk} = 8\epsilon_0 R$$

where:

C – capacitance (Farad)

ϵ_0 – permittivity in vacuum (Farads per meter)

R – radius (meter)

Serway and Jewett (2014: 779) does not use the term “self-capacitance”, but on the page following the page where a capacitor is defined, it is indicated that “Although the most common situation is that of two conductors, a single conductor also has a capacitance. For example, imagine a single spherical, charged conductor.” Griffiths (1999: 104) explains: “By the way, you will occasionally hear someone speak of the capacitance of a *single* conductor. In this case the ‘second conductor’, with the negative charge is an imaginary spherical shell of infinite radius surrounding the one conductor.”

The spheres from the previous section thus constitute capacitors, either by themselves or as pairs, as spherical conductors or electrodes. Several other shapes will also be considered shortly, including cylindrical and parallel plate. The charge distribution illustrates the creation of charged capacitors in Figure 2-3 (Figure 18.13 (d)). Each of the spheres constitutes an electrode and the separation between the electrodes constitutes the dielectric – which is air in the present case.

For now – even as Earth might have been circled by spheres, Earth might also have been circled with serially connected capacitors. Both could function in the same way when exposed to electrostatic induction. Two points must be made:

- The equator is approximately 40 075 km long. The inherent physics would support electrostatic induction charging to occur over this whole distance – or any further distance for that matter.
- Electrostatic induction charging of capacitors are common occurrences, and in fact constitute part of the standard introduction to electrostatics and physics, as published in OpenStax College (2012: 634).

Effectively all humans spend all their lives in a capacitor! Earth is negatively charged while the ionosphere is positively charged. In between is a layer of air – the dielectric – so the combination of Earth, air and ionosphere constitutes a natural capacitor, apparently with a potential difference of 300 kV between Earth and the ionosphere.

Two more historical examples of electrostatic charging of capacitors will now be discussed: Faraday’s ice pail experiments as well as the Wimshurst electrostatic generator or influence machine. These are by no means the only examples of electrostatic induction in history. The electrophorus is another example of a research instrument in common use that utilises electrostatic induction.

2.5 Historical precedent: electrostatic induction charging of capacitors during Faraday's ice pail experiments

To Michael Faraday, the value of his ice pail experiments resided “in their power to give a very precise and decided idea to the mind respecting certain principles of inductive electrical action” as “They are the expression and proof of certain parts of my view of induction.” (Faraday, 1843b: 199). Faraday appreciated the importance of the experiments, perhaps without appreciating the full impact thereof. This section will demonstrate that Faraday also used an isolated capacitor (the charged ball) and created an isolated ice pail capacitor, as well as a system of serially connected ice pail capacitors – and also used electrostatic charging to create energy in the capacitors.

Faraday did not directly acknowledge that the ice pail experiments originated with Franklin's “silver pint cann” (Franklin, 1769) and later the electric wells of Beccaria (1776) and Cavallo (1777). However, he did acknowledge that “These are all well-known and recognised actions.” (Faraday, 1843b: 200). In his lecture delivered on 20 January 1843, he referred to ice pails as cells, and once as a well – possibly a typographical error (Faraday, 1843a).

All of the above was actually predated by the invention of the Leyden jar. The Leyden jar was invented in both 1745 and 1746 by Ewald Jürgen von Kleist and Petrus van Musschenbroek respectively and independently (Dorsman & Grommelin, 1957). Both Franklin's experiments with the “silver pint cann” and Faraday's ice pail experiments effectively became Leyden jars when the electrostatic charge was inserted.

2.5.1 Single ice pail experiment

The experiment involved an insulated pewter ice pail A, connected by thin wire to an electroscope E. C is a round brass ball hanging by an insulating thread, charged a distance away from the ice pail and then lowered into the ice pail. As C is lowered into the ice pail, the leaves of the electroscope extend.

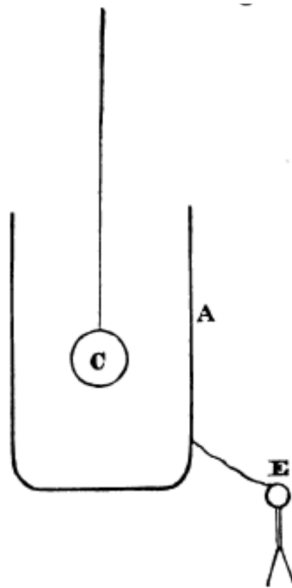


Figure 2-13: Faraday's single ice pail setup (Faraday, 1843b: 200).

A charge q is created on ball C. As C is lowered into A, an equal charge with an opposite polarity is electrostatically induced on the inside of A, and simultaneously an equal charge with similar polarity is induced on the outside of A. The process of electrostatic induction effectively involves pairwise electrostatic induction of charges, where the pairing refers to opposite polarity charges on the near surface and opposite polarity charges on the far surface. This corresponds with Faraday's understanding of the experiment. Typically, all charges on A would disappear if C is withdrawn. However, by touching C to the inside of A, the internal charges eliminate each other and the charges on the outside of A are fixed.

If ball C is touched, electrostatic charges would be conducted. Without touching, only electrostatic induction charging is involved.

Van de Graaff used a shell, similar to an inverted ice pail, as the charge collector and accumulator in an electrostatic generator (1931). It is thus apparent that the ice pail constituted a single isolated capacitor exhibiting self-capacitance – and that electrostatic energy is created in the ice pail whenever the charged brass ball is inserted. It is significant that the electrostatic energy is created in the single isolated capacitor through electrostatic induction charging – if no conduction occurs.

The charged ball C already constitutes an isolated single capacitor also with the property of self-capacitance, containing the charge q in a capacitor with a determinable capacitance.

2.5.2 Multiple ice pail experiment

Faraday also created a multiple ice pail experiment, using four concentric ice pails. Shellac was used to offset the ice pails. The cavities between the ice pails further contained air.

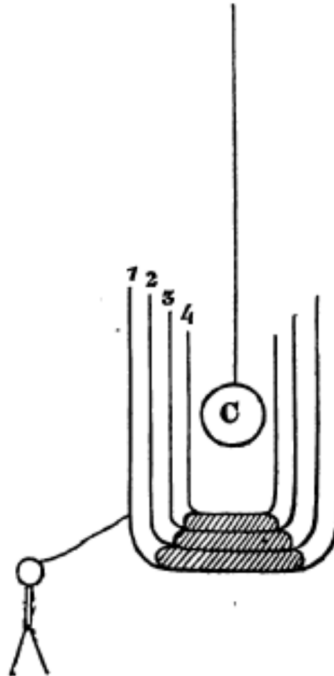


Figure 2-14: Faraday's multiple ice pail experiment setup (Faraday, 1843b: 201).

As the charged ball C is lowered into the cavity of ice pail 4, charges are induced on the insides and outsides of the individual ice pails in the concentric ice pail assembly until charges are induced on the outside of ice pail 1. The charges electrostatically induced on the outside of ice pail 1, activating the leaves of the electroscope, indicates that the intermediate capacitors (4-3, 3-2 and 2-1) must have been energised. The electrostatic induction process had to have proceeded via these intermediate capacitors, as it cannot jump intermediate conductors. Inducing charges on the electrodes of a capacitor, implying capacitance, necessarily implies the induction of electrostatic energy in the capacitors.

Faraday effectively created a set of three serially connected ice pail capacitors, which he then charged via electrostatic induction. Energy was thus induced in each of the capacitors, and removed when he bridged from ice pail 4 to 3 and later also from ice pail 3 to 2.

The created energies were very low – and might thus explain why Faraday did not notice sparks generated during bridging.

Nevertheless, Faraday did electrostatically charge a series of ice pail capacitors.

Even more significantly, Faraday appreciated that if a thousand ice pails (Faraday, 1843a) or even an infinite number of ice pails and insulating layers were used, the electrostatic induction process and the charge induced would remain exactly the same. Faraday posed this as a thought experiment (Gooding, 1985). He appreciated that the action remains exactly the same, without “exaltation or extinction” or even “compression or condensation”, for those following the “idea of the electric force by a fluid” (Faraday, 1843b: 203).

2.5.3 Capacitive consideration of the multiple ice pail experiment

Faraday did not directly associate his experiments with capacitors – but it is vital to evaluate them now from that perspective. Figure 2-15 shows what Faraday achieved electrostatically when he lowered the charged sphere into the inside of the four nested ice pails:

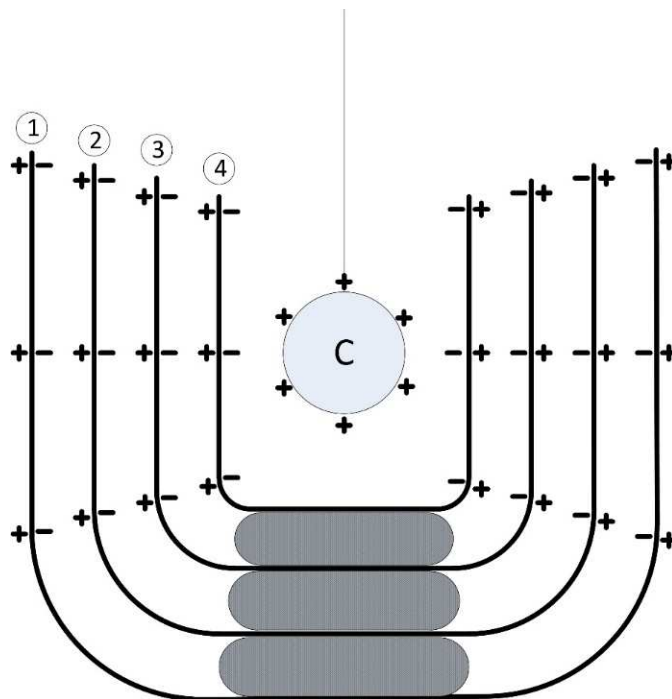


Figure 2-15: Faraday's multiple ice pail experiment setup from an electrostatic perspective.

Faraday's description and illustration of the experiment was used to estimate the energies created in the experiment. Faraday worked at the Royal Institution, which was thus contacted to

establish the whereabouts of the ice pails. Alas, the ice pails are no more – but the archivist, Professor James, recommended relevant literature and also provided access to specific articles.

It appears from Faraday's given diameter of the ice pail and the drawing that the brass ball C might have been 50 mm diameter. Use the equation:

$$C = 4\pi\epsilon_0 R$$

where:

C – capacitance (F)

ϵ_0 – permittivity in vacuum

R - radius

Thus the capacitance of the brass ball C might have been 278 pF.

Faraday's article was published in February 1843, which is just after the European mid-winter. A commentary on London weather (https://booty.org.uk/booty.weather/climate/1800_1849.htm) indicates that 1842/43 was a mild winter. Nevertheless, Faraday likely conducted the experiments in a heated laboratory – with low humidity. Thus, the breakthrough voltage of the air might be assumed as 3 million volts per meter as a maximum value. The air in London, being close to the sea, might, however, easily break through at lower values. The maximum charge on the brass ball C may then be calculated using:

$$Q = ER^2/k$$

where

Q – charge (C)

E – electrostatic field strength (N/C or V/m)

R – radius (m)

k – electrostatic constant of $8,99 \times 10^9 \text{ N.m}^2/\text{C}^2$

Thus, the maximum charge prior to spontaneous discharge would be $2,086 \times 10^{-7} \text{ C}$.

The maximum electrostatic energy stored on the brass ball may now be calculated using:

$$U = Q^2/(2C)$$

where

U – internal energy (J)

Q – charge (C)

C – capacitance (F)

The internal energy is calculated as 0,008 J. This then is the electrostatic energy lowered into the inner ice pail (pail 4).

The following dimensions were used for the pails in the multiple ice pail experiment:

Table 2-5: Dimensions used for the individual ice pails			
	Outer diameter	Inner diameter	Height
Pail	(m)	(m)	(m)
1	0.178	0.174	0.267
2	0.154	0.150	0.243
3	0.130	0.126	0.219
4	0.106	0.102	0.195
Wall thickness	0.002	m	
Gap between pails	0.010	m	

A capacitor is formed between each adjacent pair of ice pails. To estimate the capacitances, three sets of approaches were used:

- The ice pails were replaced by open-ended tubes of equivalent dimensions, to calculate the cylindrical capacitance.
- ANSYS Electronics Desktop 2018.2 was used to calculate the capacitance of the gap between adjacent ice pails, disregarding Faraday's insertion of a shellac disk at the bottom.
- ANSYS Electronics Desktop 2018.2 was used to calculate the capacitance of the gap between adjacent ice pails, including Faraday's insertion of a shellac disk at the bottom.

Table 2-6 summarises the capacitances:

Table 2-6: Capacitance calculation per gap and approach			
Capacitor gap	Open-ended tubes (F)	Pails without shellac (F)	Pails with shellac (F)
Pail 1 - Pail 2	1.107E-10	1.33E-10	1.74E-10
Pail 2 - Pail 3	8.514E-11	1.02E-10	1.30E-10
Pail 3 - Pail 4	6.276E-11	7.47E-11	9.32E-11

The progression in capacitance from an open tube system to two nested pails without shellac, and then to two nested pails with shellac at the bottom, provides a relatively comprehensive view. As the surface area increases from the nested tube assembly to a nested ice pail assembly – the capacitance increases. The capacitance then further increases as shellac, with a higher relative permittivity of 3,5 versus approximately 1 for air, is added at the bottom of the ice pails. The progression lends credibility to the capacitance for the nested ice pails with shellac.

The calculated maximum charge ($2,086 \times 10^{-7}$ C) that can be inserted via brass ball C is now inserted into the cavity of ice pail 4 – to electrostatically induce the same charge in the serially connected capacitors. Table 2-7 summarises the induced potential differences between the electrodes (ice pails) of each capacitor as well as the induced internal energy:

Table 2-7: Potential difference and internal energies of capacitors					
Capacitor gap	Potential difference (V)	Internal energy (J)	Longest spark length (mm)	A (mm²)	L = A^{0.5} (mm)
Pail 1 - Pail 2	1 202	0.00013	0.40	849	29
Pail 2 - Pail 3	1 600	0.00017	0.53	638	25
Pail 3 - Pail 4	2 239	0.00023	0.75	456	21

Faraday did discharge the capacitors between pails 4 and 3 and then also between pails 3 and 2 (Faraday, 1843b). Nevertheless, he did not indicate that he saw any sparks as he discharged the capacitors. This may be due to any of three reasons:

- Faraday was watching the leaves on the electroscope, as he reported that the discharge did not affect the leaves (Faraday, 1843b).
- The energy involved is very small – ranging from 0,00017 to 0,00023 J for the two relevant gaps. The spark lengths might have been 0,53 to 0,75 mm at best.

- His method of bridging the gap was via a wire suspended from a silk thread, which likely caused the bridging to occur below the rim of the ice pail assembly (Faraday, 1843b) – reducing the likelihood of observation. The likelihood of sparks not being seen would have increased if the wire was suspended longitudinally from the silk thread – which would have ensured that contact would only be made towards the bottom part of ice pails.

The last two columns of Table 2-7 demonstrates the area and square length of parallel plate capacitor electrodes with equivalent capacitance to the relevant ice pail capacitor gap, assuming a 130 micron thick Mylar[®] dielectric between the electrodes. In such an experiment, the actual capacitance may be measured to compare to the required capacitance, and then the capacitor may be charged to the relevant potential difference. Then note the difficulty of observing a spark at bridging the electrodes.

Faraday may be forgiven for not seeing the sparks, and thus not realising that he electrostatically induced energy in the capacitors.

2.5.4 Review of Faraday's ice pail experiments

Faraday:

- Charged capacitors via electrostatic induction, as discussed.
- Perceived that electrostatic induction would function the same, whether there are only four or a thousand ice pails (Faraday, 1843a) or an infinite number (Gooding, 1985). “Not the smallest amount of power is lost in these experiments (Faraday, 1843a: 178). Note that Faraday actually referred to energy when he used the term “power”.
- Faraday unfortunately did not see that he could increase the number of capacitors and especially the electrostatic energy induced in them, to infinity without losing the smallest amount of energy. Faraday paused at the threshold of his biggest discovery.

Why did he not see? The transcript of the lecture at the Royal Institution on 20 January 1843 (Faraday, 1843a) contains multiple references indicating that his primary objective was to convey his thoughts on atmospheric electricity. His letter to Phillips of 4 February 1843 (Faraday, 1843b) also culminates with thoughts on lightning. Pasteur refers to the “prepared

mind” as prerequisite for observation. Faraday was definitely not focused on perceiving new insights at the time. For some reason, atmospheric electricity absorbed him. His mind was thus prepared for atmospheric electricity.

Furthermore, Faraday’s faith in the law of conservation of energy also prevented him from seeing what he attained:

All the variation we make in the power, whether you dispose of it here, or by induction, either on the outside, or making it exert a thousand varying powers of different radii, all these cause not the slightest disturbance in the ultimate power; owing to this one thing, that you cannot create power nor destroy it, although you may convert one force into another; as, for example, the heat of fuel into the power of the steam-engine; but you can neither add nor take away, although you may waste and divert. (Faraday, 1843a: 178).

Despite all deliberations, Faraday would have been the first to witness that it was simply not God’s will to reveal specific insights at the time.

2.6 Historical precedent: electrostatic induction charging of capacitors within the Wimshurst machines

2.6.1 The Wimshurst machine

James Wimshurst built his influencing machine in 1881 (Thompson, 1888: 611), using the influence or electrostatic induction mechanism.

Bringing a charged source closer to a conductive target, as in Figure 2-3 (Figure 18.13 (b)), initiates the functioning of a Wimshurst electrostatic generator:

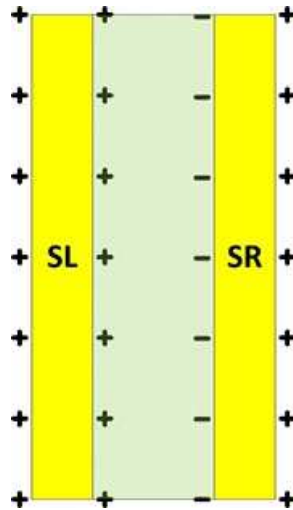


Figure 2-16: Electrostatic induction of charge on opposing sector (SR).

A charge, here indicated with a positive polarity, on SL (sector on left hand wheel) electrostatically induces a negative charge on the nearside face of the opposing SR (sector on right hand wheel). Simultaneously a positive charge is induced on the far side face of SR.

The above charge distribution is based on the assumption that the initial charge distribution on SL is unaffected by the electrostatically induced opposite charge on SR. Thus, if SL was far away from any other conducting body, and given that SL is in fact a thin sheet, the charge distribution on both sides would be uniform. The assumption is then that the initial charge distribution is not changed when SR is brought in proximity to SL.

2.6.2 Does charge always distribute uniformly, and what does it mean?

If the initial charge distribution on SL is not maintained, that would imply that all the charge on SL would eventually migrate to the face closest to SR1 (this SR is denoted 1 to differentiate it from a coming SR2). Then the charge distribution over SL and SR1 would be presented as:

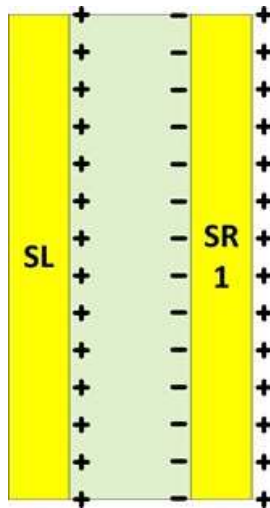


Figure 2-17: Electrostatic induction of charge on opposing sector, assuming charge concentration on source.

The face closest to SR1 would have double the previous charge density – while the face away from SR1 would have no charge. This actually contravenes Thomson’s theorem of electrostatics, which may be stated as: “The electrostatic energy of a body of fixed shape and size is minimized when its charge Q distributes itself to make the electrostatic potential constant throughout the body.” (Zangwill, 2012: 128). A non-uniform charge distribution over uniform geometry would cause non-uniform electrostatic potential, which is not possible. The assumption would thus be correct.

To support this conclusion, consider the final charge distribution if a second electrode sector (SR2) were to be added on the side of SL, away from SR1:

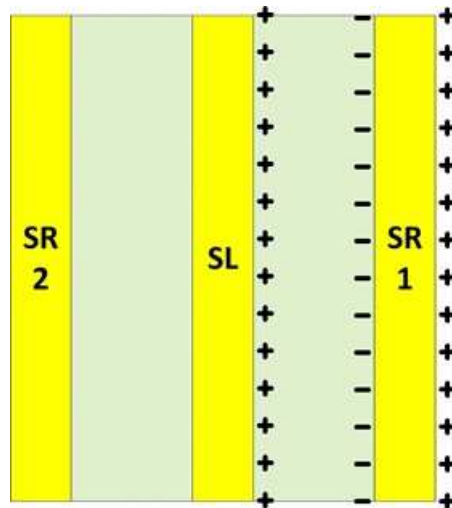


Figure 2-18: Charge distribution after addition of further sector (SR2), assuming charge concentration on source.

If no charge appeared on the side of SL closest to SR2 – then no charge would appear on SR2, as shown.

However, if the charge on SL was uniformly distributed:

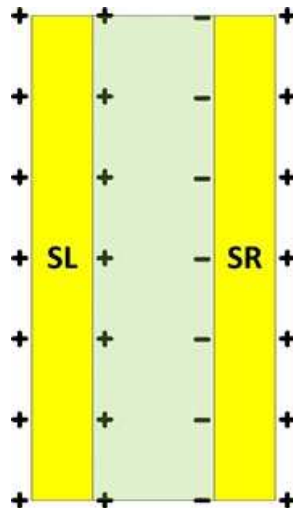


Figure 2-19: Electrostatic induction of charge on opposing sector (SR) assuming uniform charge distribution on source.

Then the final charge distribution after addition of SR2 would be as follows:

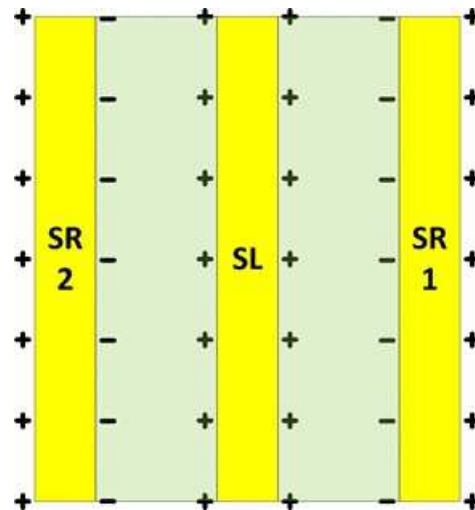


Figure 2-20: Charge distribution after addition of further sector (SR2) assuming uniform charge distribution on source.

It would have been untenable to have two different charge distributions, depending on the order in which a set of bodies is created.

2.6.3 Now that we agree on uniform distribution of charge

In the Wimshurst electrostatic generator, a set of SL and SR would rotate past brushes that are earthed by a conducting arm. Typically, at that stage the away brush (SR1) would be in contact with a diametrically opposed sector (SR2 – diametrically away from SR1 on the disc). The electrostatic field between SL1 and SR1 would ensure that the positive charges on SR1 would attempt to get as far away as possible from SL1. The brushes and conducting arm present an escape route to SR2 (even further away from SL1), as presented:

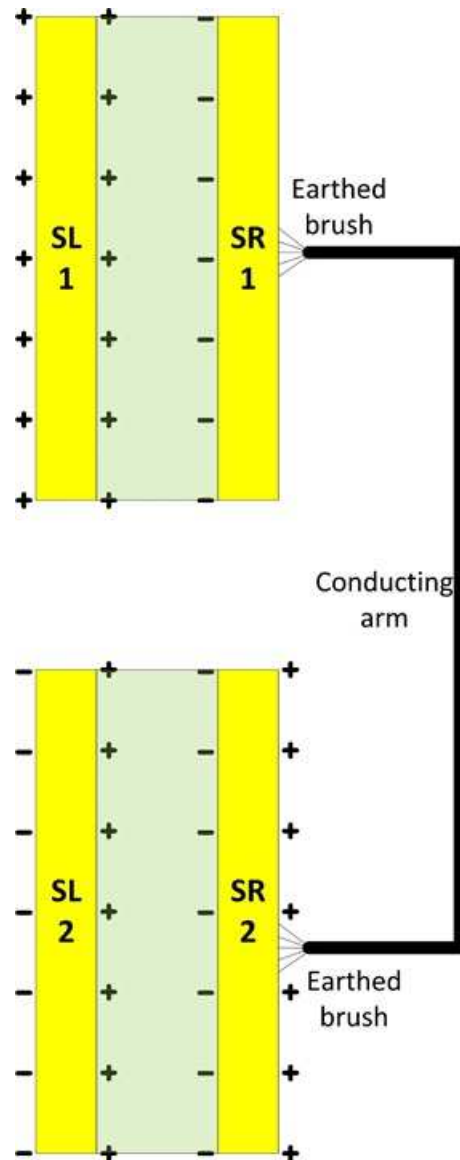


Figure 2-21: Using the outside charge on SR1 to charge second capacitor.

The operation of a Wimshurst machine may be split between generation and harvesting. The generation cycle would contain two activities:

- Electrostatic induction of charge on opposing sector (SR) as shown in Figure 2-16.
- Using the outside charge on SR1 to charge second capacitor (SL2 and SR2) as shown in Figure 2-21. Note that charge was created on the outside face of SL2. This charge could be utilised to initiate a next generation cycle.

Electrostatics illustrate the dual role of capacitors (best illustrated with parallel plate capacitors):

- Both steps in the generation cycle of the Wimshurst machine's operation illustrate capacitors functioning as pipelines or conduits or conductors for electrostatic charge. A charge added to an outside face of a capacitor will be repeated on the other outside face of the capacitor, of the same magnitude but with an opposite polarity. Similarly, a charge added to a serial stack of parallel plate capacitors would emerge on the other side, with an opposite polarity.
- The conduction of charge through the capacitor would then also activate the classical role of a capacitor: as an energy storage device.

The Wimshurst machine does not extract the energy created in the sector capacitors. It only extracts and stores the transmitted charges for storage in Leyden jars, which are also capacitors.

2.6.4 Possible improvements to the Wimshurst machine

A Wimshurst machine relies on capacitors being charged. It currently utilises sectors mounted to the outsides of two counter-rotating discs. The Wimshurst operation continuously deposits and removes charges from the outsides of the capacitors – where charges are not electrostatically bound by Coulomb forces, as are the charges on the insides of the sectoral electrodes.

Therefore, the capacitors on the insides of the electrodes are never tapped. The energy is never harvested. This energy might be harvested and, in fact, increased by adding stationary discs with sectors between the rotating discs, as shown in Figure 2-22.

The objective of the Wimshurst is to create electrostatic energy, typically via the two Leyden jars which conventionally accumulate the charges. This energy might thus be increased.

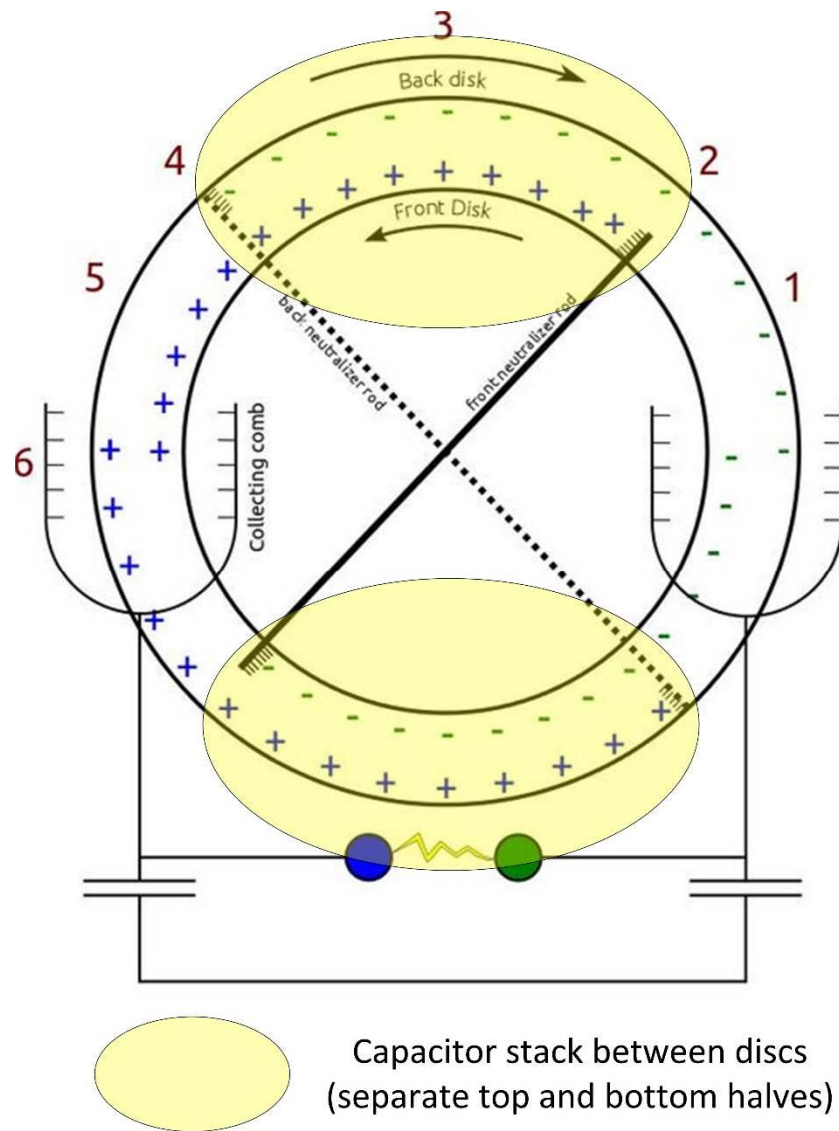


Figure 2-22: Improved energy collection. Modified from (Strait, 2019).

The collecting combs removing charge to the Leyden jars are typically aligned in a horizontal plane and they collect charge from the outsides of both disks simultaneously. This leads to an inefficiency, where the electrostatic charge on the outside face of a sector is not automatically stationary and pushing the charge onto the opposite face towards that side's collecting comb. At the moment, the collecting combs appear to try to collect the pushing and the pushed charges simultaneously.

Charge collecting efficiency will be improved by delaying charge collecting on both sides of, for example, the front disk (as shown in Figure 2-23); such that the front disk's collecting combs, on both sides, would then be mounted one sector later (in terms of the direction of rotation) than the collecting comb of the back disk.

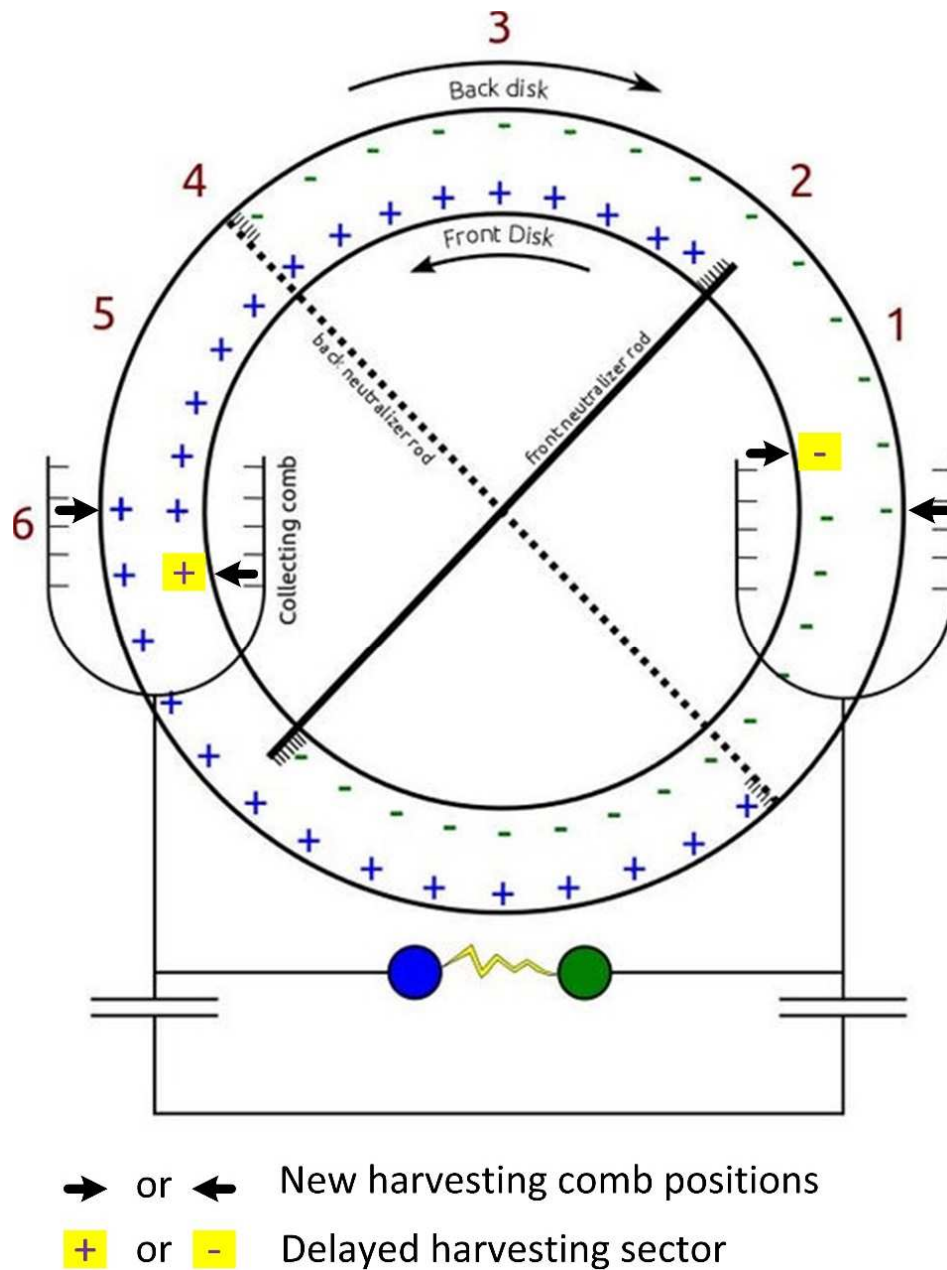


Figure 2-23: Improved charge collection. Modified from (Strait, 2019).

This section supports electrostatic induction charging of capacitors as a known phenomenon.

2.7 Revisit history: impact of electrostatic induction charging of a capacitor on Maxwell's equations

"Maxwell's electromagnetic theory is one of the founding theories on which modern electrical science is based." (Selvan, 2009: 36). This sentiment prevails through most of literature.

Several articles describe Maxwell's innovation of the displacement current, enabling him to complete the set of four equations and particularly enabled Ampère's law to be applied to non-continuous loops as encountered when charging a capacitor, using an electromagnetic conduction current. Griffiths (1999: 322) explains the initial fatal inconsistency in Ampère's law which becomes evident when the divergence is taken on both sides:

Ampère's law in differential form: $\nabla \times \mathbf{B} = \mu_0 \mathbf{J}$

Applying divergence: $\nabla \cdot (\nabla \times \mathbf{B}) = \mu_0 (\nabla \cdot \mathbf{J})$

The left-hand side of the above equation would be zero, as the divergence of a curl must be zero. However, the right-hand side (permeability of free space multiplied by the divergence of the current density) only approaches zero with a steady current as a magnetostatic configuration. The Amperian loop consideration also shows the inconsistency where the currents flowing through different surfaces culminating in the same Amperian loop are not equal. Multiple authors illustrate the Amperian loop with one surface outside and another surface inside a capacitor:

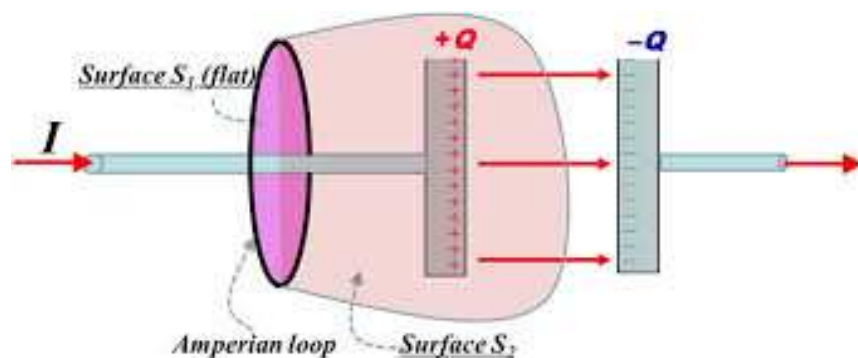


Figure 2-24: Amperian loop showing inconsistency in Ampère's law (Danylov, 2018: 4).

Maxwell then creatively introduced the displacement current to solve the inconsistency (Griffiths, 1999), (Selvan, 2009), (Danylov, 2018):

Ampère-Maxwell law in differential form: $\nabla \times \mathbf{B} = \mu_0 \mathbf{J} + \mu_0 \epsilon_0 \frac{\partial \mathbf{E}}{\partial t}$

The Maxwell displacement current stimulated controversy, but laid the foundation for the electromagnetic wave equation and led to the discovery of radio waves by Hertz in 1887 with publication in 1888 (Griffiths, 1999), (Sengupta & Sarkar, 2003). Even in 1964, Professor Richard Feynman was teaching at the California Institute of Technology: “All of electromagnetism is contained in the Maxwell equations.” (Feynman, 1964b: 2).

The displacement current is still a controversial research topic. One example of such research is by Paulus and Scheler (2015). They conducted heterodyne detection of the displacement current:

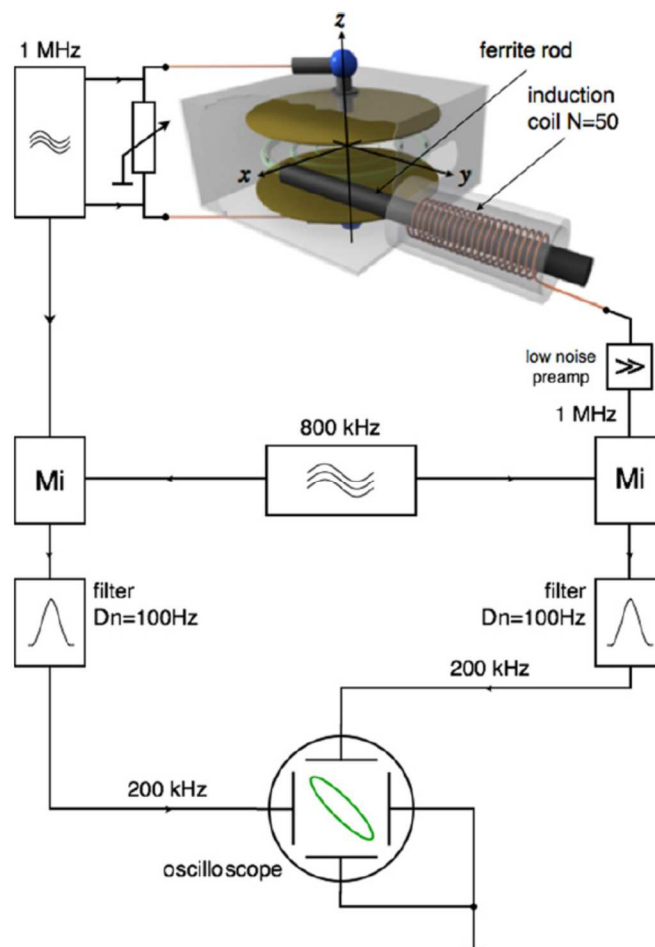


Figure 2-25: Heterodyne detection of the displacement current (Paulus & Scheler, 2015: 6).

The present research allows less complex detection of the displacement current, albeit in an indirect way. Consider the more explanatory version of the Ampère-Maxwell law, after Feynman (1964a):

“For a surface S bounded by the curve C , Equation 1.9 holds:

$$c^2(\text{circulation of } \mathbf{B} \text{ around } C) = \frac{d}{dt} (\text{flux of } \mathbf{E} \text{ through } S) + \frac{\text{flux of electric current through } S}{\epsilon_0}$$

The constant c^2 that appears in Eq. (1.9) is the square of the velocity of light. It appears because magnetism is in reality a relativistic effect of electricity. The constant ϵ_0 has been stuck in to make the units of electric current come out in a convenient way.”

The existing magnetic field would thus be caused by the changing electric field (Maxwell called this term the displacement current) as well as a conventional current. Displacement current research might have to take special measures to reduce the impact of the conventional current. Current research might now investigate the validity of the Ampère-Maxwell law without any conventional current being present; by electrostatic induction charging of a capacitor.

It is accepted that a changing electric field would cause a magnetic field. “The presence of the term $\delta D/\delta t$ in the right-hand side of Ampère’s law literally means that a changing electric field causes a magnetic field, even when no conduction current exists” (Selvan, 2009: 41). “According to Roche [5], the investigations by Purcell, Zapolsky, and Bartlett demonstrated that ‘the displacement current of a rapidly changing induced electric field will generate a significant magnetic field.’” (Selvan, 2009: 42). Also: “A changing electric field induces a magnetic field.” (Griffiths, 1999: 323).

One of the major breakthroughs by Maxwell (1865) was to predict electromagnetic waves due to the interplay between electric fields and magnetic fields. Now, given that the capacitor was a material component in finalising the Maxwell equations, it would be significant if:

- a capacitor could be charged via electrostatic induction, that is without any conventional current being present; and
- that capacitor then indicated the presence of a displacement current by emitting electromagnetic pulses which could be related back to the capacitor.

Roche (1998: 160) discussed some of the disputes on Maxwell’s equations. Lorentz postulated an equation for the magnetic field intensity – where no displacement current is present. “In Lorentz electromagnetism, however, the interpretation of $\delta D/\delta t$ as a displacement current now

lost all justification because it did not represent a disturbance of an ether, nor did it produce a magnetic field, nor was it acted on by a magnetic field.” (Roche, 1998: 160). Given success with the experiments, some doubt will be cast on Lorentz’s equation.

Roche (1998: 161) further shared: “In 1922 Max Planck (1858–1947) accepted that $\delta D/\delta t$ produces a magnetic field, but demonstrated that the symmetries of this function ensure that no magnetic field is actually produced when the changing electric field is a conservative field.” An electrostatic field is by nature a conservative field, where changes in the position of charges may imply storage of potential energy. It would be a challenge to establish whether the Van de Graaff source of electrostatic charge would constitute a conservative field, especially when it changes, and whether a magnetic field will then be produced.

Roche (1998: 161) further shared other experimental findings: “Purcell, Zapolsky and Bartlett’s investigations make it clear that, even in Maxwell theory, only the displacement current of a rapidly changing induced (or vortex) electric field will generate a significant magnetic field. In the special case of a steadily charging capacitor the magnetic field between the capacitor plates is entirely caused by the currents in the leads and in the plates. The displacement current itself then makes no contribution.”

Even after this overview, Roche (1998: 162) proceeded to put himself at risk: “The above results suggest that only a very small component of the magnetic field between the plates of a capacitor, if indeed any at all, will be caused by displacement currents—even if we accept Maxwell’s theory.” An experiment without any conduction currents would thus provide vital insight.

Roche (1998: 162) described the charging currents for a circular plate capacitor; to then conclude: “... both the electric and magnetic fields between the plates are caused by the conduction currents alone. The quantitative association between these two fields is expressed by Maxwell’s magnetic vorticity equation $\nabla \times \mathbf{H} = \frac{\partial \mathbf{D}}{\partial t}$.” (Roche, 1998: 163).

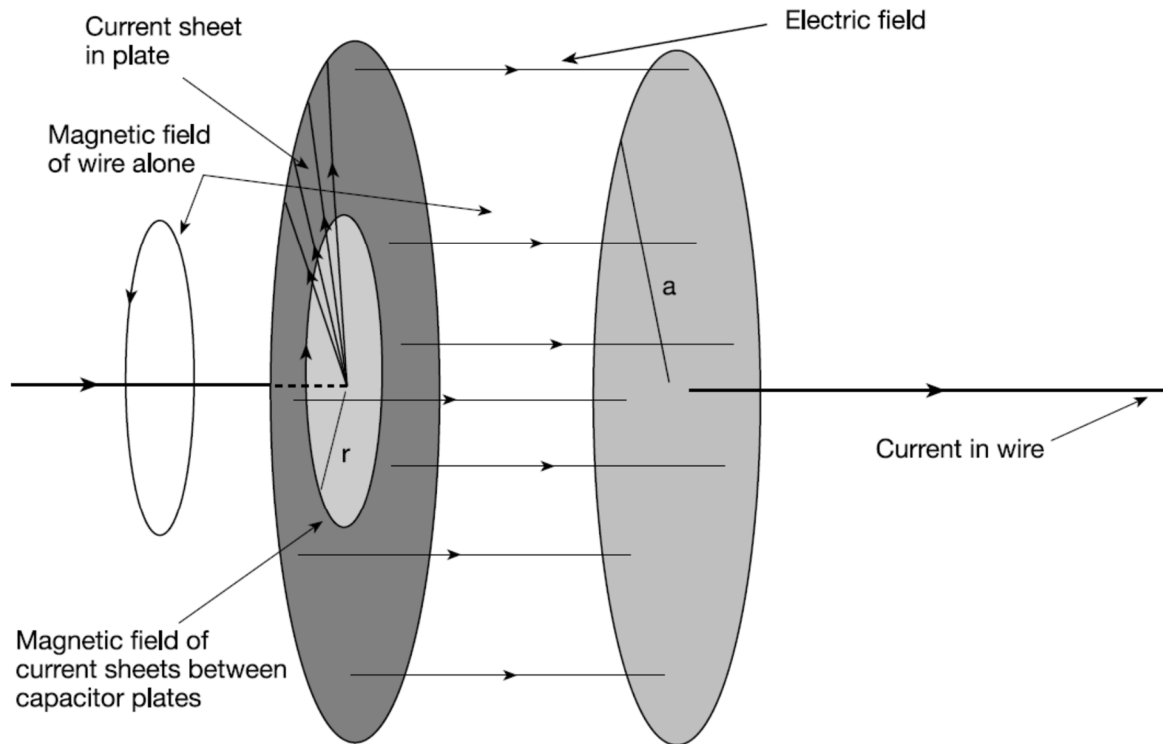


Figure 2-26: Roche's capacitor for calculation of the displacement current (Roche, 1998: 163).

In order to compare with Roche's conclusion, it would be good to use a circulate plate capacitor in the experiment, and then to charge it via electrostatic induction, in the absence of any conduction currents.

Jackson (1999) disagrees with Roche's treatment and conclusions regarding the displacement current during charging of a capacitor. Alternative treatments are provided, which will better inform the experiments. In conclusion: "Maxwell is wrong if he asserts that the displacement current is a real external current density on a par with the conduction current density, but he is right if he says that it is electromagnetically equivalent (in the sense that it can appear on the right-hand side of the Ampère–Maxwell equation together with the conduction current density)." (Jackson, 1999: 499). Roche (2000) replied to Jackson's comment. Jackson (2000) commented in turn to Roche's response.

In the conceptual setup of the experiment, there would be only a changing electric field, with no movement of particles. Some authors depend on particle movement to explain phenomena.

These experiments will be discussed in Chapter 4. Note that the detection of electromagnetic waves will support Maxwell's insistence that the displacement current exists, and that it is "electromagnetically equivalent" to the conduction current. The electromagnetic equivalence will be very interesting as the displacement current can be shown not to flow as a conduction current (the loop is open), yet it might induce electromagnetic waves.

Given all the uncertainties on the interpretation of Maxwell's displacement current, a next round of experiments where the electrostatic source is a radioisotope would add insight. In such an application, the growth rate of the electric field is stable, there is no conduction current at all, and care should be taken to prevent polarity reversal on the Faraday shell.

Electromagnetic waves, including the electrostatic induction signals, generate a spectrum of harmonics which may obscure the intended results. Initial pulse generation might thus rather be a cyclic signal than a pulse signal. It would be imperative to consult radio frequency experts to design the test protocol, as that can yield additional credibility.

2.8 From history to the present: Electrostatic induction in TENG and MEMS

TENG refers to triboelectric nano generators, seeking to "convert mechanical energy into electricity, which are mainly based on the coupling between triboelectrification and electrostatic induction" (Lin *et al.*, 2016: 1). TENG uses four electrostatic induction approaches:

- "(a)The vertical contact-separation mode.
- (b)The in-plane sliding mode.
- (c)The single electrode mode.
- (d)The free-standing triboelectric-layer mode."

illustrated as:

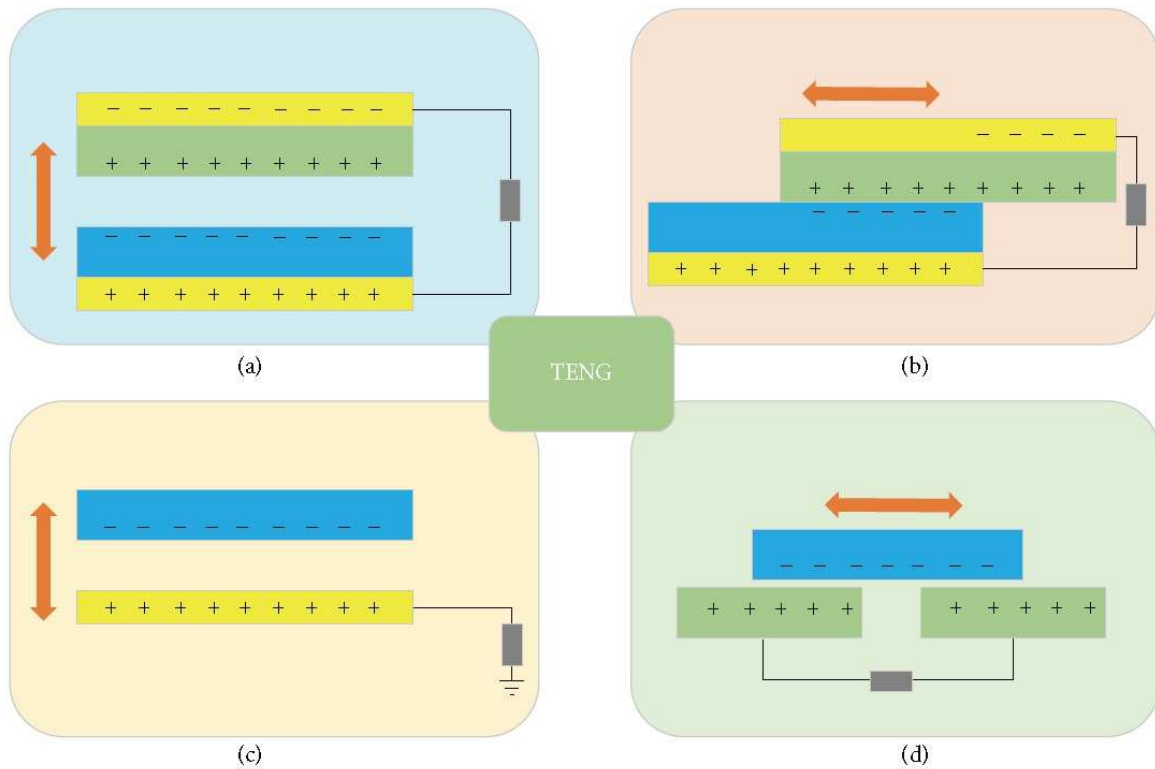


Figure 2-27: Four fundamental modes of TENG (Lin *et al.*, 2016: 2).

TENG requires access to specialised materials and research resources, and relies on friction-based triboelectricity. For these reasons TENG was considered to be outside the scope of the current research.

An example of MEMS is the paper on “Generating electric power with a MEMS electroquasistatic induction turbine-generator” (Steyn *et al.*, 2005). The same evaluation as with TENG holds. MEMS research required resources, such as microscopes and micro-machining abilities beyond current access.

2.9 Comparison between electrostatic induction charging of a capacitor and conventional current charging

What are the performance differences of electrostatic induction charging of capacitors versus the conventional way using electromagnetic conduction currents? Review the energy physics of charging capacitors in either modality.

2.9.1 Charging a capacitor via electrostatic induction

2.9.1.1 Physics of electrostatic induction of conductors

Electrostatics radiate from the attraction of oppositely charged entities as well as the repulsion of similarly charged entities, as quantified in Coulomb's law (for charges q_1 and q_2 at separation r_{12} in direction $\mathbf{e}_{12}$):

$$\mathbf{F} = \frac{q_1 q_2}{4 \pi \epsilon_0 r_{12}^2} \mathbf{e}_{12}$$

Feynman (1964b: 2) held that: "Everything can be obtained from Coulomb's law and some integration ...", while Purcell and Morin (2013: 11) concluded: "In principle, Coulomb's law is all there is to electrostatics. Given the charges and their locations, we can find all the electrical forces."

Purcell and Morin (2013: 12) highlighted the nature of an electrostatic field and the utility of energy considerations due to the conservative nature: "Energy is a useful concept here because electrical forces are conservative. When you push charges around in electric fields, no energy is irrecoverably lost. Everything is perfectly reversible." Another consequence of this conservative nature, is that the energy associated with charge movement is path independent (Feynman, 1964b: 5). Purcell and Morin (2013: 12) concurred: "This work is the same whatever the path of approach." Else: "The electrostatic or Coulomb force is conservative, which means that the work done on q is independent of the path taken. This is exactly analogous to the gravitational force in the absence of dissipative forces such as friction. When a force is conservative, it is possible to define a potential energy associated with the force, and it is usually easier to deal with the potential energy (because it depends only on position) than to calculate the work directly." (OpenStax College, 2012: 664)

Another building block of electrostatics is that charge is quantized. An electron and a proton carry charge of equal magnitude but opposite polarity. While these atomic particles are built up of quarks – no single quark has yet been measured. A quark carries 1/3 or 2/3 of the standard electron charge.

The combination of path independence and charge quantization implies that electrostatic problems, which this research is concerned with, are reduced to either:

- energy being required to move a certain quantity of charge (irrespective of the polarity) to a higher potential energy in the electric field; or that

- energy becomes available by moving a quantity of charge to a lower potential energy position.

The current section deals with conductors in the electrostatic field. Griffiths (2013: 98) summarises the properties of conductors in electrostatic fields:

- The electric field $E = 0$ inside the conductor.
- The electric charge $\sigma = 0$ inside the conductor (provided no specific and isolated charge has been located inside the conductor).
- Net charges can only exist on the surface.
- The same potential must be present throughout the conductor.
- The electric field E must radiate perpendicular to the surface, directly outside the surface.

Given that these properties are respected in any potential charge distribution, the uniqueness theorems ensure that such a possible solution is in fact the only solution (Griffiths, 2013: 119).

A conductor placed in an electric field will thus exhibit the following charge distribution:

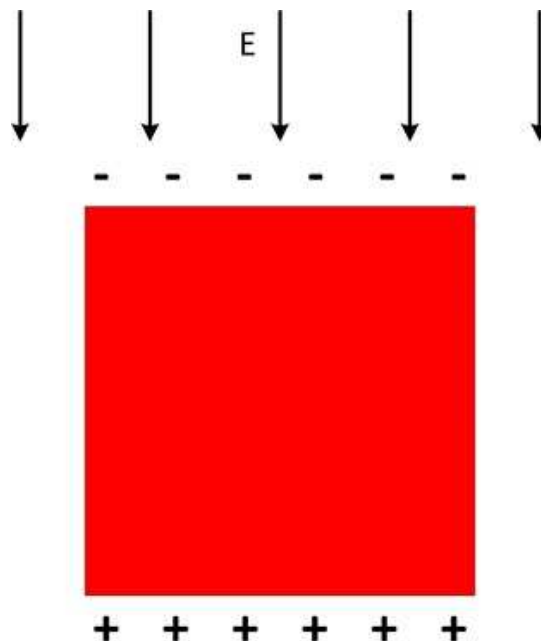


Figure 2-28: Charge distribution on conductor in an electric field.

However, the conductor does not have to be a solid. It may comprise different conductors, electrically connected. Zangwill (2012), for instance, considered the calculation of a dipole moment, using two separated conducting spheres connected by a thin conductor:

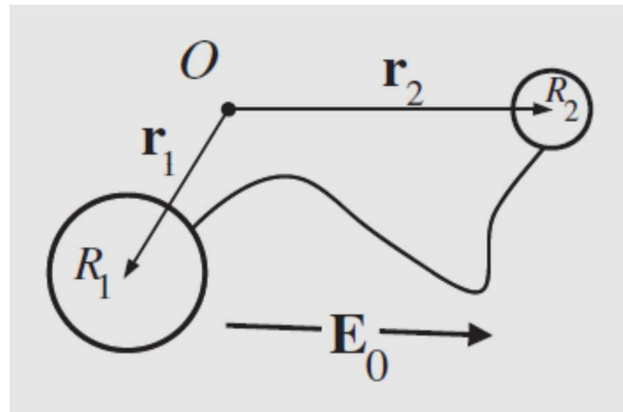


Figure 2-29: Single conductor within an electric field. (Zangwill, 2012: 130).

Charge on the conductor polarizes in the electric field such that each sphere will carry an opposite polarity. It is thus possible to incorporate a switch in the intermediate conductor. This switch will capture or freeze charge polarization, enabling the different charges to remain on the spheres even after the electric field is removed.

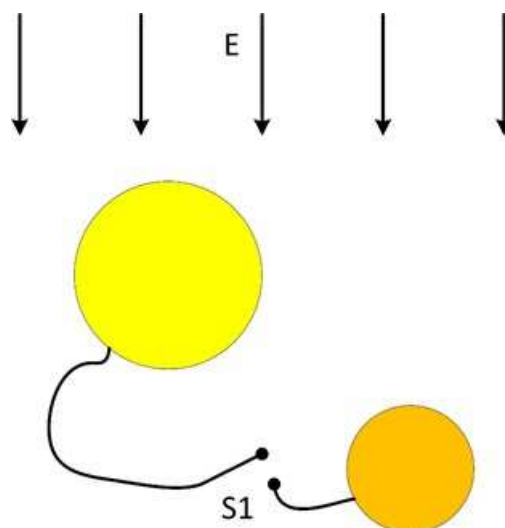


Figure 2-30: Two spheres with intermittent connection in electric field.

By proper timing of the switch closure and opening, charges with opposing polarities might be captured on separate spheres – without the conventional work input to move charge from one position to another in an electric field.

It is vital to recognise this important advantage of electrostatic induction: charges can be moved a required distance in the electric field without doing any work. Then the charges might be frozen in position, implying that the energy is now available for use.

2.9.1.2 Charging a double plate capacitor via electrostatic induction

This system with two spheres is generically equivalent to a capacitor. Consider the following capacitor, placed in an electric field with the resulting charge distribution:

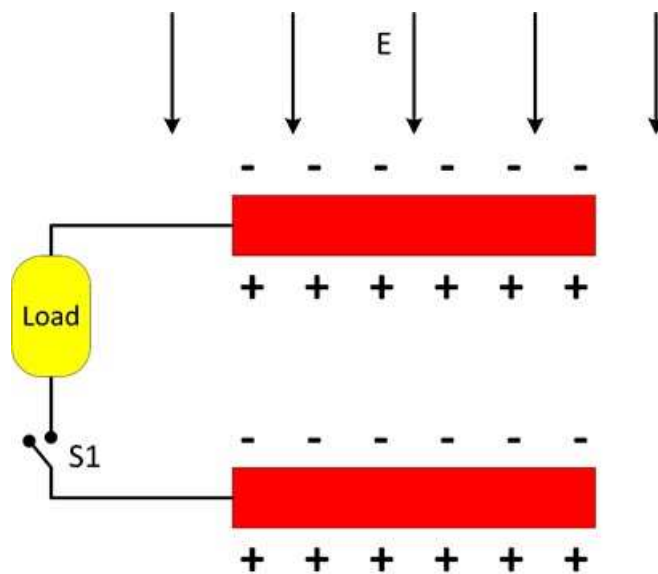


Figure 2-31: A capacitor in an electric field, prior to energy harvesting.

When switch S1 is closed, the charges inside the capacitor are used to send energy through the load:

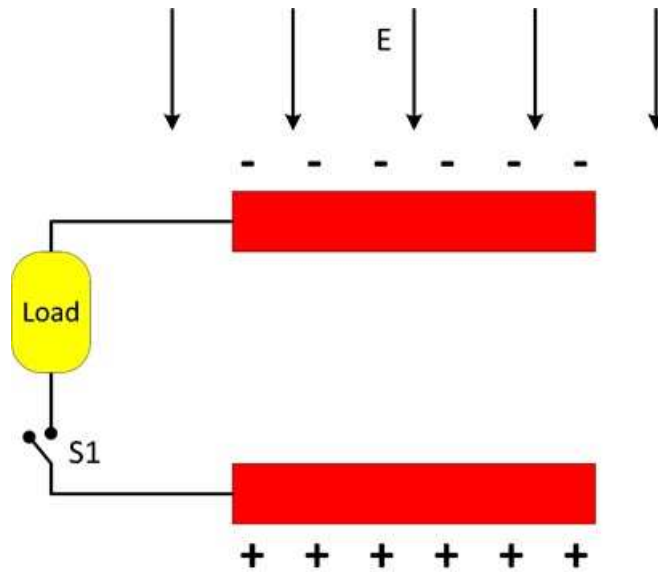


Figure 2-32: A capacitor in an electric field, after energy harvesting.

2.9.1.3 Charging a single plate capacitor via electrostatic induction

The review of capacitor principles in paragraph 2.4 on page 40, introduced the concept of self-capacitance. Self-capacitance is a well-known phenomenon in electrostatics, especially via the Van de Graaff electrostatic generator. The conducting spheres used to convey charges also exhibit self-capacitance. Charge may also be conveyed using an electrophorus, the single conducting disc with an isolated handle. The electrophorus is thus another single plate capacitor in common use.

Due to self-capacitance, a single plate will also constitute a capacitor, and it can also be charged via electrostatic induction. Figure 2-33 shows the single plate capacitor in the electrostatic field, with the electrical layout required for effective operation:

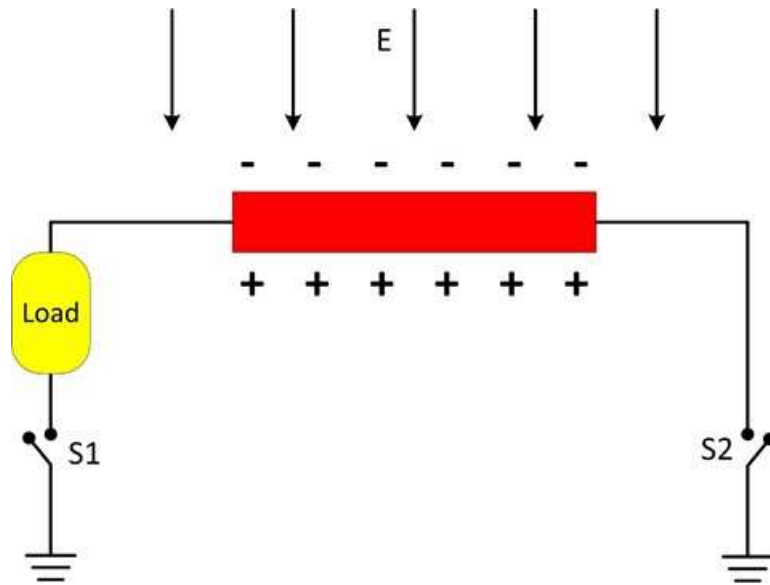


Figure 2-33: A single plate capacitor in an electric field, after electrostatic induction.

Charges will be generated maximally if the single plate capacitor is oriented perpendicular to the direction of the electric field. This will offer the maximum cross-sectional area for electrostatic induction.

At this stage, the charges and the energy on the capacitor are not available for use, and if the capacitor is now removed from the electric field, the charges would disappear. After the capacitor has been charged, the charges on the face of the capacitor that is away from the source of the electric field must be removed by closing switch S2 to earth. This action ensures that the remaining charges will exist even if the field is interrupted. Directly after grounding, switch S2 is opened again. The “away-side” charges are no longer on the capacitor:

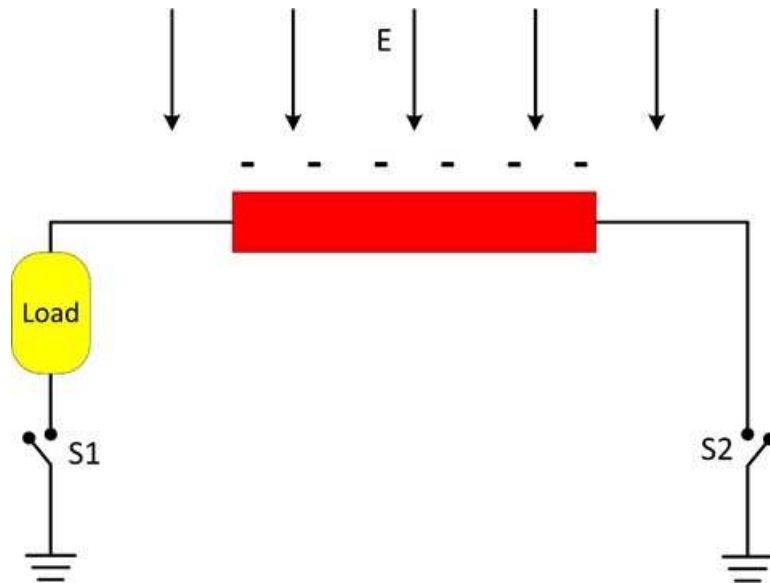


Figure 2-34: A single plate capacitor in an electric field, after charge removal.

The electric field E must now be removed, or the capacitor removed from the field E , or the capacitor shielded from the field, before the energy on the capacitor can be harvested. Once the capacitor is isolated from the field, charges will distribute themselves over the whole capacitor, and may be channelled via the load once switch $S1$ is closed. By closing switch $S1$, the energy on the capacitor is used in the load:

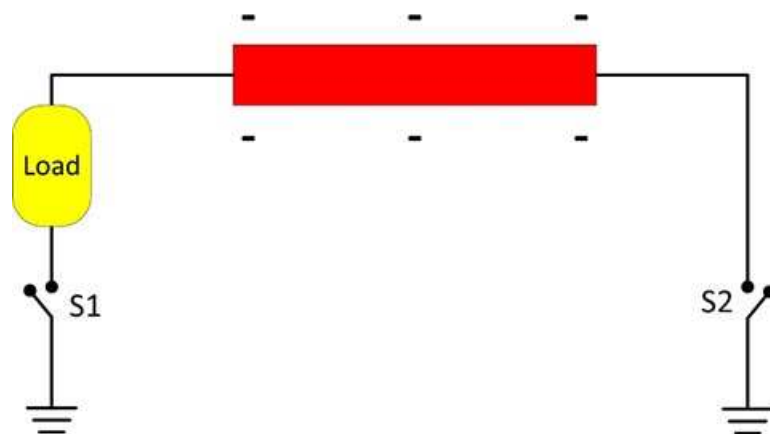


Figure 2-35: A single plate capacitor, prior to energy harvesting.

The above cycle demonstrates the concept, but can be improved to utilise all charge, on both the nearside and the away side faces of the single plate capacitor. Charge availability can be doubled by using the load connection to divert the away side charges. Herewith the single plate

capacitor with the modified electrical layout. It is Grace that more output may be generated with less resources:

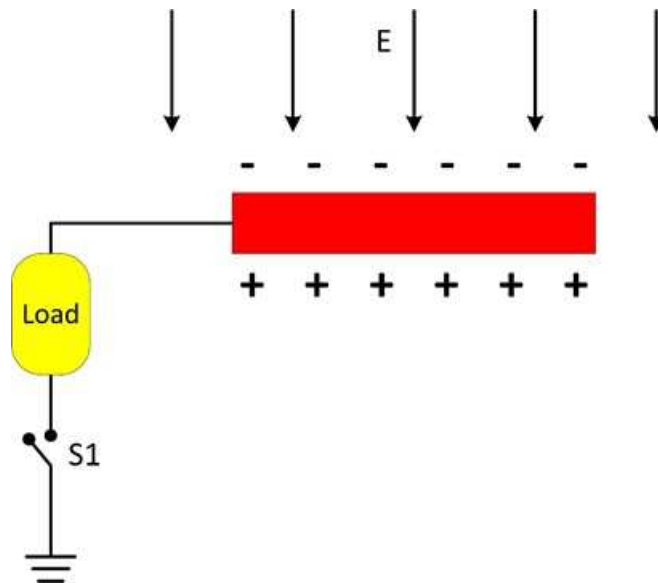


Figure 2-36: A single plate capacitor in an electric field, prior to initial energy harvesting.

When switch S1 is closed, the away side charge and energy channels through the load. Figure 2-37 shows the set-up directly after the away side charges have been removed:

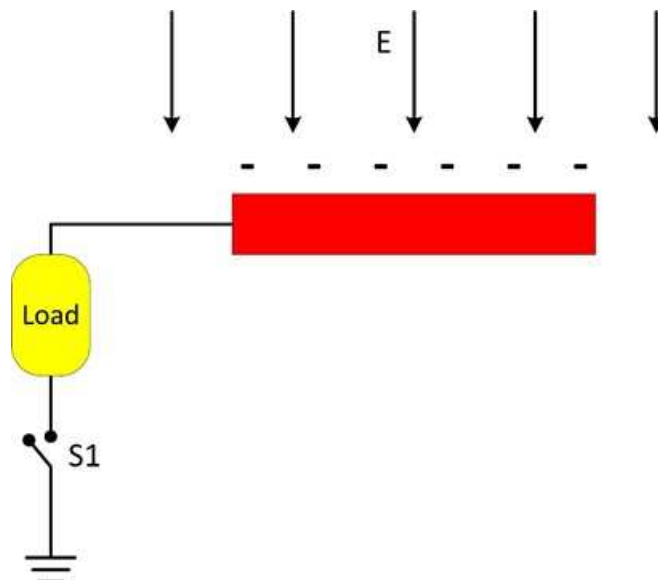


Figure 2-37: A single plate capacitor in an electric field, directly after initial energy harvesting.

The single plate capacitor must now be shielded from the electric field, prior to the second round of energy harvesting. Charges will redistribute themselves in the absence of the electric field exposure:

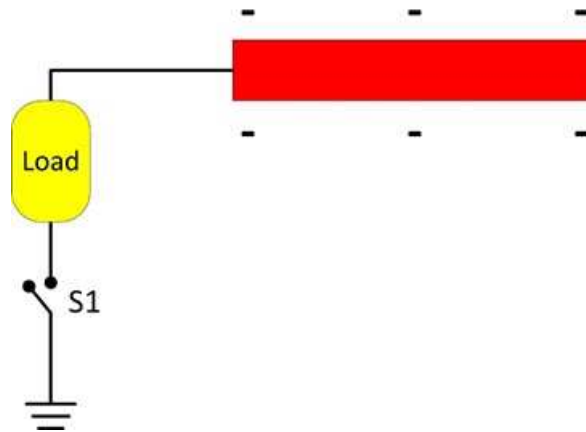


Figure 2-38: A single plate capacitor in an electric field, prior to final energy harvesting.

The complete operations cycle, using the improved electrical layout for the single plate capacitor, will include:

- exposing the single plate capacitor to the electric field in order to effect electrostatic induction;
- harvesting a first round of energy by utilising charge on the away side of the capacitor;
- interrupting exposure of the single plate capacitor to the electric field through one of the following: by removing the electric field, by removing the capacitor from the field, or by shielding the capacitor from the electric field;
- harvesting a second round of energy by utilising remaining charge on the capacitor;
- repeating the cycle.

Discharging a double plate capacitor will always occur according to the well-known exponential decay curve based on the time constant (τ). It will be discussed in the next section (paragraph 2.9.2 on page 77) that these patterns may have to be verified for single plate capacitors. There is a possibility that these patterns might differ between single and double plate capacitors, for reasons to be discussed.

2.9.1.4 Energy requirement for electrostatic induction charging of capacitors

There are two categories of energy requirements pertaining to electrostatic induction charging of capacitors:

- The energy requirements related to providing the electrostatic source that will generate the electric field.
- The energy requirements related to the electrostatic induction itself.

2.9.1.4.1 Energy requirement related to providing the electrostatic source

It is vital to recognise that the electrostatic source does not and should not be consumed per each electrostatic induction. An available electrostatic source, for example the charged dome of a Van de Graaff generator, represents a specified amount of energy which can be easily calculated. However, the source does not have to sacrifice any of its energy during electrostatic induction.

The source will continue radiating the electric field, whether it is used for electrostatic induction or not.

The specific circumstances around a particular set-up might dictate that the source energy is continually leaked to the environment due to humidity or some other source of parasitic leakage like the cosmic radiation discovered by Victor Hess (he received a Nobel Prize on 10 December 1936 for this research, using an electroscope to measure the energy decay due to cosmic radiation). Such circumstances dictate a usable life for the charge and then the energy requirement per instance may be calculated by dividing the initial set-up energy by the number of inductions.

This is an accounting approach, based on perhaps poor engineering that does not sufficiently protect the electrostatic source. Intrinsically, the source operates in a similar manner to a chemical catalyst, by initiating a certain action but without direct participation in it.

On physical basis, it would be equitable to consider a null energy contribution from the electrostatic source towards the electrostatic induction occurring in the electric field.

2.9.1.4.2 Energy requirement related to the electrostatic induction itself

On macroscopic scale, at which classical electrodynamics would operate, there is no indication that electrostatic induction requires any energy to sustain its propagation. Thus, paragraph 2.3 on page 20 describes an attempt to develop a theory on microscopic level electrostatic induction. Also no literature has been found that would provide such insight – but some theory had to be generated, specifically in order to answer the question at hand.

No theory could be found, neither on macroscopic scale nor on microscopic scale – indicating that electrostatic induction requires any ongoing energy for propagation. The own theory supports this perspective.

Literature does frequently provide a comparison between electric and gravitational fields. There are several similarities. The energy requirement for field propagation might be a new similarity, in that both fields can propagate without a continued infusion of energy. In fact, both fields will radiate without even an energy source at the origin, to initiate the field.

On physical basis, it would be equitable to consider a null energy contribution per instance of electrostatic induction occurring in the electric field.

2.9.1.4.3 Combined energy requirement related to electrostatic induction

Electrostatic induction will occur without any energy requirement per instance of electrostatic induction.

2.9.2 Charging a capacitor via conduction current

Classical electrodynamics would view charging a capacitor via a conduction current as follows, for an RC circuit with a direct current source:

- Remove an electron from an electrode. This electrode then becomes the positively charged electrode.
- Cause an electron to become available at the other electrode, whether by transporting the original electron through the circuit, or by sending an electromagnetic wave signal, the actual process is not material for the present consideration.
- Add an electron to the other electrode. This electrode then becomes the negatively charged electrode.

The first electrode constitutes the easy part of the process. From here on, charging becomes a progressively more difficult electrostatic process, because:

- As more electrons are removed from the positive electrode, it becomes even more difficult to remove the latest electron. The electric field created by the previously removed electrons became stronger.
- As more electrons are added to the negative electrode, it becomes even more difficult to add the latest electron. The electric field created by the previously added electrons became stronger.

The ultimate irony of a capacitor as an energy storage device is that as more energy is drawn from the capacitor, there is an increased reluctance or reduced willingness to impart with the remaining energy. The charging process works in reverse:

- As more electrons are removed from the negative electrode, it becomes less easy to withdraw the latest electron. The remaining electric field becomes weaker.
- As more electrons are added to the positive electrode, it becomes less easy to add the latest electron. The remaining electric field becomes weaker.

The energy storage efficiency of a capacitor will be reviewed. Thereafter follows a review of the two capacitor problem, concluding with a comparison to a two tank analogy. Then follows a comparison to pumped hydro storage schemes, indicating that the withdrawal of energy from a capacitor possibly also incurs an energy cost which is made visible in the two capacitor problem.

The present review is aimed only at direct current applications. Alternating current implies charging and discharging of capacitors at a frequency of 50 Hz (in South Africa), given that they are connected in series. The energy penalties in charging and discharging the capacitor are thus incurred 50 times per second. Capacitors are rather used as filters in alternating current circuits.

2.9.2.1 Conduction charging of a capacitor from an energy perspective

The equation for the internal electrostatic energy U of a capacitor is:

$$U = \frac{1}{2} \cdot \frac{Q^2}{C} = \frac{1}{2} \cdot Q \cdot V = \frac{1}{2} \cdot C \cdot V^2$$

The first set of equations indicate the relationship between internal electrostatic energy U and charge Q . The equation indicates a quadratic relationship between charge and the internal energy. Figure 2-39 shows that as a capacitor is charged, progressively more internal energy is thus established for additional units of charge. In an analogy with displacement, speed and acceleration:

- The internal energy curve bends upwards, showing that more internal energy is attained for additional charge.
- The first derivative of the internal energy curve is a linear curve, with a gradient of 8% points, implying that the addition of internal energy speeds up per additional charge.
- The second derivative of the internal energy curve shows the gradient of the previous curve, at a flat 8%.

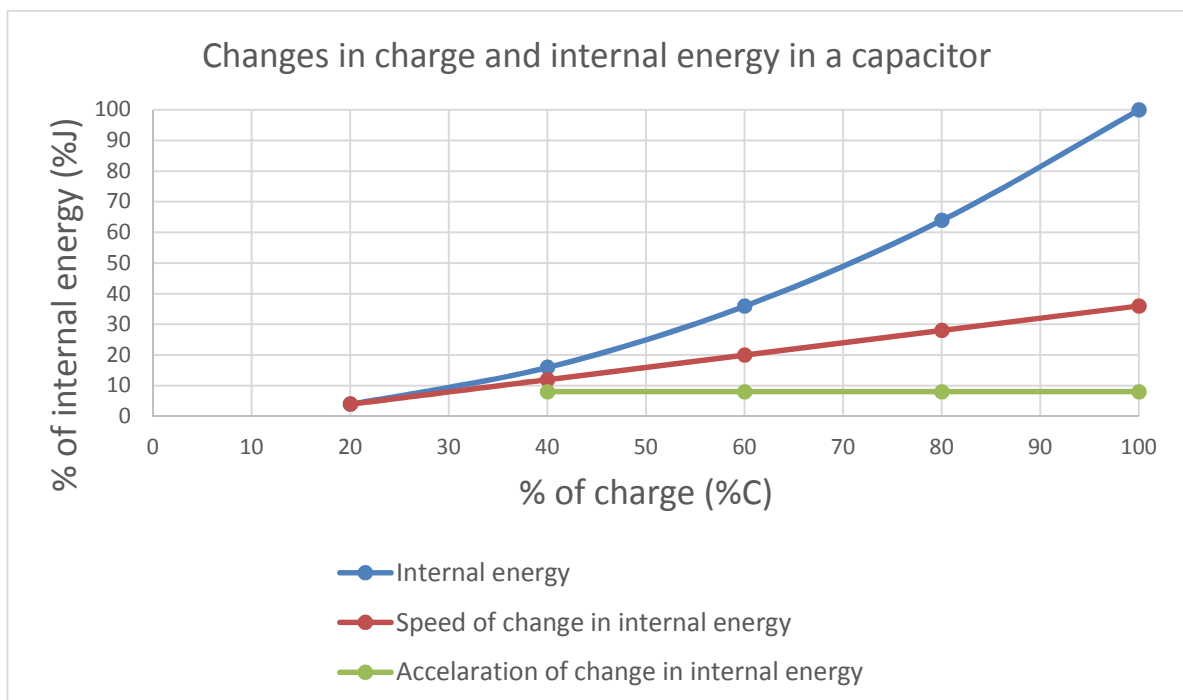


Figure 2-39: Relationship between charge and internal energy of a capacitor.

This analysis illustrates that all charge in a capacitor does not have the same value. The last 20% of charge added, generated an additional 36% of internal energy. Intuitively this implies that the last 20% of charge also cost more in terms of energy to input, which reflects the increasing electric field. This intuition will be investigated hereafter.

The equations for charging of capacitors are well known, specifically for potential difference (V_{cap}), current (I) and charge (Q). The energy efficiency equations are less well known. Consider an elementary RC circuit:

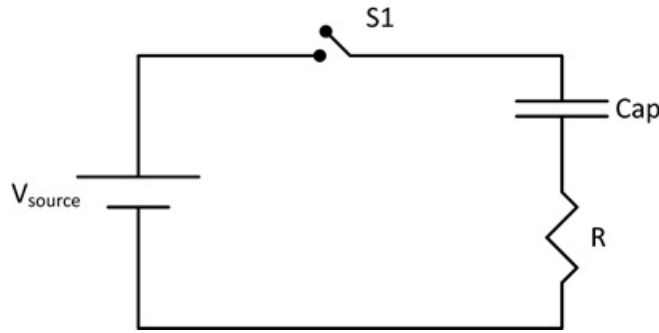


Figure 2-40: RC circuit for capacitor charging analysis.

An elementary RC circuit is used to reduce the variables under consideration to a minimum. The capacitor and an energy source must necessarily be included. The resistance is included as no ideal conductors with zero resistance are available, but also as a safety measure. The charging current is inversely related to the resistance value (R), and a low resistance would cause a high current.

Efficiency ($\eta_{cap}(t)$) involves comparison between an input and the resultant output. Here, the input is the energy supplied by the battery ($U_{source}(t)$) and the output is the energy captured in the capacitor and available for later use ($U_{cap}(t)$):

$$U_{source}(t) = \frac{V_{source}^2}{R} \int_0^t e^{-t/\tau} \cdot dt = \frac{V_{source}^2}{R} (1 - e^{-t/\tau})$$

$$U_{cap}(t) = \frac{C}{2} [V_{source} (1 - e^{-t/\tau})]^2$$

$$\eta_{cap}(t) = \frac{U_{cap}(t)}{U_{source}(t)} = \frac{1}{2} \cdot (1 - e^{-t/\tau})$$

$$Cost_{cap}(t) = \frac{1}{2} + e^{-t/\tau}$$

Note that the efficiency equation only considers capacitor-specific parameters within the power τ , where the circuit relevant details of capacitance and resistance is captured. The only impact is to accelerate or retard a specific efficiency level. The basis efficiency curve is thus the same for all capacitor charging via conduction currents, as shown in Figure 2-41:

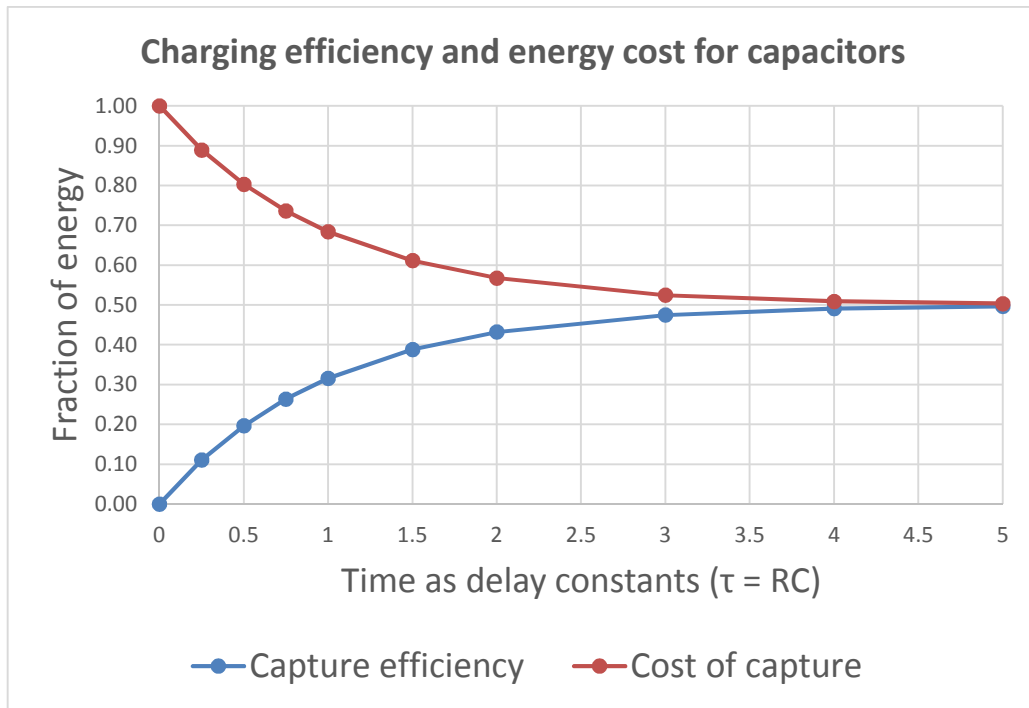


Figure 2-41: Charging efficiency and energy cost for capacitors.

Similarly, the cost of capture curve ($\text{Cost}_{\text{cap}}(t)$) appears essentially insensitive to better capacitor design or fit between capacitance and voltage. Voltage seems to have no bearing on either charging efficiency or cost of capture. The cost of capture is very high at the start and then tapers off, indicating that the instantaneous cost of capture approaches nil towards the end of the charging cycle at 5τ . Both these curves illustrate the averaged values at a given moment in time.

The cost of capture curve's equation is that of the current, without the V_{source}/R coefficient and with addition of a $\frac{1}{2}$. The $\frac{1}{2}$ is the maximum efficiency fraction. There is thus a perfect correlation between cost of capture and current – indicating that current flow determines the

cost of capture. It is significant that this conclusion negates the starting discussion where the increasing field strength was perceived as a driver of charging energy cost.

The curves indicate that for the moment, all RC-charging of capacitors will imply a 50% loss of energy. McDonald (2009) showed that a: “capacitor can be charged with only modest energy loss in an underdamped series RLC circuit if the battery is disconnected after $\frac{1}{2}$ cycle.” Thus, “... the capacitor can be charged with only small loss of energy to Joule heating by use of a large L, small R, and connecting the battery for only $\frac{1}{2}$ of a (damped) cycle. As a bonus, the resulting voltage on the capacitor is nearly twice that of the battery.” However, analysis was based on RC analysis to best attempt evaluation inherent capacitor performance.

2.9.2.2 Two capacitor paradox

The two capacitor paradox add further insight into capacitor operations. Two capacitors, one charged and other uncharged, are connected. The paradox emanates from the fact that there is a fixed and unambiguously determinable initial equilibrium state and then also a fixed and unambiguously determinable final equilibrium state. The paradox is that there appears to be several plausible routes between the equilibrium states.

The two capacitor paradox is vital for the present research as capacitors constitute the core building block towards attaining the research objective. Only by gaining a deep understanding of a capacitor, is there hope of attaining the research objective.

In Circuit a, ideal connectors without resistance is assumed, while a resistance R is shown in Circuit b:

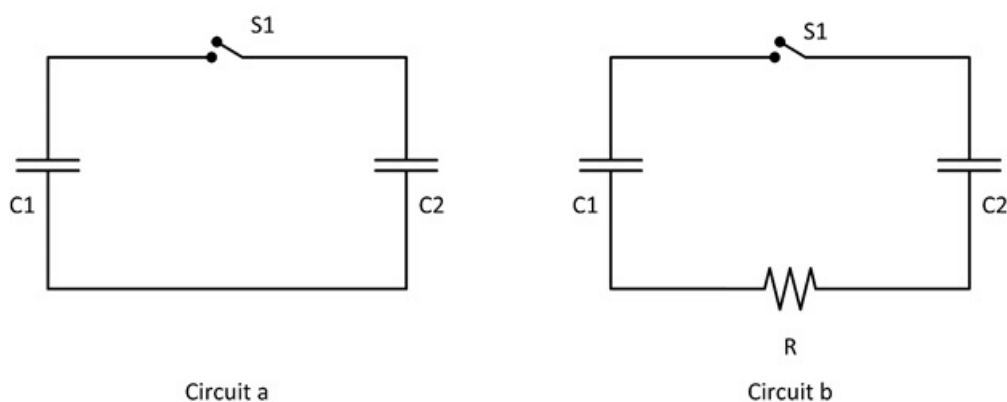


Figure 2-42: Circuit diagrams for the two capacitor paradox.

There is no question of the circuit being a parallel connection, even though Circuit a might initially create that possibility. The moment switch S1 is closed, current flows from the high potential electrode of the charged capacitor to the lower potential electrode of the charged capacitor; obviously via the uncharged capacitor.

The parallel versus series connection debate actually highlights an important difference between the situations where energy is sourced from a battery versus sourcing from another capacitor. With a battery in the loop, the electrode connected to the positive terminal will become positively charged. With a charged capacitor in the loop, the electrode connected to the positive electrode will become negatively charged. This behaviour specifically indicates a serial connection, as the initial potential difference is now serially shared between two capacitors, whilst maintaining the direction of the potential difference as would be expected in a serial connection.

This debate is probably the first paradox, as the circuit behaviour is a hybrid. It does not exhibit true serial or parallel behaviour for capacitor charging. When two capacitors are charged simultaneously:

- in parallel, the same potential difference appears across both capacitors and the charge is shared between them; or
- in series, the same charge appears in both capacitors and the initial potential difference is shared between them.

In the two capacitor circuit, after equilibrium has been reached, the initial potential difference as well as the initial charge is halved between the capacitors. The connection is thus not serial or parallel as thought of in simultaneous charging, perhaps as this case involves subsequent charging.

The two capacitor paradox must be very old. McDonald (2018) lists 38 publications, the oldest of which is (Zucker, 1955). Even Zucker (1955: 469) stated: “In most elementary physics textbooks one comes upon the following problem” The two capacitor problem thus dates from before 1955.

Unfortunately Zucker (1955) treated the problem as a parallel connection between the capacitors, yet amazingly still arrived at a 50% loss of energy. Zucker (1955: 469) proposed heat loss in the resistor as the culprit, and made the interesting observation: “The resistance in the diagram will drop out of the final calculation. This, of course, indicates that the heat lost is

independent of the value of the resistor.” It sounds contradictory that the actual resistance value would not contribute to the magnitude of heat loss.

Kahn (1988: 37) considered the series Circuit b and calculated that half the energy is lost and that this corresponds to the heat loss in the resistor, concluding: “no recourse to radiation losses or radio waves is needed”.

Moore (1989) disagreed with Kahn’s approach, indicating:

- As the switch is closed, there is a rapid change in the current from nil to maximum value instantaneously. Moore (1989: 256) possibly incorrectly applied the Ampère-Maxwell law as: “... an effect which would generate magnetic fields changing at an infinite rate with the consequent generation of large electric fields according to Maxwell’s equations.” The conventional understanding of the Ampère-Maxwell law is that the changing magnetic field is caused by a conduction current flow as well as the rate of change of electric field flux.
- As the switch is closed, an arc will typically be formed, which dissipates energy.
- The rate of rise of the current will typically induce back electromotive force, which further dissipates energy.

Mayer *et al.* (1993: 307) investigated the electromagnetic radiation (EMR) route: “The wires are assumed to be perfectly conducting and without electrical resistance. The circuit then behaves as a loop antenna and radiates energy in the form of EMR. All loss of energy in the system can be accounted for through EMR considerations.” There was no need to account for any Joule heating or thermal radiation, via a resistor. Mayer *et al.* (1993) reflected on their research, and noted that:

- Ten assumptions had to be made to resolve a simple circuit.
- The real life EMR should be orders of magnitude smaller than real life Joule heating, which is why “radiation resistance effects are usually negligible in the presence of electrical resistance or other forms of energy loss” (Mayer *et al.*, 1993: 309).
- The assumptions make the two capacitor problem easier to resolve. “If the scope of the two-capacitor problem is expanded to include circuits in which the above assumptions are not reasonable, then the problem becomes more complex.” (Mayer *et al.*, 1993: 309).

Mita and Boufaida (1999: 737) stated that “the missing energy is due to too much idealization of the real system, resulting in an instantaneous process”. Four circuits were analysed and compared:

- Circuit 1a: Battery charging capacitor, no resistor
- Circuit 1b: Capacitor charging capacitor, no resistor
- Circuit 2a: Battery heating resistor
- Circuit 2b: Battery and inductor, no resistor

Mita and Boufaida (1999) then created a further two circuits: Circuit 1a where the conducting wires are assumed to have a small resistance R_W and a sixth circuit where the previous R_W is replaced by a small amount of inductance L_C . It is shown that the inductance will account for the missing energy (even in an LC-circuit without R) but also claimed that R_W will account for missing energy. Kahn (1988) did show that a resistor in the circuit will account for the energy lost. However, real wires have both resistance and inductance. It is then fortunate any energy is saved in the capacitor, as one half could have been lost to resistive heating and the other half to induction.

The Mita and Boufaida (1999) solution was to eliminate the step discontinuity when a power supply is switched on. Reference was made to a specialised power supply that can divide the initial voltage into infinite sub steps, thus eliminating the energy loss in the resistor (Heinrich, 1986). A suggestion was made for a new power supply, but it is not clear how the problem of an initial step function is eliminated. Mita and Boufaida (1999) relied on Oliver Heaviside’s step-function leading into an integral with a Dirac delta function. The discontinuity at switch-on presents a problem in this approach.

McDonald (2018) ably considered electromagnetic radiation, and in fact designed the circuit to operate as a dipole. Then it is demonstrated that the radiation is magnetic dipole radiation, rather than electric dipole radiation. It is calculated that with larger R – resistive dissipation would account for the missing half, whereas with smaller R (0,05 Ω in the Williams (1970) experiment) magnetic dipole radiation would account for the missing half, albeit after a long period of oscillation.

McDonald (2018) stated that of the 38 articles dealing with the two capacitor paradox, only Williams (1970) reported on experimental results, and he reviewed that experiment. Heinrich (1986) also conducted experimental work to resolve the two capacitor paradox – implying that only 5% of the reported research (2 out of 40 articles) contained experimental validation.

Williams (1970: 92) postulated a very interesting set-up for the two capacitors, in the form of two adjacent co-axial cylindrical capacitors, sharing the same outer electrode:

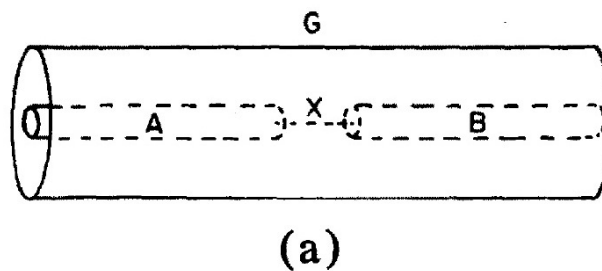


Figure 2-43: Two capacitors as joined cylindrical capacitors (Williams, 1970: 92).

McDonald (2018: 2) reminded: "... that in Poynting's view [40], the energy that is transferred from one capacitor to the other passes through the intervening space, not down the connecting wires." Poynting transport would certainly occur easily in the joined cylindrical capacitors. As an aside, Choy (2004: 668) investigated the radiation from capacitors, and found it "... small but not insignificant" and "We then included the self-inductance and an external resistance R , showing that a minimum value R_m , which must be approximately 10^6 times the wire resistance R_w , is needed to suppress the radiation."

Electromagnetic field theory is initially compared with lumped circuit theory. At high values of the resistor ($2\,000\ \Omega$ here for capacitances of $100\ \text{pF}$ each and a characteristic impedance of the cylindrical configuration of $50\ \Omega$), the two theories provide essentially the same solution, but solutions diverge at lower values of the resistance.

Williams (1970) also short-circuited two capacitors and observed the short circuit discharge current's oscillation being damped to nil after a few cycles.

Heinrich (1986: 742) designed an experiment to demonstrate that an "irreversible process can be transformed into a reversible one, if the transition from a certain initial state to a given final state is divided into N quasistatic steps and if N tends to infinity". It is demonstrated that, as per the terminology used in present research:

$$U_{resistor} = \frac{U_{cap}}{N}$$

$$U_{source} = U_{cap} \left(1 + \frac{1}{N}\right)$$

As the steps increase, energy dissipated in the resistor tends toward nil, and the energy captured in the capacitor tends towards the energy delivered from the source. The research demonstrated that the theory holds for 1, 4 and 6 steps.

The best way to close this review of research on the two capacitor paradox might be to consider the title of a presentation by Jelinek (2018): “Capacitor Paradox: An electromagnetic theory course in a single problem.” The preceding overview demonstrates that there are multiple considerations. Jelinek identifies:

- Electrostatics
- Quasi-electrostatics
- Quasi-magnetostatics
- Radiation
- Waveguiding

Jelinek’s success as a teacher is demonstrated by a paper submitted with a student, Petr Ourednik. The joint paper addresses the two capacitor paradox, considering the “inductance part in the form of wave-guiding phenomenon” (Ourednik & Jelinek, 2018). The solution utilized the Telegrapher’s equations from Oliver Heaviside, to solve the propagation of a transverse electromagnetic wave in an open-ended transmission line. The following very interesting model is used:

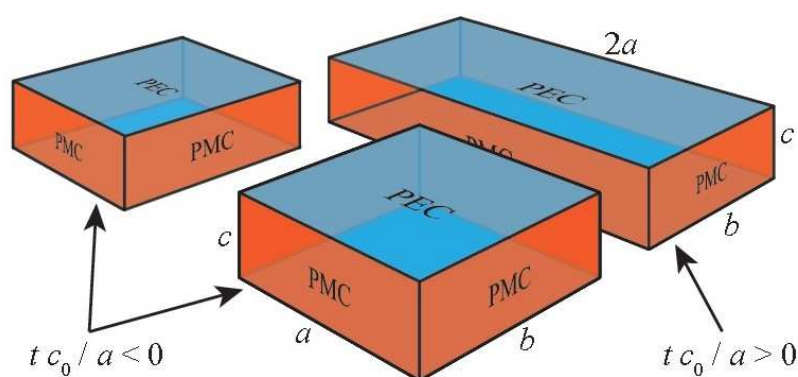


Figure 2-44: Wave-guide model for two capacitor paradox (Ourednik & Jelinek, 2018: 1).

Initially the two capacitors are separated, and are then physically joined into one capacitor, without extraneous switching or connectors. Connection occurs via the electrodes and the dielectric and includes electric and magnetic waves. It is claimed that the capacitors can be joined in this way without any loss of energy.

Jelinek (2018) highlighted five aspects to be considered as relevant to capacitors. The prior review indicated also Joule heating (Kahn, 1988), the quasi-static power input (Heinrich, 1986) and combination of capacitors in an RLC-circuit with special rules (McDonald, 2009). Subsequent discussion will indicate there are even more aspects that are relevant. Two vital points from this overview, at this stage, are:

- A capacitor is very complex, and multiple aspects are simultaneously at play during use.
- The real paradox is that some considerations might be presented as if they suffice to explain the total energy loss. This cannot be true. Optimal design and use of capacitors necessitate unambiguous understanding of the physics.

2.9.2.3 Two tank analogy

McDonald (2018) listed Parton (1989) as the first contributor raising the two tank analogy, as a hydraulic analogy for the two capacitor paradox. Hydraulic analogies are used widely to clarify electrical concepts. Moore (1989) considered the analogy inappropriate as water cannot exhibit electromagnetic behaviour. However, Parton (1990) indicated that analogies are frequently used from outside the current discipline, and also that the overarching principle is that energy is almost inevitably lost upon transfer from one store to another, perhaps excepting for heat.

The two tank analogy starts with one tank with the water at a certain level, and the other tank empty:

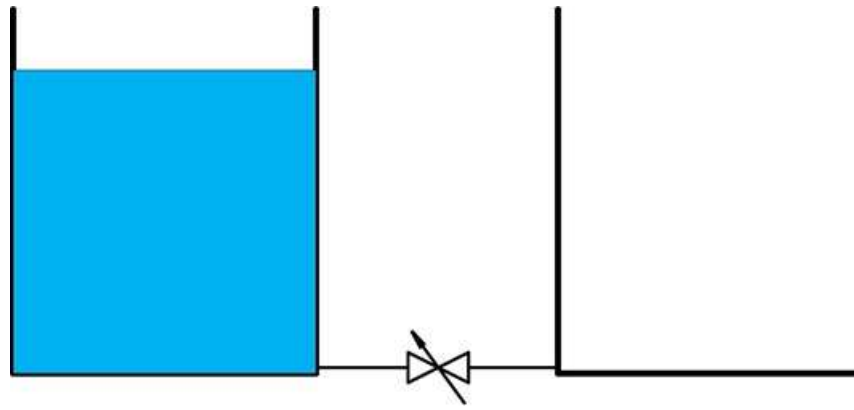


Figure 2-45: Two tank analogy with first tank full.

The valve in the connecting line at the bottom is opened and the water is shared between the two tanks:

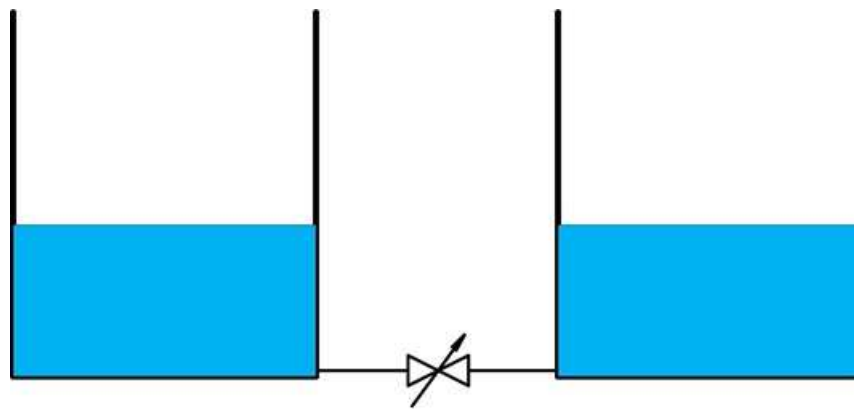


Figure 2-46: Two tank analogy with the water shared.

The water volume and height in the first tank contained a certain amount of potential energy. After sharing, half of the initial energy is lost, similar to the two capacitor paradox.

A first temptation is to effect less turbulent fluid flow between the tanks or to attempt to counter the reality that incoming water in the second tank will always enter against a head (back pressure from the water already present). The height of the connecting line might also be changed, even up to half height of the initial water level. Yet the potential energy loss will remain at 50%. These remedies might be analogous to design better resistance matching or electromagnetic shielding. None of these make any impact. The reality is that the potential energy was lost, without any compensating gain. Refer to the next paragraph, on pumped hydro storage schemes.

2.9.2.3.1 Consideration of pumped hydro storage schemes

An initial explanation for the energy loss in the two tank analogy might be that the set-up is biased as the inflow into the second tank is entering against the head. This sounds intuitively as corresponding with the struggle against electric fields in capacitors.

However, the pumped hydro storage schemes perform well and sometimes against significant heads. Barta (2018) discussed South African pumped hydro storage schemes and their efficiencies, known as round-trip efficiency (RTE):

- Steenbras pumped storage scheme -
- Drakensberg pumped storage scheme RTE ~ 73%
- Palmiet pumped storage scheme RTE ~ 78%
- Ingula pumped storage scheme RTE ~ 76%

Eskom also lists efficiencies for Drakensberg and Palmiet, concurring with Barta (*Palmiet pumped storage scheme*, 2005). Eskom also indicates that the generation and pumping efficiencies are around 90%. Barta indicated that tunnel efficiencies might also be around 90%.

It thus appears that these efficiencies are in the similar order of magnitude (around 73%) as would be achieved if a serial efficiency model of $90\% \times 90\% \times 90\% = 73\%$ is assumed for:

- Pumping water to upper dam 90% efficiency
- Allowing water flow back via tunnel 90% efficiency
- Generating electricity from down flow 90% efficiency

Attaining round-trip efficiencies of approximately 73% for pumped hydro storage schemes indicates that the 50% energy loss in the two tank analogy could not be caused by any hydraulic issue. It is a basic energy issue.

2.9.2.3.2 Reconsidering the two tank analogy

Upon reflection due to the pumped hydro storage benchmark, it became evident that the problem is indeed about the energy itself. Consider a two tank analogy version where two tanks filled with water are stacked, one on top of the other:

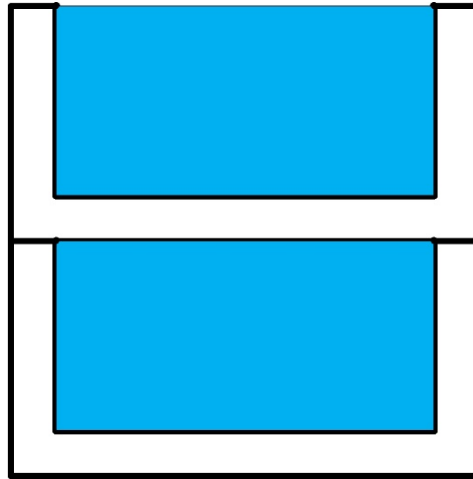


Figure 2-47: Stacked two tank analogy – energy at maximum.

Now the top half is moved to the same level as the bottom half, without causing turbulence or heat or any of the reasons typically advanced as a cause for the energy loss:

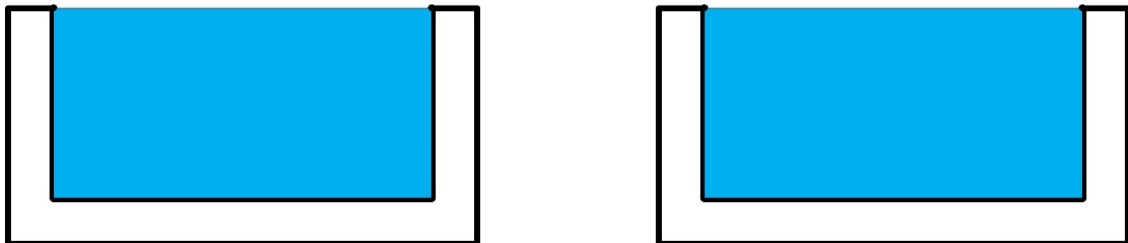


Figure 2-48: Stacked two tank analogy – energy halved.

Thus the problem might also be approached by attempting to reduce loss by infinite intermediate storages, a quasi-static approach. Consider the layout of the initial tank and “second tanks” at different levels:

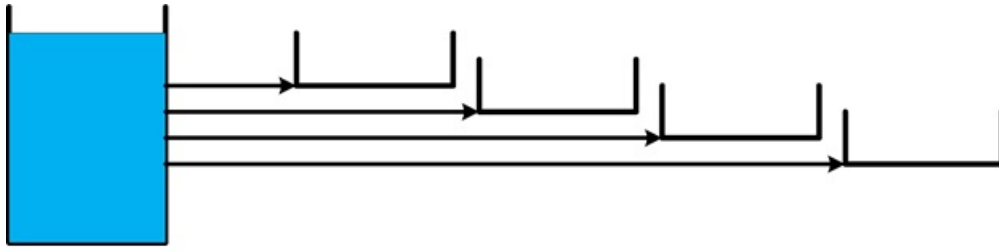


Figure 2-49: Layout of a quasi-static stacked two tank analogy.

Consider now the filling sequence. The “second tanks” are filled in sequence from top to bottom:

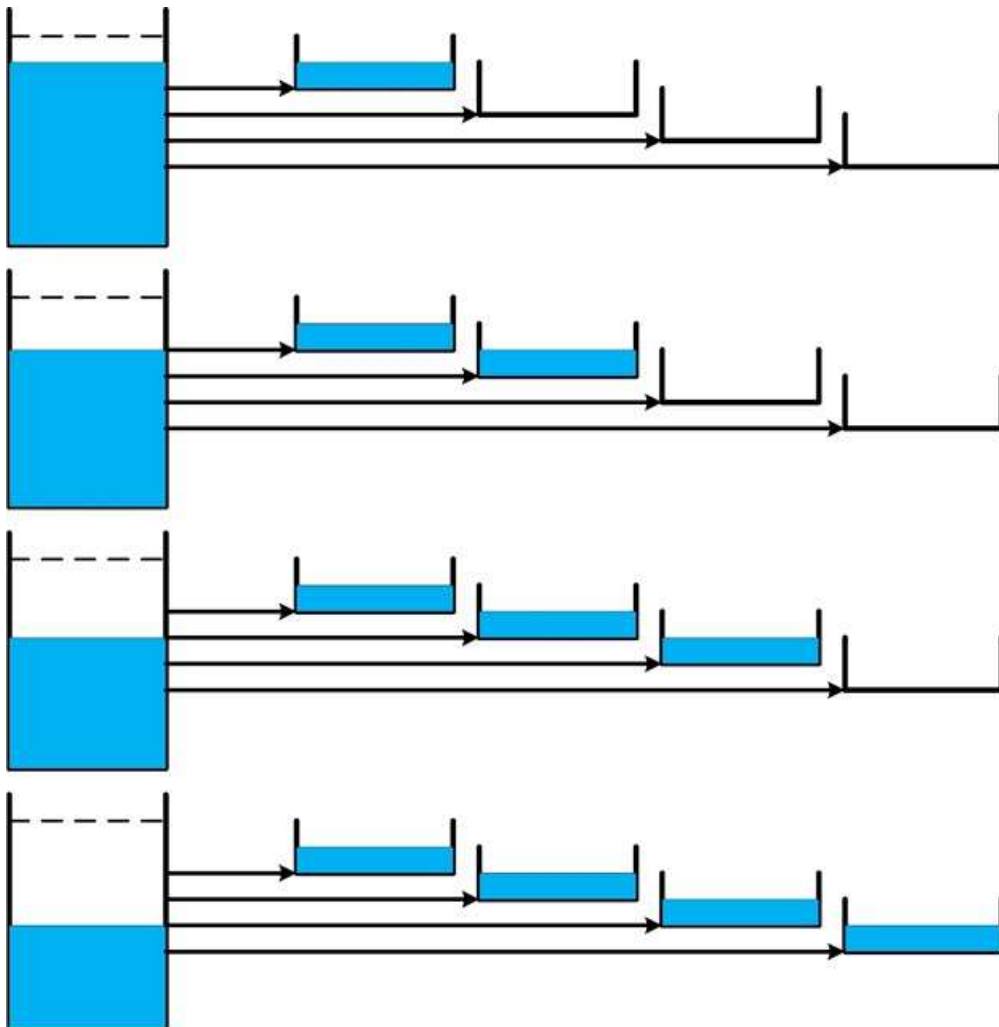


Figure 2-50: Filling sequence for a quasi-static stacked two tank analogy.

The impact of the quasi-static stacked two tank analogy is that only the energy corresponding to half a step height had been lost. This compares to 50% in the original version. By tending the step height to nil, the energy loss would also tend towards nil.

The exquisite tastes of discerning customers might be satisfied by a spiral configuration. The “first tank” could be arranged as a central cylindrical column with the required volume. “Second tanks” are then arranged in a spiral, mounted to the central column. The number of “second tanks” would then correspond to the number of quasi-static steps to be taken. This configuration might almost be operated in reverse, again with the penalty of losing half a step’s energy. In the current set-up, the last “second tank” would become unusable for the sake of feeding back.

2.9.2.4 Reconsidering the two capacitor paradox

The two tank analogy and especially the realisation that the missing 50% of the initial energy went missing as the potential energy lost potential, and not because of turbulence or any other factor, necessitates a reconsideration of the two capacitor paradox.

A capacitor is an energy storage device, and its principal operational relationship is:

$$U_{cap}(t) = \frac{1}{2} \cdot \frac{Q^2(t)}{C}$$

The equation indicates a quadratic relationship between charge and internal electrostatic energy of the capacitor. The mechanics of the relationship is that later additions of charge would have a greater impact on internal energy as compared to earlier additions. Reversibility would dictate that a charge retains the memory, almost a spatial memory, when considering the next analogy, of the circumstances when it was added to the electrode and returns the input energy at output. This is not an argument according to “historic cost”, as the following analogy will reveal.

The input and output of charges is similar to the compression of a spring. A capacitor is frequently compared to a spring. Now, even as the relationship between the spring deflection and the spring compression force is a linear relationship, more force must be applied for a unit of deflection towards the end of compression than what was required at the start of compression. When the spring is progressively relaxed, the output force is not an average of all the input forces pertaining to the units of deflection during compression. There is rather a spatial inevitability dictating that if a certain amount of force was required for deflection at a certain

stage in the process, that same amount of force (discounting losses) will be returned during output from that stage of deflection.

Electrostatic charge will operate as a spring, implying that whatever amount of energy is associated with it during input, will also be associated with it during output. The argument is not made that specific units of charge must always retain the last-in-first-out (LIFO) memory inside the electrode. There is likely rather an equalisation process in operation. However, the relationship between a quanta of charge is maintained with a quanta of electrostatic energy. This interpretation on reversibility of the process is supported by Griffiths (2013: 93): “That’s how much work it takes to assemble a configuration of point charges; it’s also the amount of work you’d get back if you dismantled the system.”

When a second capacitor is brought into the circuit, the existing charge is distributed equally between the two capacitors. The initial capacitor must surrender half of its charge:

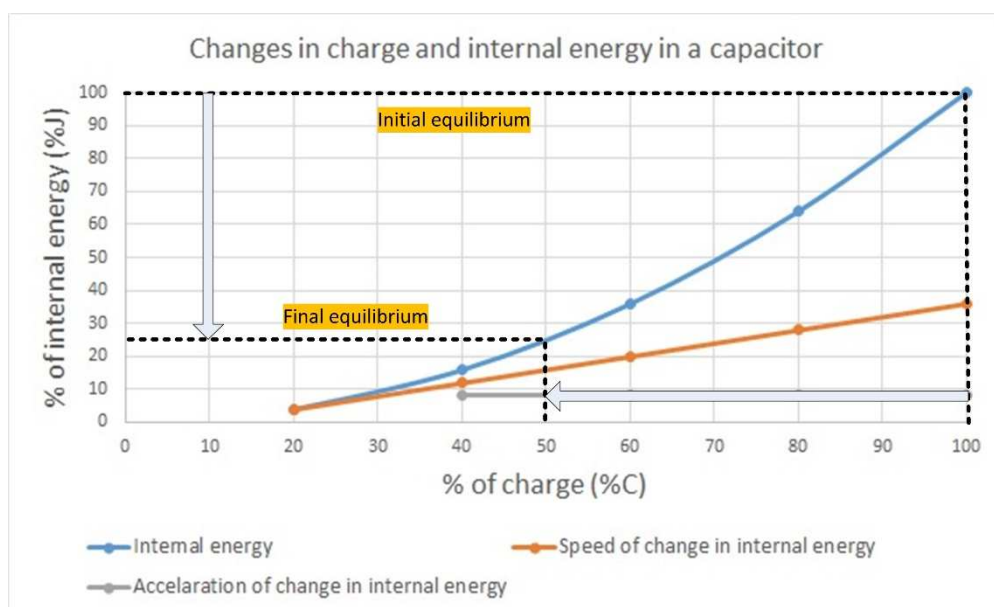


Figure 2-51: Charge and internal energy relationship for capacitor.

The inherent physics of a capacitor dictates that, as 50% of the charge is removed from the initial 100%, the internal energy must sacrifice 75%. The same physics dictate that as the freed 50% of charge is transferred to the second capacitor, only 25% of the possible internal energy (as per the initial equilibrium on the first capacitor) will be attained. The transfer process thus cost 50% of the initial energy, irrespective of Joule heating, electromagnetic radiation or any such effect.

This behaviour, where a 50% change in current leads to a 75% change in energy and also then where that 50% charge only causes a 25% energy in the uncharged capacitor, exactly reflects the impact of the electric fields in the various electrodes. The initial process, as described in paragraph 2.9.2 on page 77, is thus valid.

This review and conclusions directly apply for the case of capacitor to capacitor transfer, but only selectively to charging from a battery. Batteries are not essential for the present research.

When charging from capacitor to capacitor, a serial connection is established between the two capacitors. Then the capacitor behaviour should also be considered from a serial connection perspective, which would dictate that the same charge appears throughout the serial connection. The two capacitors in series may be consolidated into a single equivalent capacitor:

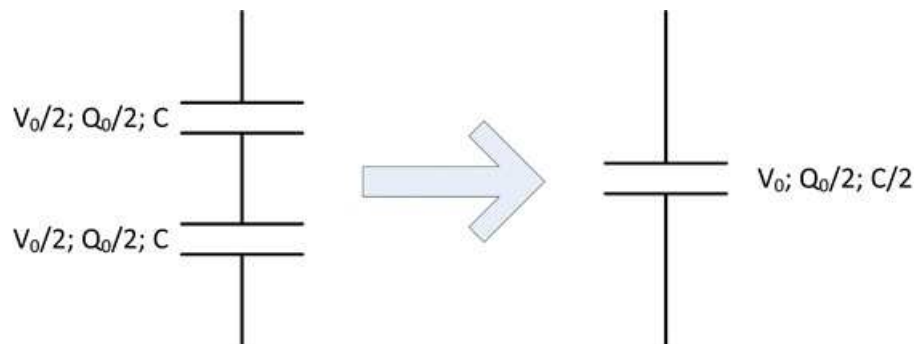


Figure 2-52: Equivalent capacitor to the two capacitors in series.

There was Q_0 charge in the charged capacitor prior to the connection being closed. Now only $Q_0/2$ charge remains. $Q_0/2$ charge has thus disappeared from the circuit. However, it did not disappear into thin air. It moved from the one electrode of the originally charged capacitor to the other electrode, via the circuit. Along the way it charged the originally uncharged capacitor, but as a flow of charge constitutes current, it also caused the multiple effects associated with current flow. This flow of the $Q_0/2$ charge is then the root cause for:

- Joule heating
- Electrostatics
- Quasi-electrostatics
- Quasi-magnetostatics
- Radiation
- Waveguiding

The two capacitor paradox is useful, as it offers a secure platform from which multiple effects may be investigated and it might assist in improving capacitors and their application. However, with Jelinek (2018), the two capacitor paradox must be recognised for its vital role in disclosing the full complexity of conduction current flow.

Exactly because the two capacitor paradox is such a wonderful research and education resource, further resource must continue to identify new rules of practice.

Also, it is not sustainable to have such ambiguity about a vital component such as a capacitor, that there will be such a range of possible applications for the lost 50%. The two capacitor paradox is an elementary circuit with defined initial and final equilibrium states and should ideally be fully exploited. All that can be learnt about capacitors will find immediate application in industry. Despite the range of articles on the paradox, in only 5% of cases were there actual experiments conducted. There is thus a need for well-designed experiments that can empirically resolve the ambiguity and break new ground with respect to capacitors.

The two capacitor paradox must also now be investigated specifically from an essentially electrostatic approach, where no direct flow of conduction current will occur. Three prior papers indicated how this research might proceed:

- Williams (1970) created the concept of two co-axial cylindrical capacitors that can be located adjacent to each other. See Figure 2-43 in this regard. Maxwell (1873: 195) created a concept that is in effect the inverse of Williams':

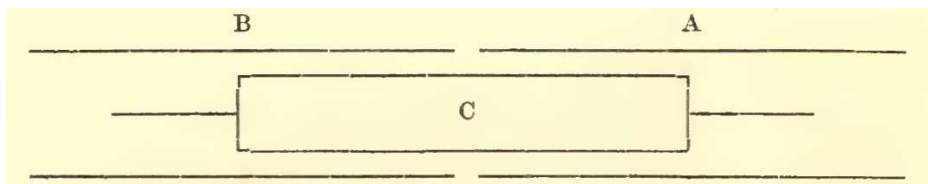


Figure 2-53: Maxwell's (1873: 195) co-axial cylindrical capacitors.

- Singal (2013) proposed stretching a single parallel plate capacitor into two adjacent parallel plate capacitors, effectively transferring all charge without conduction currents, albeit with mechanical movement of charge:

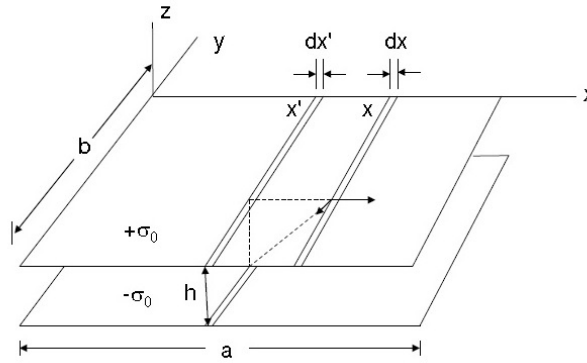


Figure 2-54: Singalian electrode stretching (Singal, 2013: 5).

- Ourednik and Jelinek (2018) created the concept of two co-planar parallel plate capacitors that can be located adjacent to each other. See Figure 2-44.

Ourednik and Jelinek (2018) reviewed the fringing fields of capacitors and Choy (2004) reviewed capacitor radiation and the concept of a capacitor antenna. The final charge transfer mechanism might be an amalgamation of conventional electrostatics, their work and some random quantum perturbation initiating charge movement across adjacent electrodes. Singal (2013) provided detailed analysis of the forces involving charges on electrodes when they are to be stretched. These forces might impact movement of charges.

The two capacitor paradox is grounded in the wish to transfer charge from one capacitor to another. The literature indicates that the transfer might only occur without substantial energy loss, if it is conducted electrostatically. Dissectible Leyden jars might offer such an opportunity. Note the following set-up. The Leyden jar in part a has been charged, components in parts b and c are uncharged:

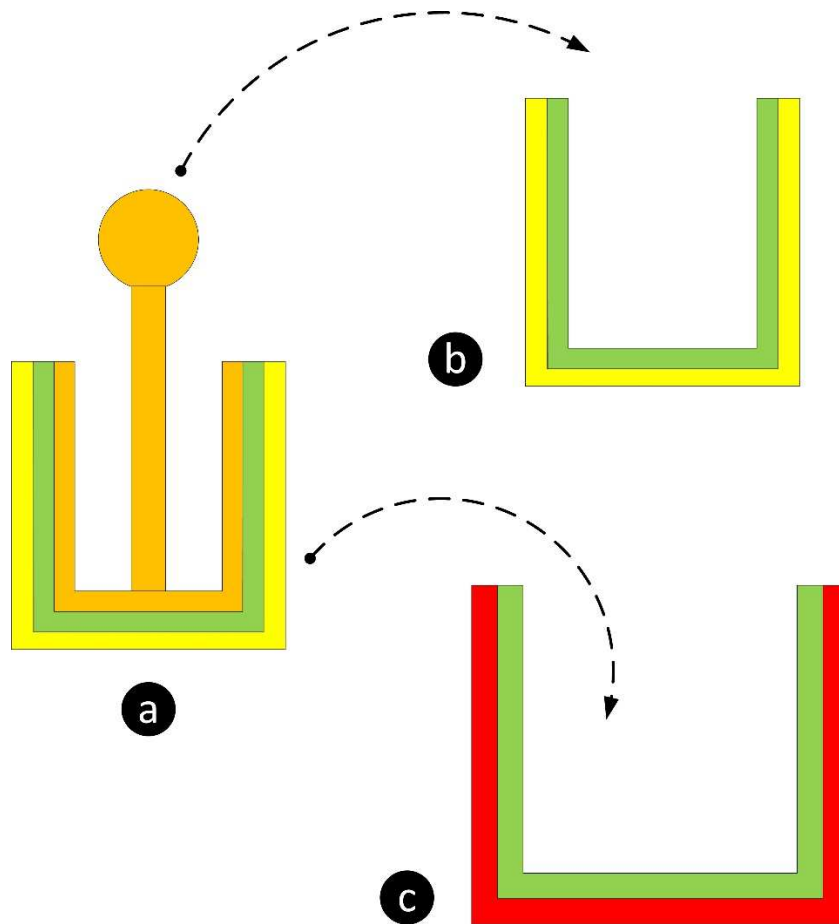


Figure 2-55: Dissectible Leyden jar before charge transfer.

The arrows indicate the transfer of components. Components must be transferred to their new locations without earthing, which would remove the charge:

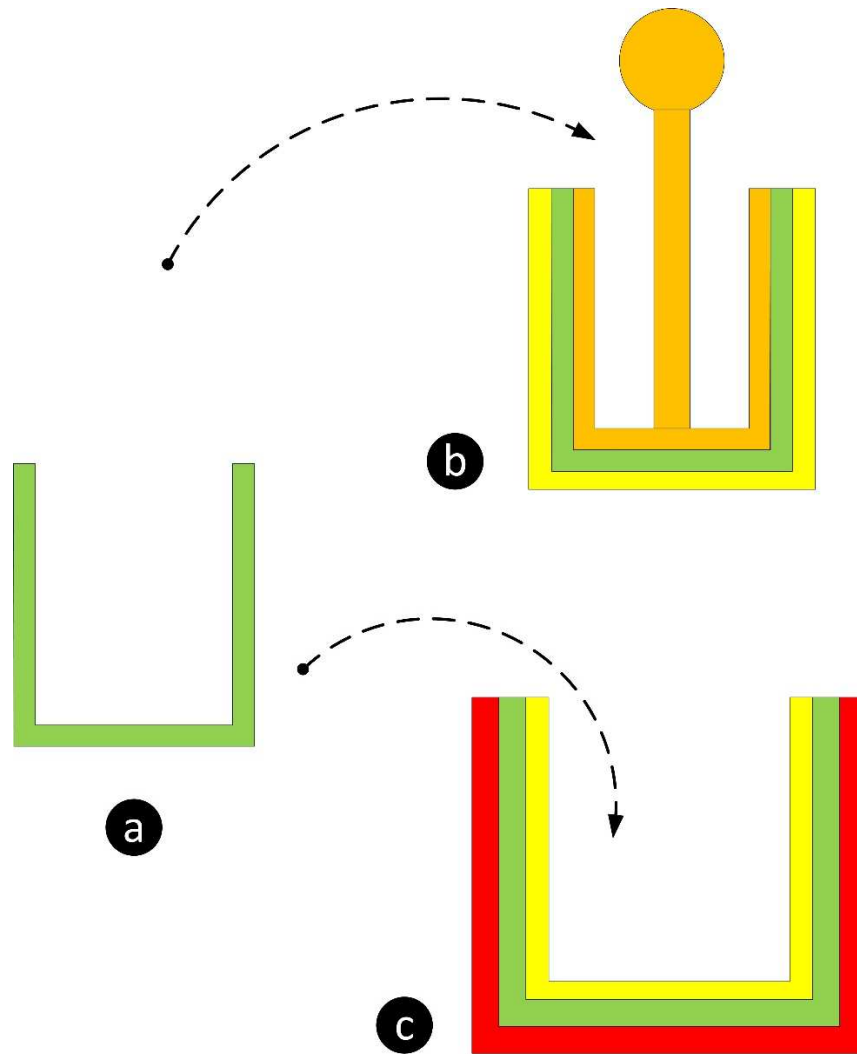


Figure 2-56: Dissectible Leyden jar after charge transfer.

After transfer and insertion in the cup in part b, the part a inner will electrostatically induce charge on the cup. The outer cup of part a would transfer its charge to its outer face, especially if transferred without the dielectric. This charge can then electrostatically induce charge inside the cup in part c.

The charge from part a has been transferred to parts b and c and had, by Grace, in fact been multiplied. There might have been an 18th century demonstration like this.

2.9.2.5 Exergy

This review is one of few that focusses on the core energy considerations of the two capacitor paradox, and seemingly the first that will take exergy into account.

Iizuka and Fan (2017: 1) defined exergy as: “The maximum amount of usable work extractable from a given radiative heat flow ...” The two capacitor paradox does not deal with radiative heat flow, yet the vital part of the definition is “maximum amount of usable work extractable”. Another definition is: “The maximum useful work which can be extracted from a system as it reversibly comes into equilibrium with its environment. In other words, it is the capacity of energy to do physical work.” (What is exergy?, 2019)

Exergy is introduced as pertaining to four aspects (What is exergy?, 2019):

- Exergy reflects the quality of energy which indicates the utility or usefulness of the energy. Coal-fired electricity generating plants release huge amounts of steam at the end of the thermodynamic cycle, but the exergy of the steam is too low to empower further use with present day technology. Torricelli’s law might have been an early pioneer of exergy:

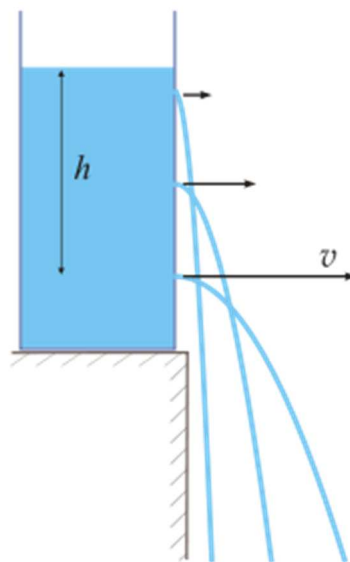


Figure 2-57: Torricelli’s law or theorem as applied to water flow (Torricelli’s law, 2019).

Figure 2-57 illustrates that water with more pressure behind it, will have more kinetic energy and that jet will reach further. Such a jet will also have more exergy available.

- The first law of thermodynamics dictates that energy can never be destroyed. However, exergy can and is destroyed in every transformation process.

- The exergy at every stage is defined relative to the environment. The diagram illustrates the difference between a situation without exergy as opposed to another situation with exergy:

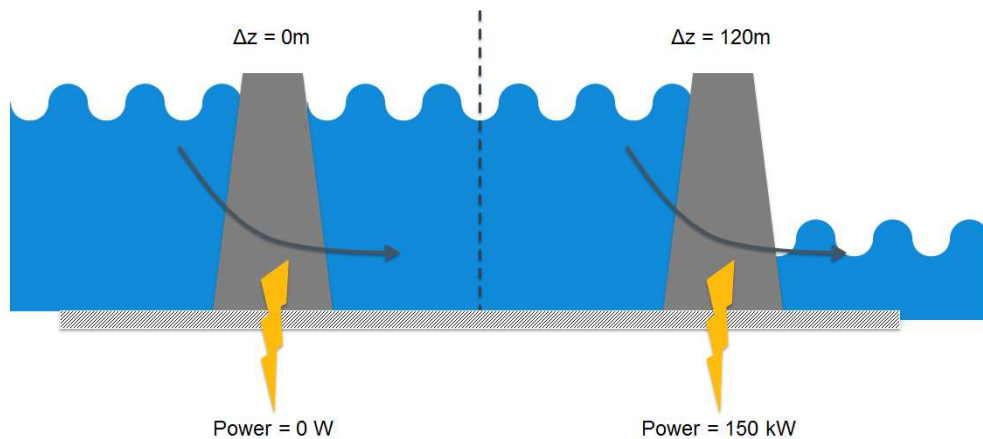


Figure 2-58: Exergy is always relative to the immediate environment (What is exergy?, 2019).

The waste steam could contain a lot of energy. Aljundi (2009) stated that for a plant in Jordania, 134 MW is emitted through the condensers, while the plant capacity is 396 MW. The plant's environment reference temperature and pressure are 298,15 K and 101,3 kPa. If the steam could rather be ejected in outer space at 2,73 K and 1.322×10^{-11} Pa, the condensers would be the most important parts of the plant.

- Exergy efficiency illustrates the scope for improvement in the efficiency of a conversion process. How big is the gap between current and maximum efficiency?

In general, it is evident that exergy is a vital concept pertaining to capacitors. While a capacitor will surrender all of its stored energy according to the time constant τ of the circuit, the voltage would decrease over time. The voltage might be regarded as the pressure ensuring that current will keep flowing. This pressure might then become too low for the particular use.

An exergetic analysis would include review of the exergy balance, of which a simplified version would be:

$$\text{Exergy}_{\text{in}} = \text{Exergy}_{\text{out}} + \text{Exergy}_{\text{destroyed}}$$

In the two capacitor paradox, a simplified interpretation would regard the 50% energy loss as the amount of exergy destroyed. Noting that a capacitor's energy must always be compared with the application (environment) where it is intended to be used, the reality is that most of the initial exergy would have been destroyed. The 50% that was destroyed would be exergetically much more valuable than the 50% remaining. The opportunity then is to design a system that will improve the exergy of the remaining energy, which can obviously not occur should a thermodynamic law prevent it. However, the ingenuity and insight of the two capacitor paradox community could take up the challenge. This then will be of value for all capacitors.

Step-up transformers or DC-DC converters might be devices to improve exergy.

Costa (2016) provided an overview of recent exergy research and highlighted that exergy is at the moment primarily focussed on thermomechanical processes. Literature indicates that the chemical processes also recognise the value of exergy. There might be an excellent opportunity to incorporate exergy approaches in electrical processes. The abundance of literature on exergy at power stations indicate electrical experts should be familiar with exergy already. However, it would be valuable for society if exergy can be incorporated into detailed thinking and analysis of electrical processes, as can be seen concerning the two capacitor paradox.

2.9.2.6 Additional insight into capacitors from single plate capacitors

A possible method to get additional insight into capacitors, both from a charging and discharging perspective, would be to:

- Establish the charging parameters for a single plate capacitor, including the voltage and current curves. This information does not appear to be available. Comparing these curves to that for double plate capacitors might provide additional insight. Note the following guidelines in such experiments:
 - Charging characterisation might first proceed with a bare single plate capacitor, to establish a baseline.
 - Then, it would be best to cover the single plate capacitor with dielectric sheets on both sides and perhaps insert the assembly into a vacuum bag, which can be sealed after vacuuming. This will protect the single plate capacitor against self-discharge, especially to the atmosphere.
- Caution. A single plate capacitor would be continually searching for another electrode and might use the supporting structure or the rest of the circuit as a second electrode. This might have unintended consequences. An approach to minimise risk is to use only

a single wire to suspend the capacitor, say from the ceiling. This wire then connects the capacitor to the remainder of the circuit:

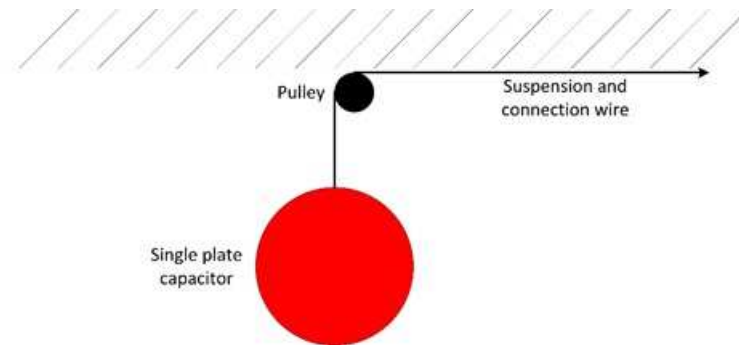


Figure 2-59: Characterising the charging performance of a single plate capacitor.

- The electrical layout of the experiment would be as follows:

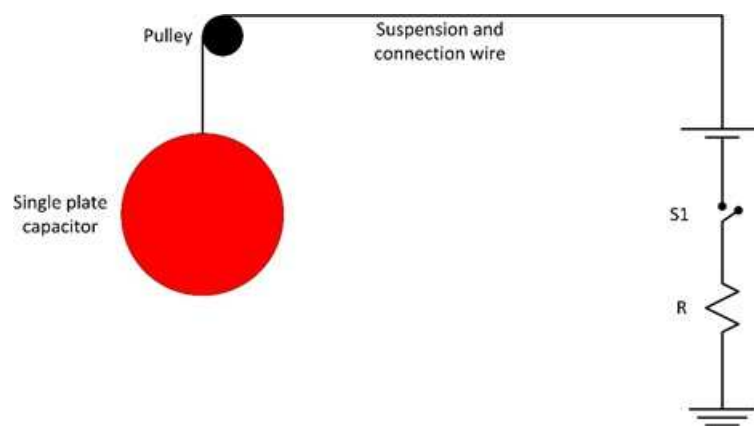


Figure 2-60: Circuit for characterising the charging performance of a single plate capacitor.

2.9.2.7 Consolidation of comparison between conduction current charging and electrostatic induction charging of capacitors

The section thus far has demonstrated that both conduction current and electrostatic induction may be used to store energy in a capacitor. Table 2-8 illustrates the differences between the methods:

Table 2-8: Comparison between conduction current and electrostatic induction charging of a capacitor		
Aspect	Conduction current	Electrostatic induction
Charging time	Typically 5 * Tau (time constant = resistance times capacitance) for 100% charging.	Instantaneous, or at whatever rate electrostatic induction occurs. This might be instantaneous. No indication has yet been found of empirical speed measurements.
Charging energy requirement	Typically 50% of charging energy is lost during the process of charging.	No indication that electrostatic operation of a capacitor in charging mode would consume any energy. A less than 100% yield is possible if some charge is lost along the pipeline, possibly due to charge transmission inadequacies, yet to be identified.
Charge decay	Charge decay is known and measured per product.	Charge decay may be higher for parallel plate capacitors than for conventional film capacitors as at least one external face of an electrode must be exposed for access by the electrostatic field. Such exposure allows charged atmospheric particles to impact the electrode face. The presence of free charge, unbound by electrostatic fields, on the external faces of a capacitor may increase the risk and onset of charge decay, as the free charges may migrate through the electrode towards the charges with opposing polarity on the other face of the electrode. To the extent that charge is then neutralised, internal energy is reduced.

The comparison in Table 2-8 highlights a vital feature of electrostatic charging of capacitors, namely that it seemingly can occur without incurring any obvious energy costs. The comparison is supported by the review as reflected in paragraph 2.3 on page 20. Now, it is evident that once energy has been created or stored – and that it seemingly occurred without obvious and specific energy input – it would be highly significant to a world that depends on energy.

Extensive literature survey did not indicate any energy cost to the electrostatic induction itself. There are energy costs to the creation of a charged source and for moving it proximate a target – but from there, electrostatic induction occurs seemingly without any energy cost. Then, if the amount of energy created via electrostatic induction could exceed the amount of energy used to

create and move and maintain the electrostatic source, an efficient generator of energy could be established.

2.10 Preferred capacitor topology for a capacitor stack

There are various capacitor topologies available: film wound, parallel plate, cylindrical or spherical. Which topology is best suited for consideration to propagate electrostatic induction charging, particularly with the view of harvesting the energy?

As a start – film wound capacitors are excluded as an efficient topology for electrostatic induction. Only a very limited fraction of only one of the external faces of the capacitor is accessible, even if there is no metallic container on the outside of the capacitor. Exposing only a fraction of a face to an electrostatic field reduces the charge density attainable over the whole electrode face. Furthermore, film wound capacitors are typically cylindrical and if they are thus radiated by an electrostatic field while the central axis is orthogonal to the field direction, the upstream half would be polarised as one polarity while the downstream half would be oppositely polarised. The nett effect would be nil.

The following topologies will be considered:

- Spherical capacitors
- Cylindrical capacitors
- Parallel plate capacitors

2.10.1 Spherical capacitors

The capacitance of a spherical capacitor is:

$$C = \frac{4\pi\epsilon_r\epsilon_0}{\left(\frac{1}{a} - \frac{1}{b}\right)}$$

where

C – capacitance (Farad)

ϵ_r – relative permittivity of the dielectric between electrodes

ϵ_0 – vacuum permittivity

a – external radius of inner body (electrode)

b – internal radius of external body (electrode)

When a spherical capacitor is charged (Q coulombs), the internal energy available would be:

$$U = \frac{1}{2} \cdot \frac{Q^2}{(4\pi\epsilon_r\epsilon_0) / \left(\frac{1}{a} - \frac{1}{b}\right)}$$

where

U – internal energy (Joule)

Q – charge (Coulomb)

Re-arranged:

$$U = \frac{1}{8\pi\epsilon_0} \cdot \frac{Q^2 \left(\frac{1}{a} - \frac{1}{b}\right)}{\epsilon_r}$$

The objective of the evaluation is to establish how the internal energy (U) might be increased for a given charge (Q):

- The first term, $\frac{1}{8\pi\epsilon_0}$, is a constant and cannot be manipulated to increase U.
- The radial term $\left(\frac{1}{a} - \frac{1}{b}\right)$ can be increased in two ways:
 - The outer shell might be extended to infinity, which would drive the $\frac{1}{b}$ to 0. There is thus a limit to the impact of this approach.
 - The inner core might be shrunk towards 0, in which case the $\frac{1}{a}$ term would approach infinity. This approach would have significant mathematical impact – but it is physically very problematic. The problem is that as the core diameter is shrinking, the charge density and thus also the static potential is increasing. As

soon as the static potential reaches the breakthrough strength of the surrounding medium, an arc would flash over. Furthermore – it is also very problematic to attain a higher charge density in the target conductor than was present in the source conductor. Thus, there would be a breakthrough risk both at the source and the target (the core).

- The relative permittivity, ϵ_r , of the dielectric might be reduced. Note that the relative permittivity can only be reduced to unity, at which stage it equals the permittivity of vacuum and air. There is thus a limit to the impact of this approach.

Mathematical consideration of the equation for the internal energy of a spherical capacitor thus does not offer any feasible avenue for significantly increasing the internal energy, given a set charge.

There is also a physical constraint, as electrostatic induction requires that the target conductor be exposed to an electrostatic field emanating from a source conductor. A first problem then is the presence of an outer conducting shell. No electrostatic field can penetrate an outer conducting shell. Furthermore, even if this problem might be resolved by locating the source conductor inside the outer shell, the spherical core would, in the presence of the electrostatic field, acquire charges of one polarity in the upstream half and opposite polarity charges in the downstream half. This has no useful impact regarding the outer shell and establishment of a capacitor.

The target conductor might be hollowed, and it could be attempted to then charge it in a similar method as the charging of the dome of a Van de Graaff electrostatic generator. This method would then limit shrinking of the core as a method to increase internal energy.

Thus, mathematically and physically, a spherical capacitor is eliminated from consideration.

2.10.2 Cylindrical capacitor

The capacitance of a cylindrical capacitor is:

$$C = L \cdot \frac{2\pi\epsilon_r\epsilon_0}{\ln\left(\frac{b}{a}\right)}$$

where

C – capacitance (Farad)

L – length (m)

ϵ_r – relative permittivity of the dielectric between electrodes

ϵ_0 – vacuum permittivity

a – external radius of inner body (electrode)

b – internal radius of external body (electrode)

When a cylindrical capacitor is charged (Q coulombs), the internal energy available would be:

$$U = \frac{1}{2} \cdot \frac{Q^2}{L \cdot (2\pi\epsilon_r\epsilon_0) / \ln\left(\frac{b}{a}\right)}$$

where

U – internal energy (Joule)

Q – charge (Coulomb)

Re-arranged:

$$U = \frac{1}{4\pi\epsilon_0} \cdot \frac{Q^2 \cdot \ln\left(\frac{b}{a}\right)}{L \cdot \epsilon_r}$$

The objective of the evaluation is to establish how the internal energy (U) might be increased for a given charge (Q):

- The first term, $\frac{1}{4\pi\epsilon_0}$, is a constant and cannot be manipulated to increase U.
- The radial term $\ln\left(\frac{b}{a}\right)$ can be increased in two ways:

- The outer shell might be extended to infinity, which would eventually drive the radial term to infinity, albeit very slowly. Table 2-9 illustrates the slow – and actually slowing – increase in the value of $\ln(b/a)$ as b/a increases:

Table 2-9: Monitoring the impact of increased b/a on $\ln(b/a)$		
b/a	$\ln(b/a)$	Increase in $\ln(b/a)$
1	0.0	
10	2.3	
100	4.6	100%
1 000	6.9	50%
10 000	9.2	33%
100 000	11.5	25%
1 000 000	13.8	20%
10 000 000	16.1	17%
100 000 000	18.4	14%

Note that with every subsequent tenfold increase in b/a , the value of the increase in $\ln(b/a)$ continuously decreases. $\ln(b/a)$ doubles from 10 to 100 – implying a 100% increase. Thereafter the increase drops continuously.

- The inner core might be shrunk towards 0, which would also drive the radial term to infinity, albeit slowly. This approach would have significant mathematical impact – but it is physically very problematic. The problem is that as the core diameter is shrinking, the charge density and thus also the static potential is increasing. As soon as the static potential reaches the breakthrough strength of the surrounding medium, an arc would flash over. Furthermore, it is also very problematic to attain a higher charge density in the target conductor than was present in the source conductor. Thus, there would be a breakthrough risk both at the source and the target (the core).
- The length L might be reduced – which would drive the overall term to infinity, but this approach has the same problems as shrinking the core.
- The relative permittivity, ϵ_r , of the dielectric might be reduced. Note that the relative permittivity can only be reduced to unity, at which stage it equals the permittivity of vacuum and air. There is thus a limit to the impact of this approach.

Mathematical consideration of the equation for the internal energy of a cylindrical capacitor thus does offer at least the one feasible avenue for significantly increasing the internal energy, given a set charge, by increasing the outer shell radius. However, Table 2-9 illustrates that this is not a very useful option.

There is also a physical constraint, as electrostatic induction requires that the target conductor be exposed to an electrostatic field emanating from a source conductor. A first problem then is the presence of an outer conducting shell. No electrostatic field can penetrate an outer conducting shell. Furthermore, even if this problem might be resolved by locating the source conductor inside the outer shell – the spherical core would, in the presence of the electrostatic field, acquire charges of one polarity in the upstream half and opposite polarity charges in the downstream half. This has no useful impact regarding the outer shell and establishment of a capacitor.

The target conductor might be hollowed, and it could be attempted to then charge it in a similar method as the charging of the dome of a Van de Graaff electrostatic generator. This method would then limit shrinking of the core as a method to increase internal energy.

However, the core conductor of a cylindrical capacitor might also be extended from the outer shell; such that the extension may receive the electrostatic charges.

Thus, mathematically and physically, a cylindrical capacitor is a possible topological modality for possibly retrieving more energy from the capacitor than what is used to initially energise it. It is a more feasible modality than a spherical capacitor.

2.10.3 Parallel plate capacitor

The capacitance of a parallel plate capacitor is:

$$C = \frac{\epsilon_r \epsilon_0 A}{d}$$

where

C – capacitance (Farad)

ϵ_r – relative permittivity of the dielectric between electrodes

ϵ_0 – vacuum permittivity

A – area (m²)

d – thickness of the dielectric between electrodes

When a parallel plate capacitor is charged (Q coulombs), the internal energy available would be:

$$U = \frac{1}{2} \cdot \frac{Q^2}{(\epsilon_r \epsilon_0 A)/d}$$

where

U – internal energy (Joule)

Q – charge (Coulomb)

Re-arranged:

$$U = \frac{1}{2\epsilon_0} \cdot \frac{Q^2 \cdot d}{\epsilon_r \cdot A}$$

Note that the electrostatic field from a parallel plate electrode would experience fringing at the edges. Fringing should not occur with spherical capacitors and only marginally with cylindrical capacitors. A practical approach to constrain the fringing effect is to ensure that the d offset between electrodes is significantly smaller than the dimensions of the electrodes. For parallel plate capacitors this would imply the use of a set of equivalent serially connected parallel plate capacitors. For such a stack of serially connected capacitors, the equivalent capacitance would be:

$$C_t = \frac{C_i}{n}$$

where

C_t – equivalent capacitance of the stack (Farad)

C_i – capacitance of a unit (Farad)

n – number of units in the stack

Re-arrange the internal energy equation for a stack of capacitors:

$$U = \frac{1}{2\epsilon_0} \cdot \frac{Q^2 \cdot d \cdot n}{\epsilon_r \cdot A}$$

The objective of the evaluation is to establish how the internal energy (U) might be increased for a given charge (Q):

- The first term, $\frac{1}{2\epsilon_0}$, is a constant and cannot be manipulated to increase U.
- The offset between electrodes, d , might be increased – and the increase will improve the internal energy linearly. Unfortunately, as the offset is increased, fringing losses would increase, reducing the charge Q . This loss impacts quadratically on the internal energy.
- The number of unit capacitors in the stack, n , might be increased – and the increase will improve the internal energy linearly.
- The relative permittivity of the dielectric, ϵ_r , might be reduced. Note that the relative permittivity can only be reduced to unity, at which stage it equals the permittivity of vacuum and air. There is thus a limit to the impact of this approach.
- The area of electrodes, A , might be reduced. As the area becomes smaller, it becomes more difficult to vest the charges on it. Higher static potential is required to vest charges. This approach is also limited in positive impact.

Mathematical considerations indicate that with parallel plate capacitors, there is at least the option of increasing the internal energy linearly by increasing the number of capacitors in the stack. Note the prior discussion on reducing the offset, d , in order to reduce fringing losses.

Parallel plate electrodes are easily accessible, and it is thus relatively simple to charge them, in multiple approaches.

Other considerations, now that mathematics and physics are feasible:

- Manufacturing. It is easy to manufacture multiple parallel plate capacitors.
- Recharging is also not complicated.
- Partial harvesting. A stack of serially connected capacitors allows the choice between instantaneous total harvesting or partial harvesting. It might be more feasible to conduct subsequent partial harvests rather than one high voltage overall harvest.

There are ways to increase the output from capacitor stacks:

- Increase the harvesting frequency. Recharge occurs at nearly the speed of light, thus allowing very high harvesting frequencies.
- Higher static potential, and thus charge. This analysis considered the impact on internal energy for various topological modalities of capacitors, given a set charge. However, internal energy is related to the charge squared. Internal energy will thus increase in relation to the square of charge increases.

2.11 Insertion and removal of an electrode from between other charged electrodes

The present research was stimulated upon encountering the textbook case of a conducting electrode inserted between the plates of a parallel plate capacitor. It was hypothesised that a new electricity generator might be created by the following:

- Successively inserting two electrodes between the electrodes of a charged parallel plate capacitor – without creating short circuits.
- Harvesting the energy from the inner capacitor.
- Successively withdrawing one or both of the inserted electrodes.
- The outer capacitor should now have reverted to its initial energy state, as capacitor operations are driven by

$$Q = C \times V$$

where:

Q – charge (Coulomb)

C – Capacitance (Farad)

V – Potential difference (Volt)

- Harvesting did not change the charge on the outer electrodes and the outer capacitor reverted to its initial state, and thus capacitance, after removal of the electrodes. The potential difference, and thus the internal energy, should have reverted to its initial state. Internal energy is given by:

$$U = \frac{1}{2} \cdot \frac{Q^2}{C} = \frac{1}{2} \cdot Q \cdot V = \frac{1}{2} \cdot C \cdot V^2$$

where:

U – Internal electrostatic energy (Joule)

If it would assist in maintaining the original electrostatic status quo, the inner capacitor may be withdrawn as a unit from the outer capacitor, and the energy harvested outside.

The insertion and removal of the inner electrodes will obviously require forces and work, and the work required might exceed the energy harvested, which would imply the cycle is not sustainable from an energy perspective. However, electrostatically the original status quo should be maintained. Effective engineering would reduce the work required to maintain the cycle.

Stratton (1941: 117) specified the “Theorem on the Energy of Uncharged Conductors: The introduction of an uncharged conductor into the field of a fixed set of charges **diminishes the total energy of the field.**” (present author’s emphasis). Stratton also proves that the internal energy will reduce after an uncharged conductor is inserted. However, Stratton never stated that the original energy would be reinstated upon withdrawal of the uncharged conductor.

2.11.1 Forces modifying capacitor configuration

The forces involved in opening or closing the electrodes of a capacitor, or of inserting and removing another electrode, are vital for the functioning of TENG (triboelectric nano-generator) harvesting the energy from small movements, such as vibration or light wind, via triboelectric and electrostatic induction. Understanding the forces is also vital for the current research, in order to plan the experimental setups and also to interpret results.

There are two major forces involved in a parallel plate capacitor:

- Changing the gap between the electrodes
- Inserting or withdrawing additional electrode(s) between the original two electrodes

There is also a torque force present when a rotary variable capacitor is being operated. This is not considered for now.

There are various methods in literature of calculating these forces. They will be discussed now. All of them evolved from the equations for the internal energy (U) of the capacitor. Two main approaches are used:

- The energy method, where the force is found by differentiating the equation for the electric field (E or E_E) in the direction of displacement and also by calculating the Maxwell stress tensor approach (Hungerford, 2014: 6) or by reviewing the work done from first principles, as by Tatum (2019: 1): “The work done in separating the plates from near zero to d is Fd , and this must then equal the energy stored in the capacitor, $\frac{1}{2}QV$. The electric field between the plates is $E = V/d$, so we find for the force between the plates”:

$$F = \frac{1}{2} Q E$$

When the charge Q and the electric field strength E is expanded:

$$F = \frac{1}{2} \epsilon_0 A \frac{V^2}{d^2}$$

Shuman (2005: CP2) described this attractive force between electrodes as the basis of an accurate parallel plate mass balance and thus included a vital correction as the apparatus uses finite electrodes (D as the diameter of the electrodes):

$$F = \frac{1}{2} \epsilon_0 A \frac{V^2}{d^2} \left(1 + \frac{2d}{D}\right)$$

- The modified capacitance method. The capacitances of the starting and final configurations are calculated, as well then as the internal energy for each capacitance. The change in internal energy equates to the energy used to affect the displacement. Thus the force can be calculated. It appears that the Indian school syllabus incorporates the insertion of an electrode or a dielectric into a parallel plate capacitor. There are thus multiple videos aimed at this market on the internet, explaining the modified capacitance method. Note that the equation above, for F, may be re-arranged to get to the equation for internal energy:

$$F \times d = \frac{1}{2} \cdot \frac{\epsilon_0 A}{d} \cdot V^2 = \frac{1}{2} \cdot C \cdot V^2 = U$$

All the methods lead to the same answers, generating credibility. It would, however, be preferable to validate the results experimentally.

2.11.2 Force to change the gap in a parallel plate capacitor

Various authors (Shuman, 2005; Zangwill, 2012; Ananthasuresh, 2013; Tatum, 2019) arrived at the same formulation for the force involved when the gap between the electrodes of a capacitor is changed:

$$F = \frac{1}{2} \epsilon_0 A \frac{V^2}{d^2} = \frac{1}{2} \frac{1}{\epsilon_0 A} Q^2$$

2.11.3 Force to insert or remove an electrode in a parallel plate capacitor

Start with the first principles formulation of force as the derivative of internal energy with respect to the displacement:

$$F_x = -\frac{\delta U_E}{\delta x} = \frac{\delta U_E}{\delta x} = \lim_{\Delta \rightarrow 0} \frac{U_E(x + \Delta) - U_E(x)}{\Delta}$$

for the following diagram:

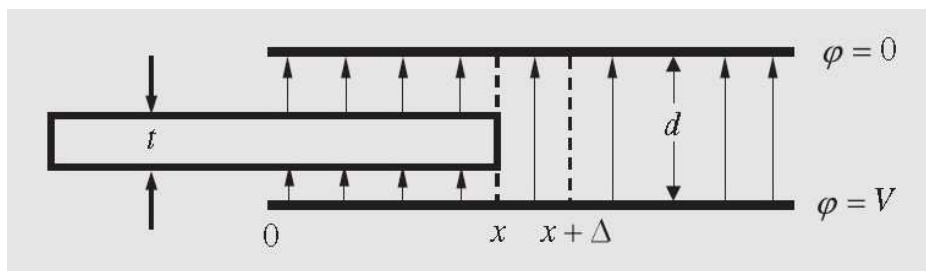


Figure 2-61: Capacitor layout to determine force to insert a third electrode (Zangwill, 2012: 146).

Zangwill (2012) concluded that the force required when an electrode is inserted or removed, is:

$$F = \frac{1}{2} \varepsilon_0 V^2 \omega \left[\frac{1}{d-t} - \frac{1}{d} \right] x$$

Hungerford (2014) arrived at the same result, using the Maxwell stress tensor.

Ananthasuresh (2013) determined the force when one electrode moves with respect to the other, as (electrode dimensions $\omega \times l$ with a gap between electrodes g):

$$F_l = - \frac{\delta E_e}{\delta l} = - \frac{1}{2} \frac{\varepsilon_0 \omega}{g} V^2$$

Note that F_l according to Ananthasuresh, is actually only one half of the F according to Zangwill, assuming that the new electrode is vanishingly thin and located right in the middle between the outer electrodes. The same answer is arrived at through compensation by the smaller g 's in Ananthasuresh – together amounting to Zangwill's d .

When an electrode is inserted, the force will be negative – indicating it is sucked in.

2.11.4 Implications of the insertion force of an electrode

Consider the equation for the insertion force of an electrode:

$$F = \frac{1}{2} \varepsilon_0 V^2 \omega \left[\frac{1}{d-t} - \frac{1}{d} \right] x$$

The two big drivers of the force would be the square of the potential difference, which would quadratically increase the magnitude of the force and then the factor term $(1/(d-t) - 1/d)$, which would have a linear impact on the force magnitude.

The potential difference would always be the largest that can be coped with, as a higher potential difference implies higher charge and thus higher internal energy. Higher internal energy might ease measurement as it offers a slight buffer against scavenging by inadequate instrumentation. However, the V^2 impact on force necessitates caution. It might expedite the experiments into the situation where the retention forces are too high to cope with.

This leaves the factor term $(1/(d-t) - 1/d)$ for manipulation, with d the gap between electrodes and t the width of the inserted electrode. The first analysis uses a constant gap of 0,52 mm, which is four times the thickness of 0,13 mm of a standard dielectric sheet.

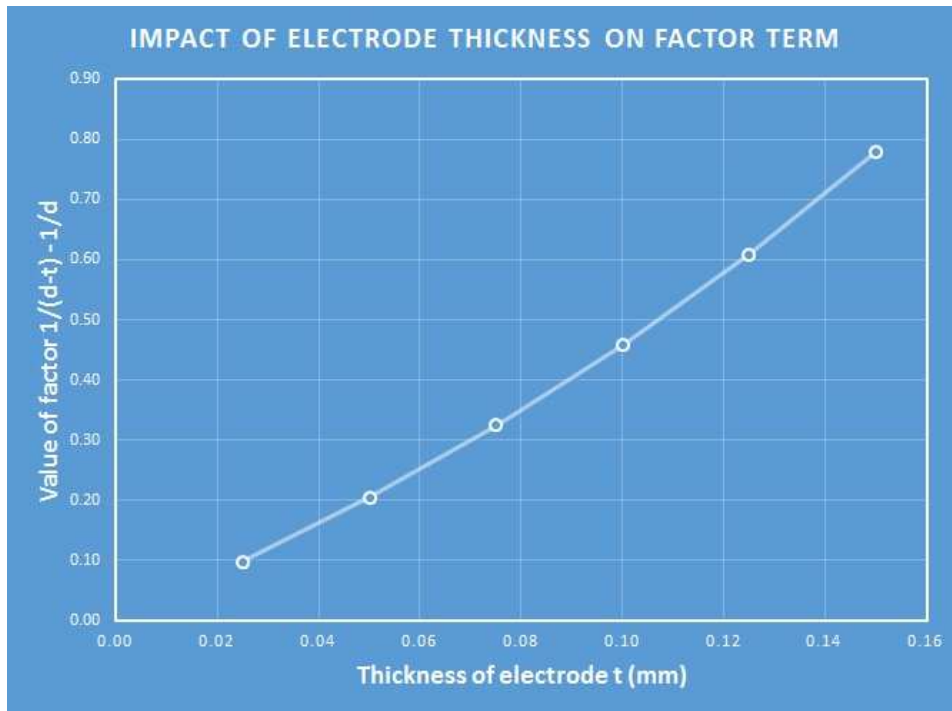


Figure 2-62: Impact of electrode thickness on factor term (gap = 0,52 mm).

Then a trial was undertaken with a gap at 5,2 mm, which is ten times the previous gap. The factor term became almost a factor 100 smaller, which is significant as it can dramatically influence the experiments:

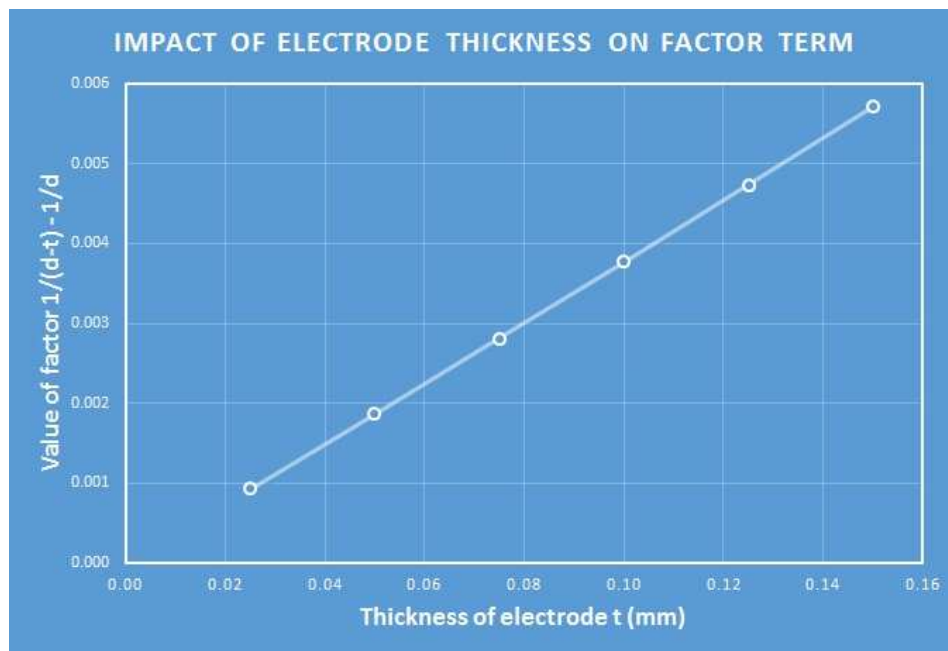


Figure 2-63: Impact of electrode thickness on factor term (gap = 5,2 mm).

Both graphs, at various gaps, show the same linear trend and gradient with respect to electrode thickness. It now became necessary to investigate the impact of changing gap on the magnitude of the factor term. A value of 0,1 mm is used for t , as that is the thickness of aluminium sheet that is readily available.

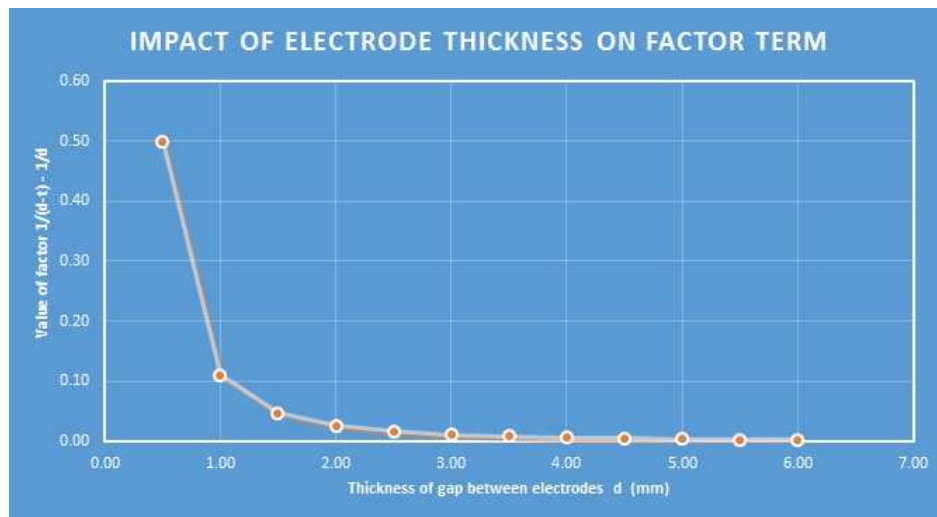


Figure 2-64: Impact of gap between electrode thickness on factor term (electrode thickness = 0,1 mm).

The graph shows that the forces might be reduced by 80%, by doubling the gap from 0,52 mm to 1 mm. If the experiment will electrostatically tolerate a gap of 4 mm, the factor term would be 0,0064 which would effectively eliminate the insertion or extraction force.

2.12 Electrostatic induction charging of a capacitor stack

The following aspects are relevant for the capacitor stacks:

- Capacitor stack design. Which principles guide design?
- Super- and ultra-capacitors might be used very effectively as capacitor stacks.
- Stack as a conduit or pipeline for charge. A stack of capacitors conduct charge as a conductor would conduct current or charge.
- Fringing of electrostatic fields are vital in capacitor stack design.
- Charge reversal might occur after arcing, and can influence effectiveness.
- Capacitor stack as an antenna. The RF aspects of capacitor stacks must be investigated to prevent problems and improve design.

- Holding mechanism for capacitor stacks. Capacitor stacks must be supported in ways to protect the energy and also to prevent harm from arcing.
- Energisation of capacitor stacks. A capacitor stack must be charged. What are the options?
- Energy harvesting from capacitor stacks. How much energy can be harvested from stacks and how?
- Energy balance. What is the relevant energy balance?

2.12.1 Capacitor stack design

The prime equations governing capacitor performance are:

$$Q = C \cdot V$$

$$U = \frac{1}{2} \cdot \frac{Q^2}{C} = \frac{\sigma^2 A d}{\epsilon_0 \epsilon_r}$$

The capacitor equation indicates that capacitor performance is determined by two out of the following three: charge (Q), capacitance (F) or potential difference (V). When two independent variables are established, the value of the third variable is determined. The third variable is thus a dependent variable.

In the capacitor stack application, the charge and capacitance can be established:

- Charge is determined by the source availability as well as the geometric relationship between the source and the target electrode of the capacitor stack.
- The capacitance of the capacitor stack is a function of the capacitance of individual capacitors in the stack as well as the number of capacitors in the stack.

As the potential difference is determined, care must be taken that the breakdown voltage of the dielectric between the source and the target electrode as well as between individual electrodes is not exceeded. If need be, an earthing spike at the appropriate distance from the source would limit source potential with respect to Earth. Better dielectrics or changed gaps would reduce arcing.

The internal energy is a function of the charge squared divided by the capacitance. The target electrode must thus be as large as possible and as close as possible to the source in order to

increase charge capture. Stacks may be positioned throughout the volume around the source to capture all charge. Stack volumetric efficiency is gained by increasing the charge density on the electrodes, especially as charge has a quadratic impact. Care must be taken to prevent arcing.

Once charge has been captured in a stack, the number of capacitors (serially connected) must be increased in order to drive the overall capacitance towards nil. That would increase the internal energy that can be harvested.

2.12.2 Super- and ultra-capacitors

The literature does not indicate that electrostatic induction had ever been used to charge a super- or ultra-capacitor. Electrostatic induction offers the immense benefit of instantaneous charging, and would thus add value to that technology. Fukuhara *et al.* (2018: 1) researched “amorphous titanium-oxide super-capacitors” which are then “dry electric distributed constant capacitor (EDCC)”. Further research on this topic is mandatory and might be very valuable.

2.12.3 Stack as a conduit or pipeline for charge

It appears that the stack functions as a pipeline for charge, in the same way a conductor would also conduct charge. With both stacks and conductors then, if charge is added or induced on the target surface, the opposing polarity charge will become free on the opposing, furthest face.

2.12.4 Fringing of electrostatic fields

Fringing refers to the property that an electric field will create additional field lines around the edges of an electrode:

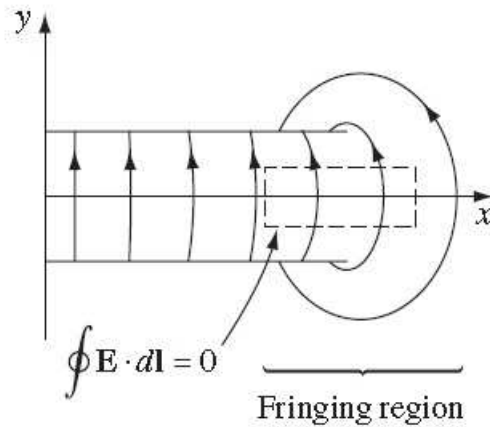


Figure 2-65: The fringing region at the edges of electrodes (Griffiths, 2013: 203).

Fringing has been known for a long time. Maxwell (1873: 491) used conformal mapping (Zangwill, 2012: 226) to construct the following diagram of equipotential lines (generally radial outwards from the edge) and electric field lines (generally ellipsoidal around the edge) in the region at the edge of a parallel plate capacitor:

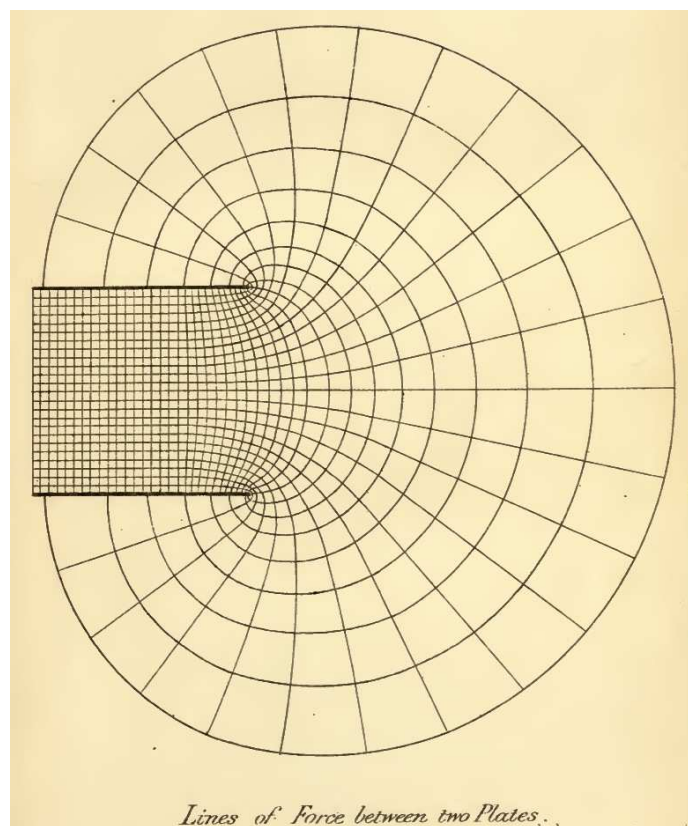


Figure 2-66: Fringing at the edges of electrodes: a conformal map by Maxwell (1873: 491).

Fringing is of concern for electrostatic induction as it may cause electric field lines not to intersect with the next electrode in the propagation sequence. However, Maxwell's careful plot illustrate the immense symmetry of the electric field lines. There is thus a possibility that if sufficient care could be exercised during construction to maintain symmetry, no charge propagation may be lost. At this stage it appears that the following experimental work would be required:

- Construct an electric field visualisation apparatus that will enable full scale simulation of the envisaged capacitor building block and at the intended potential. Experiment with the gap and potential difference to ensure that the set-up would allow all electric field lines to communicate between adjacent electrodes.
- The full-scale electric field visualisation apparatus should ideally allow visualisation of a 2D stack, with perhaps at least 10 capacitor emulators. During 2D visualisation, the full capacitor is emulated by a smaller strip. This would be a lower risk strategy, rather than to test and validate at full 3D scale.
- A 3D electric field visualisation apparatus can be constructed to allow observation of the effects at the corners. What fillet radius would allow clean propagation, with minimum noise?
- The final result may be constructed for validation by injecting a specific charge and measuring the throughput charge, perhaps after say ten capacitors in a stack.
- There is a possibility that the gap distance may be considerably expanded. In that case, 3D printing may be considered to construct a dielectric that will accurately position electrodes such that symmetry may be maintained throughout the stack. The aluminium foil of 100-micron thickness might be replaced by a stiffer aluminium sheet for the electrodes. Gap expansion and especially construction symmetry would make manufacturing easier and reduce risk and might reduce the resource footprint. Electricity harvesting might be easier, as less connections and switches might be required, although the input potential differences would be higher.

James Clerk Maxwell did excellent work, all of 146 years ago. Thank you!

There are possibly three reasons for fringing:

- Charge is always distributed equally on the surface of a conductor.

- Field lines will enter and exit a surface only as a normal to a surface, to ensure that no tangential forces may be created.
- The electric field between the electrodes is irrotational, thus the curl of the electric field is nil ($\nabla \times \mathbf{E} = 0$).

Electric fields, in the simplest representations, starts at point sources and ends at point sources:

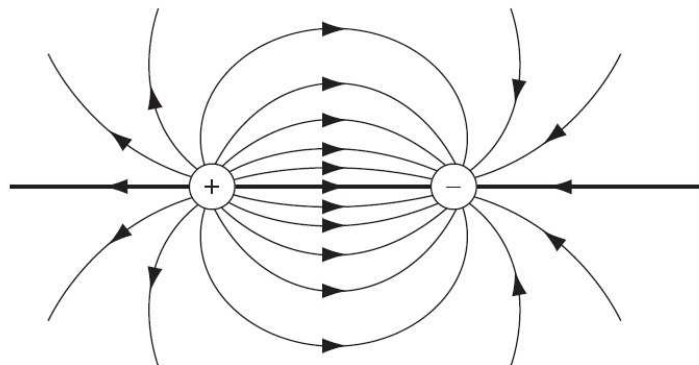


Figure 2-67: Electric field between opposite polarity charges (Griffiths, 2013: 67).

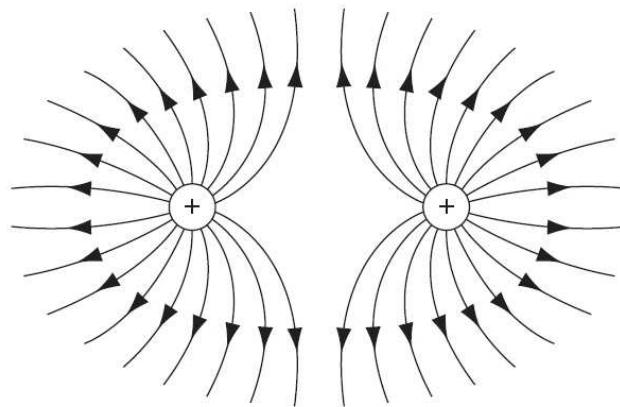


Figure 2-68: Electric field between similar polarity charges (Griffiths, 2013: 68).

These fields can be visualised using an electric field visualising apparatus, where light seeds float on oil and then orient themselves according to the applied electric field:



Figure 2-69: Electric field visualisation between cylinder and plate (Tipler & Mosca, 2004: 705).

Note specifically the behaviour of field lines at the edge of the plate. That constitutes the fringing referred to here. It is due to the fringing effects that problems in textbooks almost inevitably specify infinitely large electrodes. The edges are then pushed out to infinity.

Sloggett *et al.* (1986: 2725) noted that fringing may be an advantage, as it increases capacitance: “These departures from ideal uniform field behaviour are often referred to as ‘fringing’, and for certain applications are highly significant. For example, the elementary expression for the capacitance of parallel-plate capacitors ($C_{\text{elem}} = \epsilon A/d$ with ϵ the dielectric constant, A the plate area and d the plate separation) underestimates the true capacitance because it ignores the fringing field.”

Fringing is problematic in electrostatic induction, as it may reduce the charge that will be induced on the target electrode. The electric field that should have created more charge, possibly escaped via fringing, depending on the final embodiment.

Sloggett *et al.* (1986) researched fringing, via changes to the vertical field non-uniformity δ_y when a disc radius R is at a gap distance d from a large planar electrode, for R/d from 2 to 20. This research used a circular electrode, and the calculated capacitance is used as a measure of fringing. After literature and empirical research, their equation 36 was recommended as the top performer (C being the actual capacitance and C_{elem} the calculations according to elementary formulae from text books. C/C_{elem} indicates the error.):

$$\frac{C}{C_{elem}} \approx 1 + \frac{2d}{\pi R} \ln \frac{8\pi R}{ed} + \left(\frac{d}{\pi R} \ln \frac{d}{8\pi R} \right)^2$$

The C/C_{elem} term's behaviour for various electrode radii (R) and various gaps between the electrodes are calculated in Table 2-10:

Table 2-10: Term C/C_{elem} calculated for various R and d						
Gap between electrodes d (mm)	Electrode radius R (mm)					
	100	200	300	400	500	600
0.13	1.0074	1.0040	1.0028	1.0021	1.0017	1.0015
1.00	1.0441	1.0241	1.0169	1.0131	1.0108	1.0092
3.00	1.1136	1.0626	1.0441	1.0344	1.0283	1.0241
10.00	1.3191	1.1760	1.1243	1.0971	1.0802	1.0685

Table 2-10 shows that the error term tends to 1 as the electrode size increases. For a small gap, say $d = 0,13$ mm, the error term reaches 1,0001 when $R = 7\,600$ mm (analysis not included here). The term does not stabilise, it continues tending closer to 1, albeit slowly for larger gaps.

Chen *et al.* (2019: 3) suggested a conversion of these equations: “For square capacitor, based on the principle of equal area, R can approximately be replaced by:”

$$\sqrt{\frac{L^2}{\pi}}$$

Chen *et al.* (2019: 3) provides a tabular summary of other research towards the error term:

Table 2-11: Term C/C_{elem} from various research Chen et al. (2019: 3)

Ref.	Author	Year	Formula
[8]	Ignatowsky	1932	$C \approx C_0 (1 + \frac{2d}{\pi R} \ln \frac{32R}{ed})$
[9]	Cooke	1958	$C \approx C_0 (1 + \frac{2d}{\pi R} \ln \frac{\pi e R}{d})$
[10]	Hutson	1963	$C \approx C_0 (1 + \frac{2d}{\pi R} \ln \frac{8\pi R}{d})$
[11]	Sloggett	1986	$C \approx C_0 (1 + \frac{2d}{\pi R} \ln \frac{e\pi R}{d})$

It appears the general guidelines to reduce charge loss due to fringing, would be:

- Maintain symmetry throughout the stack, such that all electrodes and dielectric sheets are separately aligned.
- Unless further research indicates otherwise, keep gap between electrodes as small as possible and electrode size as large as possible for the application.
- Let dielectric overlap, beyond edge of electrode. Research the degree of overlap.

2.12.5 Charge polarity reversal

It appears as if an electrostatic source will induce polarity reversal in a stack, subsequent to an arc to the target electrode. Polarity reversals might be disastrous for harvesting.

2.12.6 Capacitor stack as an antenna

Multiple authors refer to the radiation from capacitors. A capacitor stack also apparently resembles a Yagi antenna. It would be prudent to conduct radio frequency research to ensure that the product design makes best use of existing expertise.

2.12.7 Holding mechanism for capacitor stacks

High voltages in the capacitor stacks present a risk, both:

- for the loss of energy if an arc occurs; or
- for damage to equipment or staff if an arc occurs.

The high voltages will, however, creep along any path, and the guiding principle then is to touch the capacitor stack as little as possible. Minimise contact, as all contact creates earthing bridges.

Arcing will not necessarily occur to Earth. Energy might also arc to lower potentials.

It appears best to stack capacitors vertically, at least for experimental purposes. It was attempted to increase the support member lengths, in an attempt to increase the creep paths, but success was limited. This is not a feasible solution, as it would be difficult to maintain stack integrity in mobile applications.

Electrostatics will inevitably polarize the molecules in isolators, so an isolator is not the full solution. Polarization might also make it easier for corona discharge to occur.

It appears as if an electrostatic creep path is longer than a conduction current creep path, and this might be due to the substantially higher voltages and lower currents and lower energies. The lower energy refers to the fact that if the energy to be stored is low, any loss is significant, whereas a store with bulk energy is more robust.

More direct research on this aspect is required, especially aided by a corona camera that will visualise the existence and movement of coronas.

2.12.8 Hollow electrodes

Popović and Popović (2000) described some fundamental conclusions about conductors in an electrostatic field:

- No electrostatic field exists inside a conductor, provided there are no charges resident inside the conductor. $\mathbf{E} = 0$.
- All electrostatically induced charges would appear only on the surface, provided there are no charges resident inside the conductor.
- The surface and volume of the conductor would be at the same electrostatic potential.
- The electrostatic field on the surface would have no tangential component.

- The normal component of the electrostatic field close to the surface would be equal to the charge density divided by the permittivity in vacuum:

$$E_n = \frac{\sigma}{\epsilon_0} \text{ volts per meter}$$

These conclusions ensure that no charge can be maintained inside a conductor **if it is in conductive contact with the conductor**. An isolated charge inside a cavity in the conductor will remain there, at least until annihilated by some atmospheric charge. Also, while the charge remains isolated inside the cavity, it will electrostatically induce charges on the inside face of the cavity as well as on the outside face of the conductor.

However, the moment the charge comes into conductive contact with the conductor, it will migrate outwards, to the surface of the conductor. It is easy to understand that internal charges will exert Coulomb repulsive forces upon one another, and thus mutually drive each other to the surface, wherefrom all electric fields radiate only with a normal component. The migration of the last charge is a mystery but might be caused by the fact that a conductor cannot tolerate a potential difference within itself, which would be a given as long as the last charge remains in situ.

The above defines the environment for a hollow electrode. Textbooks refer to a hollow conductor, but for capacitors it is important to appreciate that the hollow conductor might actually be a hollow electrode.

Hollow electrodes permeate electrostatics, indicating their use, primarily as one-way valves for charge movement:

- Leyden jar (Klein)
- Wimshurst electrostatic machine
- Faraday ice pail
- Van de Graaff generator (the dome)

The one-way valve refers to the fact that charge can only migrate outwards to the surface, never inwards.

Bringing an isolated source into a hollow electrode would induce charge inside the cavity and on the outside surface. The inside induction created a capacitor between the source and the

conductor. The charges on the inside face are bound charges that are electrostatically bound to the charges on the source, and would not migrate while the source is present.

The interesting effect is that the outside charges are free and may be channelled away. If the source is then removed, the bound charges become free and will migrate outside.

Hollow electrodes create another opportunity: All charge distribution is typically determined by the relative geometries. Charge is distributed in such a way as to ensure an equal potential voltage throughout a connected system. However, hollow electrodes appear to function as an infinite sink for all charge. It thus appears that a hollow electrode will suck all charge from the rest of the system.

2.12.9 Faraday's law of electrostatic induction

Faraday conducted his ice pail experiments and found, as did Franklin (1769) before him, that unattached charge will migrate from the inside outward in a hollow electrode (Faraday, 1843b; Faraday, 1843a). Viewed from an electrostatic perspective, the four nested ice pails become the four electrodes of three serially connected capacitors. The intermediate air gaps and shellac layers constitute the dielectric elements. When a charged ball C is lowered into the innermost cavity of ice pail 4, the redistribution of electric charges due to electrostatic induction is illustrated in Figure 2-70 (redistribution merely schematic), indicating how Faraday might have extracted energy twice from the ice pail capacitors during the ice pail experiments:

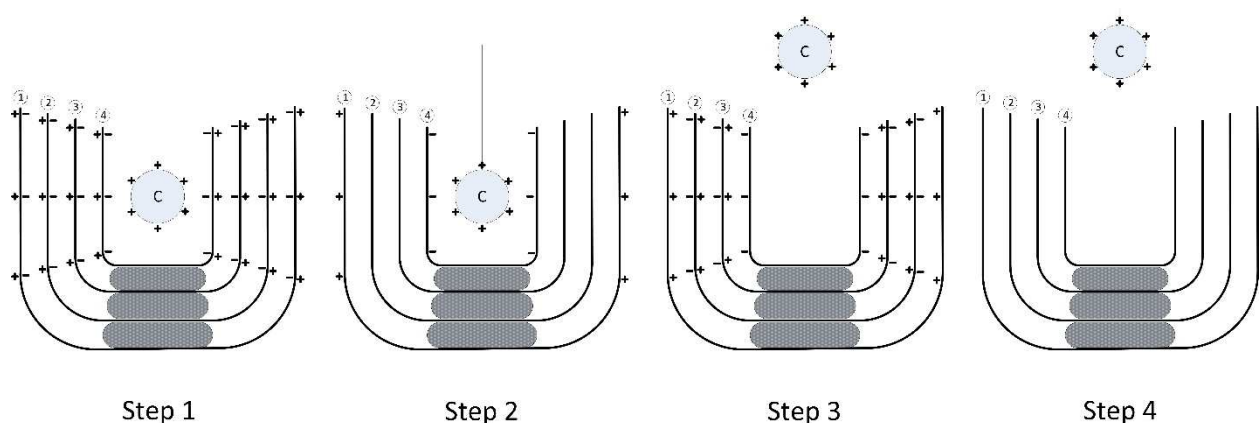


Figure 2-70: The sequence of steps in the ice pail experiments.

The electrostatic sequence is now described for steps 1 to 4:

- Step 1. The electrostatic potential energy induced in capacitors 1-2, 2-3 and 3-4 due to the charged ball C lowered into the innermost cavity.
- Step 2. The energy in capacitors 1-2, 2-3 and 3-4 is harvested. Note the remaining charges inside ice pail 4 and outside ice pail 1. Charges inside ice pail 4 are kept in situ due to the proximity of opposing polarity charges on charged ball C.
- Step 3. As ball C is withdrawn, the charges inside ice pail 4 migrate outwards, and initiate a new electrostatic charging sequence. The initial charges outside ice pail 1 remain in situ until eliminated by the electrostatic pairing of new charges induced on the inside of ice pail 1. The energy in capacitors 1-2, 2-3 and 3-4 is harvested.
- Step 4. After the second energy harvest – no charges remain in the ice pail setup.

In addition to Faraday's law of electromagnetic induction, a new law of electrostatic induction is proposed whereby the insertion or withdrawal of a charged body into a set of hollow conductors will generate energy. This is similar to the movement of magnetic flux causing the generation electric current at the insertion or withdrawal of a magnet.

2.12.10 Energisation of capacitor stacks

This section reviews the type of energy source as well as its movement requirements.

2.12.10.1 Energy source

The actual electrostatic energy source may be one of several, including:

- Electrostatic generator, including Van de Graaff generators or Wimshurst machines. Several versions are available. A number of them exploit the triboelectric effect. Such machines imply:
 - A continual replenishment of energy, which can be accommodated.
 - Volume requirements.
 - Necessity to transfer charge to the conductor wherefrom the electric field must radiate.
 - Possibly a sensitivity to movement. It is always risky to move a Van de Graaff generator, as a fall would cause harm.

- DC sliding capacitor method. It is well-known to use DC to charge a parallel plate capacitor. The electrodes are originally positioned at a gap where the forces will allow the electrodes to be slid apart. The potential difference between the electrodes is then also selected to enable sliding. As the electrodes are sliding away from one another, they will radiate electric field which can then electrostatically induce charge in a capacitor stack. This method:
 - is compact;
 - is robust; and
 - must likely be repeated frequently as the remaining charges on the electrodes are free charges. They are thus exposed to the atmosphere and will also escape if other electrostatic charges are nearby.
- D'Abramo (2011) presented a method of thermo-charging a capacitor, exploiting an available heat source, perhaps a waste heat source. It appears as if substantial research must be conducted to create a viable technology, but there is potential.
- Radiation from radioisotopes. This method is reviewed in paragraph 2.13 on page 135. It might constitute the major contribution from this research, as the radiation:
 - is static, without any moving parts nor energy inputs;
 - exploits radiation that will occur whether it is used or not;
 - allows economically feasible ways of reclaiming nuclear waste (the method might be very suited for using carbon-14 (^{14}C) waste);
 - typically has half-lives that allow very long-term energy solutions; and
 - can be mounted to either a static source or a mobile source, for example a rotating disc.

2.12.10.2 Movement

Capacitors have notoriously low energy densities. A substantial capacitor might contain less energy than a AAA battery. However, a capacitor becomes a valued part of an energy generation system once the original electrostatic charge can be recycled and re-used repeatedly. Paragraph 2.3.7 on page 36 indicated that electrostatic induction likely propagates at the speed of light, implying that the maximum electrostatic harvesting frequency might be in the GHz range, or beyond.

To achieve recycling of the electrostatic source:

- The source must be moved; or

- The source radiation must be intermittently interrupted; or
- The capacitor stack(s) must move.

An electricity generator must operate 24/7/365 for many years. It would thus be advantageous for the moving parts to be as small and as light as possible. Note also that, even if harvesting frequencies of as low as 1 000 Hz are considered, the movement would require rotation at 60 000 revolutions per minute. This is an extreme speed for continuously operating systems. It would thus be imperative to focus on small and light rotating parts.

The movement might occur in one of the following formats:

- Linear reciprocating
- Linear rotation
- Rotation

Electricity generators might operate in static or mobile applications.

2.12.11 Energy harvesting from capacitor stacks

The high potential differences in the capacitor stacks are advantageous, as step-down transformers may be used to bring the potential difference down and increase the current. Note that the potential difference may be floating.

The principle would be to harvest as many capacitors at one time as per design. Note that harvesting may occur sequentially or in groups. Groups may be connected in series or parallel for harvesting. The fact that multiple capacitors or groups of capacitors may be harvested sequentially, and especially against the standard decay curve for the capacitors and circuit impedance, creates the opportunity that bespoke composite waves may be generated.

The standard wave pattern would be the sinusoidal pattern of alternating current curves, so as to fit standard devices. Emulating AC would be useful to energise current devices and is also easy to manipulate via transformers. However, research may indicate that another wave pattern has advantages and the output can adapt for that pattern.

The intent is to create electricity on demand, and not to store electricity. The electrostatic generator allows for this feature via variation of the harvesting frequency. Increasing the frequency would impact on the system reliability, and must be investigated in future research.

Standard electrical engineering principles should be abided by for the actual circuit design. This aspect was regarded as beyond current research.

2.12.12 Electrostatic induction charging of capacitors: feasibility study and energy balance

“The two key requirements of a storage device of electrical energy are quick, powerful, and energy-rich charging and long-term discharging.” (Fukuhara *et al.*, 2014) However, it is vital to recognise that, even though the generator will extensively use capacitors which are typically storage devices, in the present application energy must be generated. The generator does not have the ability to store energy, and would rather follow demand. As more energy is required, the harvesting frequency must adapt, at least till the end of its range.

Once a final product has been designed, the following performance measures may be calculated:

- Energy density or volumetric energy density – energy per unit volume.
- Specific energy or gravimetric energy density – energy per unit mass.
- Power density of volumetric power density – power per unit volume.
- A Ragone plot may be compiled of energy density against power density.
- Self-discharge characteristics may be of lesser importance as the intent is not to store energy, probably for longer than one second, in the capacitors. Parasitic leakage is thus also of lesser importance.
- Dielectric life expectancy would be very important.
- Cycle life of overall system.
- Pulse performance – ability to deliver current.
- Internal impedance – to control energy delivery.
- Energy range, depending on the harvesting frequency range.

It would be less than useful to calculate any of these parameters now, as their final values should reflect a specific design, which is outside the scope of present research. The current objective is to evaluate whether a technology incorporating electrostatic induction would hold promise for electricity generation.

At this stage, and especially considering the proposal in the next section, the response must be that electrostatic induction does indeed have great promise as a technology for electricity generation.

An energy balance relates energy input to energy output. An energy balance, as the performance metrics mentioned before, must be considered relative to a specific embodiment of the technology:

- Baseline embodiment. The electrostatic source is carbon-14 radioisotope, emitting β -radiation towards a collector shell. Outside the collector shell is an array of Faraday shell shutters, screening off the collector shell from the target electrodes of the capacitor stacks, encompassing the volume around the source assembly.

The radioisotope emits electrons which give a negative charge to the collector shell. Some charge migrates outwards, to the outside face of the collector shell.

The negative charge induces positive charge on the inside of the Faraday shell shutter and also on the target electrode to the extent it is exposed at that time, given the rotation of the Faraday shell shutter.

As the target electrode is populated with charge, it electrostatically induces charge throughout the stack behind it.

When it is time for harvesting the energy in the stack:

- The Faraday shell shutters must completely screen off the target electrode from the collector shell.
 - The energy in the “capacitor” between the Faraday shell shutters and the target electrode is harvested.
 - The energy in the capacitor stack behind the target electrode is harvested.
- Energy balance. The input energy here rotates the Faraday shell shutters. This should be minimal. The output energy is then all that can be harvested from the capacitor stacks. The likelihood is that the energy balance will be favourable.

2.13 Electrostatic induction charging of capacitors via nuclear radiation

UCLA's Richard Kaner described static electricity as: “Static electricity occurs from the interaction of one material that captures electrons and another that gives up electrons.” (Dockrill, 2019), (Ahmed *et al.*, 2019). This typically describes triboelectricity, but is also a generic description of β – decay nuclear radiation. A source “gives up electrons” while a target will “capture electrons”.

2.13.1 Historical overview

Two published and known instances of inductive charging of capacitors are: Faraday's ice pail experiments (Faraday, 1843a) and (Faraday, 1843b), as well as the Wimshurst machine (Thompson, 1888: 611). The original electrostatic sources are typically generated from triboelectricity. Faraday (1843b) suggested that the source be charged by a machine or from a Leyden jar, while the Wimshurst machine exploits random charge differences on the sectors.

It appears that the electrostatic effects of radioactive emission were recognised from the start of research into radioactivity. R J Strutt (1903: 588) acknowledges Madame Curie's insight: "Sometime ago M. Curie (Comptes Rendus, cxxx. p. 647) showed that the β or cathodic rays from radium carried away a negative charge from the substance, leaving a positive charge upon it." Strutt recognised that Madame Curie struggled to demonstrate the effect due to the "comparatively weak radium preparations" (R J Strutt, 1903: 588) available to her and conceptualised an experimental setup to better demonstrate charge separation during radioactive emission:

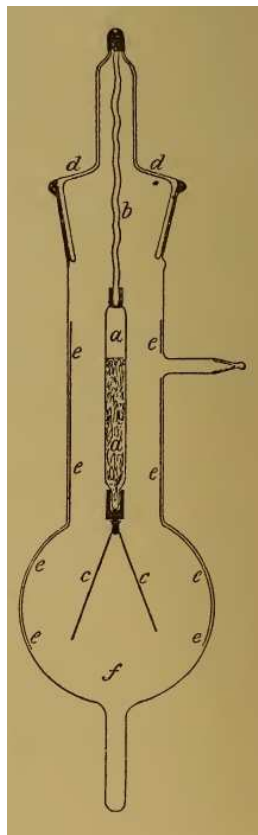


Figure 2-71: Strutt's experimental setup (R J Strutt, 1903: 588).

By 1907 this prototype had been commercialised and was marketed in Australia as a radium clock (Staff, 1907). The radioactive source would be in *a*. During emission, gold leaves *c* swing apart due to increasing charge – and eventually touch the conductive surface *e*, which has meanwhile become charged with the opposite polarity due to emission. As the leaves *c* touch surface *e* – charge is neutralised and the cycle starts again.

Moseley (1913: 471) wanted to: “measure the energy and numerical importance of each of the many distinct kinds of β -particles emitted by a single radioactive substance”, and recognised that he will base his experiment on Strutt’s radium clock:

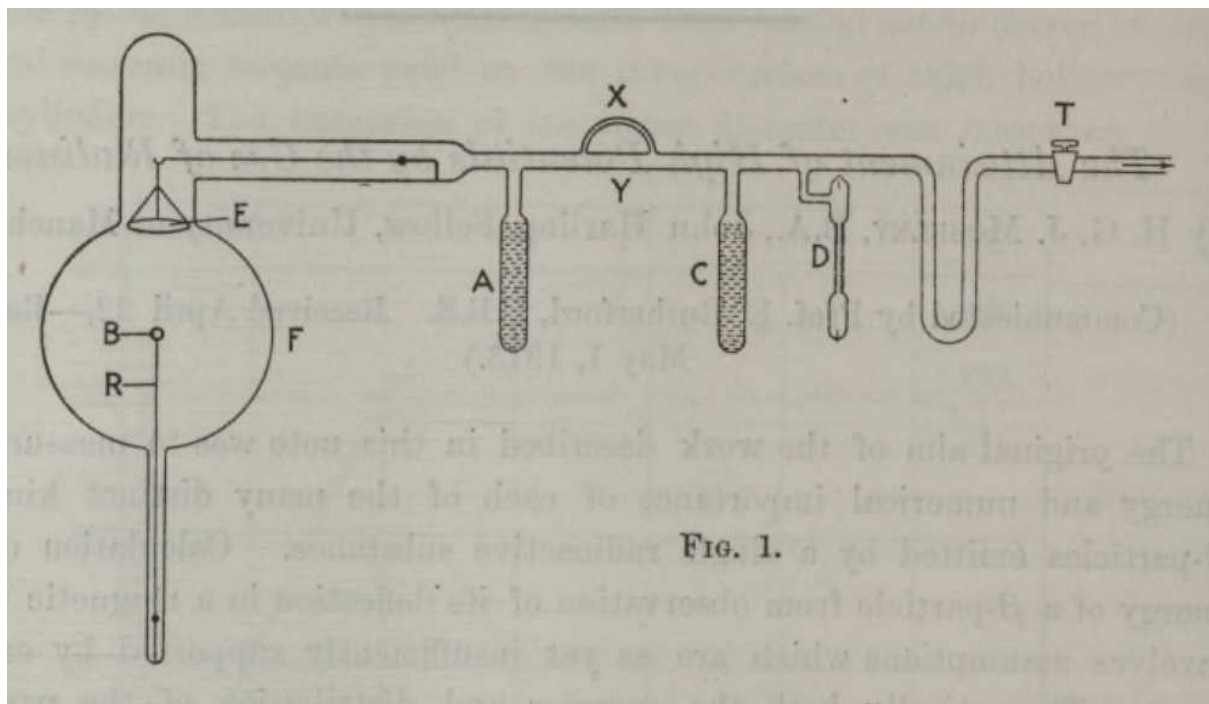


Figure 2-72: Moseley's experimental setup (Moseley, 1913: 472).

Moseley’s setup is essentially a capacitor – as was Strutt’s radium clock – yet it became known as an atomic battery. Moseley apparently preferred the term “radium battery” – yet minimal literature on this could be sourced (The Doc, 2014). Moseley’s biographer, Heilbron (1974), uses the term “radium battery”. The challenge is that Moseley was killed in Gallipoli in 1915 – and thus had a limited research career after developing the radium battery.

2.13.2 The opportunity

Strutt and Moseley's insights were to use a radioactive source as the one electrode of the capacitor, whilst particles are emitted to the opposing electrode – charging it to the opposing polarity. They thus established a third modality of charging capacitors. These are now:

- Charging via electromagnetic conduction currents – from a DC or AC source.
- Charging via electrostatic induction – from an electrostatic source.
- Charging via charged particle emission (α or β) – from a radioactive source.

The radioactive source is typically placed inside the capacitor on one of the electrodes. Electrostatic sources are typically outside the capacitor, in order to cause electrostatic induction on the target electrode, which would induce charges with opposing polarities on the near and far faces of the electrode. However, if the electrostatic source is mounted inside a conductively shielded Faraday cage, which is earthed and also provided with an aperture towards the target electrode, the source might also be mounted inside a capacitor. As the electric field hits the target electrode, induced charges would distribute themselves on the near face and mirror the electric field towards the opposing electrode. The mirrored electric field would have the same orientation (direction) as the original electric field.

Nuclear radiation offers the benefit of a continuous and long life, depending on the half-life of the radioisotope (tritium (^3H) – 12,33 years, carbon-14 (^{14}C) – 5 730 years, uranium-238 (^{238}U) – $4,47 \times 10^9$ years) (Knight, 2008). Depending on the emitted particles and corresponding shielding, it might be very safe. Design might ensure that radiation exposure is below the normal background radiation levels. The biggest benefit, however, is that a: “direct energy conversion device converts one form of energy to another through a single process” (Mitofsky, 2018: 1). There could thus be direct conversion to electricity, without intermediate processes.

However, the efficiencies attained with nuclear batteries are notoriously low. Kavetsky *et al.* (2008) published a review of 27 direct-charge cells, and the efficiencies ranged from 0,02% to 12,5%. NASA uses radioisotopes in space power packs, although typically exploiting thermo-electric effects such as the Seebeck effect. The history and target of NASA usage is (Fleurial *et al.*, 2012):

Table 2-12: Technologies used in space power packs		
Technology	Efficiency	Electrical power and density
SNAP-19 1973	6,3%	40 W _e , 3 W/kg
MHW-RTG 1976	6,5%	158 W _e , 4,2 W/kg
GPHS-RTG 1989	6,5%	285 W _e , 5,1 W/kg
MMRTG 2011	6,3%	120 W _e , 2,8 W/kg
eMMRTG future (enhanced multi-mission radioisotope thermoelectric generator)	> 15%	> 10 W _e /kg

Space power pack development is challenged by the shortage of plutonium-238 that has been used as radioactive energy source (Kramer, 2011). In 2011 there was only sufficient plutonium left to power two of the then-planned four space missions. However, the Oak Ridge National Lab might now be able to overcome the plutonium-238 shortage through process innovation (Grossman, 2019).

The opportunity is to create a generator of electricity – ideally with no moving parts – both for space and Earthbound applications. This might be achieved by merging the following features:

- Preferably β -radiation, from an emitter core to a collector shell, that will ensure that excess charge is driven to the outside of the collector shell. These charges are pushed outwards by Coulomb repulsive forces as well as the hollow electrode topology of a spherical shell.
- A Faraday shell around the collector shell. This Faraday shell is electrostatically charged by the electric field emanating from the charge on the outside of the collector shell, such that positive charges will be induced on its inside and negative charges on its outside. A spherical Faraday shell offers the benefit of uniform charge distribution on its outside face towards the inner faces of the adjacent electrodes. Uniform charge distribution is essential in the inner core (emitter core, collector shell and Faraday shell) as charge concentrations could initiate spontaneous discharge. Spontaneous discharge in the form of arcing could create various problems – including the possibility of polarity changes.
- The Faraday shell could be intermittently earthed – typically, after every harvest from the capacitor stacks – to initiate fresh electrostatic inducement of capacitive energy in the stacks. The earth connection might enable the Faraday shell to operate as a shutter to effectively allow the inner electric field to pass through or not. It emulates switching the electric field on and off. The changing electric field is essential to initiate electrostatic

induction charging of the stack capacitors. Otherwise – if the stack capacitors had been induction charged, and energy harvested – the status quo would be maintained, and no new electrostatic induction charging would occur. However, if the electric field is interrupted and “restarted”, a fresh round of electrostatic induction charging would occur.

- Note, though, the consequence of closing the earth connection to the Faraday shell in the present arrangement. Just prior to closing the earth connection, there would be charges inside and outside the Faraday shell. The charges inside the shell are not changed or moved by the connection to earth as they are capacitively coupled to the charges on the outside of the collector shell. As the connection to earth is closed, normally the free charges on the outside of the Faraday shell would have “escaped” to Earth. However, in the present case, these charges are in turn capacitively coupled to the charges on the inside face of the adjacent electrodes of the capacitor stacks. If the Coulomb forces, to both sides, are strong enough, no charges would escape. This must be verified in experiment.

However, the hypothesis is that no new charges will be added to the outside of the Faraday shell, as these would rather escape via the earth connection. This must also be verified in experiment.

The Faraday shell with an intermittent connection to earth is vital for the effective use of emitted charge, as it allows:

- Accumulation of charge. Higher levels of charge create much higher levels of energy during electrostatic induction charging of the capacitor stacks.
- Re-use of charge. A Faraday shell that can release charges, inside and outside, to earth, serves as an effective screen of the electrostatic source inside and thus enables the electric field to be changed intermittently, without destroying the source itself. Multiple re-using or recycling of the electrostatic charge improves the efficiency.

A Faraday shell is in this application both a hollow electrode with respect to the internal electrostatic source (which would be a radioisotope source for this application) as well as the inner electrode for a capacitor stack. In both directions, internal and external, the Faraday shell constitutes an electrode of a capacitor. Experience and theory on capacitors teach that charge cannot be guided out of the capacitor by connecting an electrode to earth. However, normal exposure to capacitors involve configurations where the offset between electrodes are small, and the Coulomb attraction forces between the charges with opposing polarities are much higher than the Coulomb repulsive forces

between charges on the same electrode. Also, the effect of polarized dielectric molecules adjacent to the charges must be considered. However, as long as the electric field is present – and there is no evidence indicating that it would terminate at some point – conductors in the electric field would be subject to electrostatic induction. Thus, even if charges may move to and from Earth, electrostatic induction would ensure a fresh set of charges that will ensure there are no potential differences between different points on the same conductor.

The Faraday shell has a dual function in the present configuration:

- Protects the inner electrostatic charges such that it can be used in future to electrostatically induce charge in capacitor stacks.
- Interrupts the electric field from the inner electrostatic charges such that a new cycle of electrostatic induction charging may commence.

It would be ideal to have a Faraday shell concept that can perform these functions in a static mode, without any movement. Such a concept would be especially useful in long-term extra-terrestrial applications.

However, for now, a concept that will perform the functions – involve an array of conducting rotating blades, as illustrated in Figure 2-73:

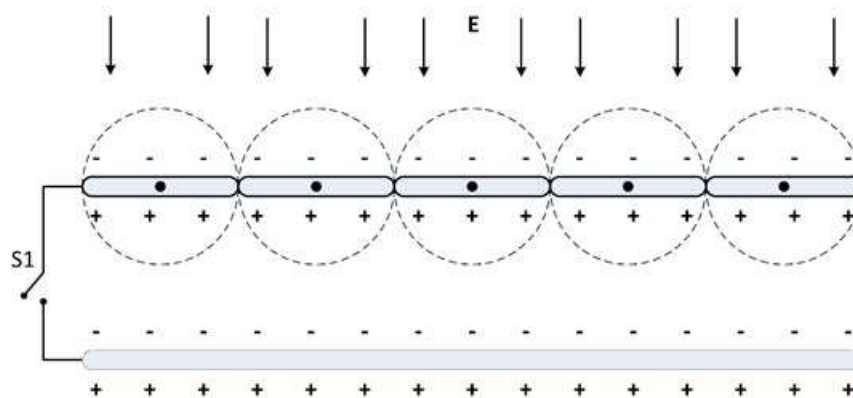


Figure 2-73: Faraday shell as blades – S1 just prior to clearance.

The electric field (E) emanates from the outside of the collector shell. The field lines should have been radial to originate from the source, but were drawn orthogonally to simplify the illustration. A capacitor is formed between the collector shell and the near face of the blade array. This capacitor must remain intact to protect the charge on the outside of the collector shell. A second capacitor is formed between the array of blades

(viewed in plan, along longitudinal axis) and the adjacent electrode. This is shown by the positive charges on the far face of the blades and the negative charges on the electrode. This capacitor must be cleared of charge by closing switch S1:

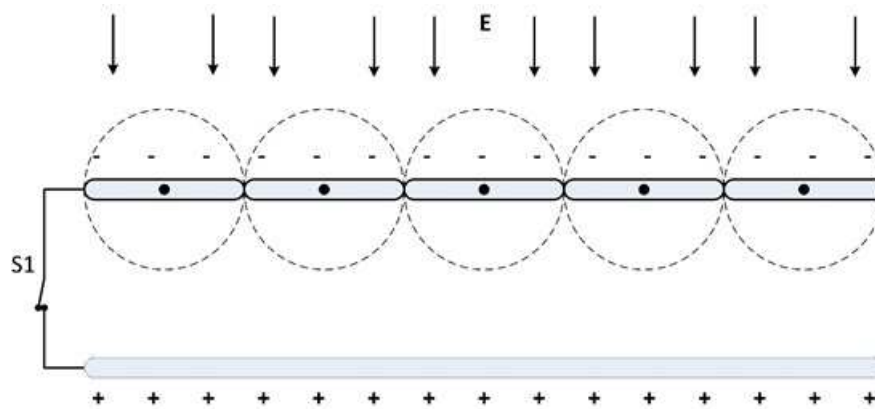


Figure 2-74: Faraday shell as blades – S1 closed at clearance.

The capacitor between the array of blades (constituting the Faraday shell) and the electrode is cleared of charge. The energy in the capacitor stacks must be harvested directly after this clearance action:

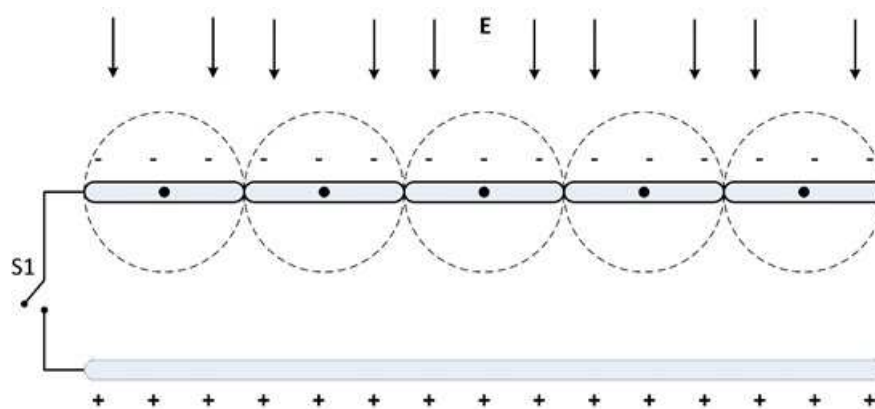


Figure 2-75: Faraday shell as blades – S1 opened just after clearance.

Once the blades rotate further, the electric field encounters an uncharged conducting object and will then, God willing, restart electrostatic inductive charging of the capacitors:

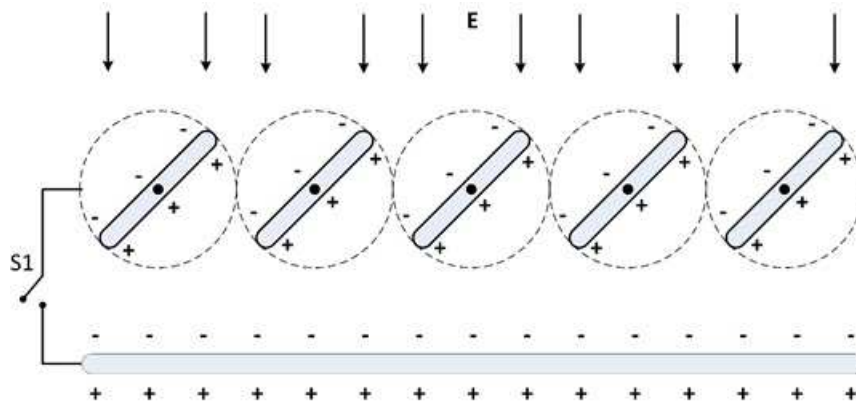


Figure 2-76: Faraday shell blades rotating.

As the blades align with the electric field, the electrode is fully exposed to the electric field, for complete electrostatic inductive charging:

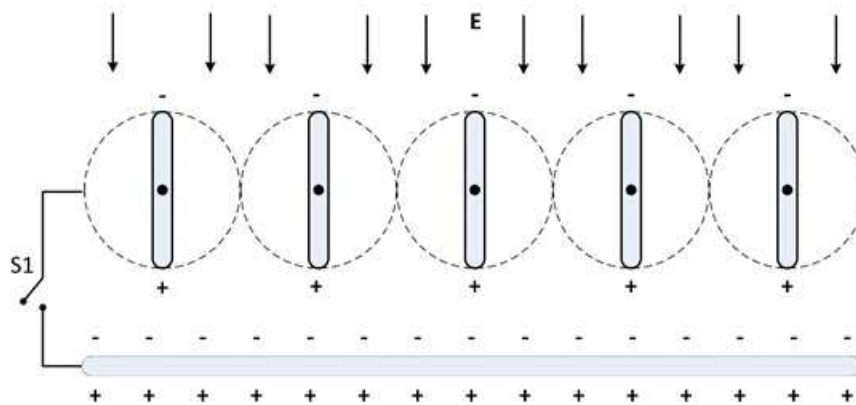


Figure 2-77: Faraday shell fully open.

Experiments should inform whether this might not perhaps be the best moment for harvesting.

This Faraday shell concept leads into the following overall layout (shown uncharged):

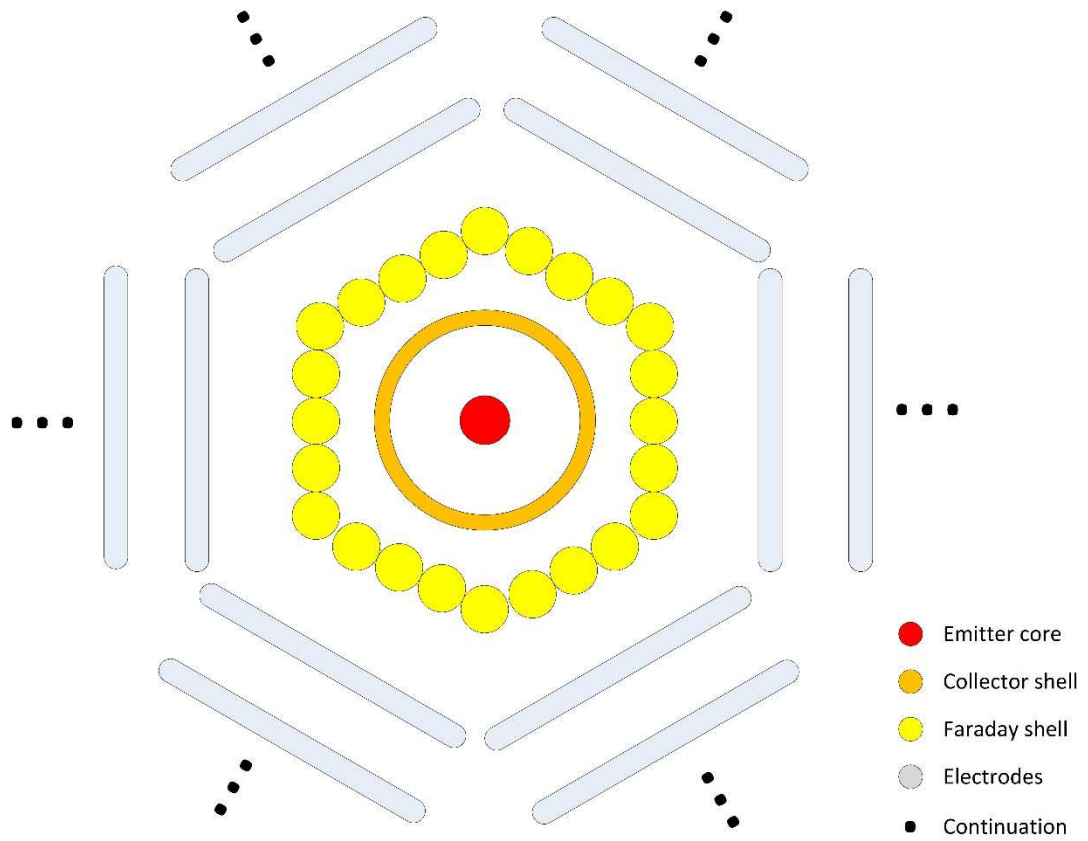


Figure 2-78: Generator layout incorporating rotating blades as a Faraday shell (shown uncharged).

The generator layout is typically charged as follows (based on β -radiation source):

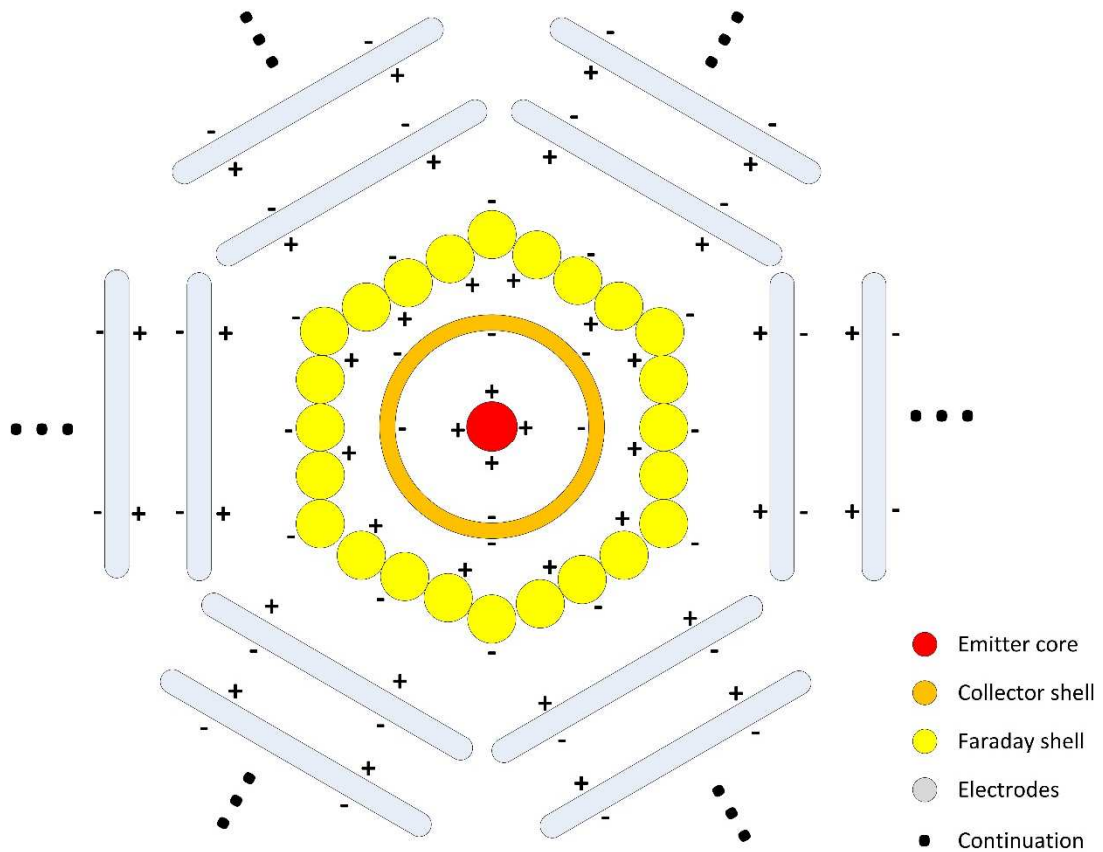


Figure 2-79: Generator layout incorporating rotating blades as a Faraday shell (shown charged).

- The illustrated embodiment uses arrays of multiple smaller conducting rotating blades to create a Faraday shell. There are other embodiments that will achieve the same overall objectives, albeit at different performance levels:
 - A larger rotor could be used in conjunction with alternating sectors for radiating capacitor stacks and shielding them from the source. Larger rotors are more difficult to rotate fast in order to increase the harvesting frequency.
 - Electrodes may slide in and out of the cavity between the collector shell and the near electrodes of the capacitor stacks. It might also prove to be a challenge to move electrodes fast enough to attain higher harvesting frequencies.
 - Electrodes constituting the Faraday shell may also be created as cavities into which a conducting fluid, for example mercury, is pumped and from where it is removed after use. This might be a fast solution but there are electrostatic challenges created by, for instance, glass walls that are polarized and might create a later barrier to the electric field.

- The generator may operate without a Faraday shell at all, but would then typically be unable to re-use charge. The overall efficiency would be reduced.
- Stacks of parallel plate capacitors surround the Faraday shell. These may be arranged to completely cover the volume around the Faraday shell – but ideally such that the initial electrodes of the various stacks do not touch and create high charge concentrations at the curved joints. Rather let some small amount of electric field escape. The initial electrodes might describe the faces of Platonic solids (tetrahedron, cube, octahedron, dodecahedron and icosahedron). The benefit of these configurations is that the building block surfaces are of the same size and shape and are equally disposed relative to the centre. A radioactive core would thus emit equal radiation to each electrode – implying equal charges to each stack.
- The induced energy in the stacks must be harvested by dedicated switches operated in deliberate sequences to generate the desired electric waveform and potential difference.

This generator will be substantially more efficient than nuclear batteries, as the emitted charged particles are used again and again to re-energise the stacks. The harvesting frequency is limited by switch capabilities only, as electrostatic induction occurs at speeds close to the speed of light. Also, even as charge leakage occur in the core capacitor (emitter core plus collector shell), new decay might replenish the charge. In fact, unless core charges are limited and excess intermittently removed, the safe functioning of the generator might be risked.

2.13.3 Radioactive emission

Radioactive decay generates three main types of particles:

Table 2-13: Radioactive decay		
Decay	Particle	Suitability current application
Alpha (α)	2 protons plus 2 neutrons	Low penetration, thus low efficiency. Unsuitable.
Beta (β)	Electrons or positrons	Penetrate up to 1 000 mm in air. Can be blocked by thin sheet of metal. Suitable.
Gamma (γ)	neutrons	Penetrate several meters. Dangerous. Unsuitable.

It appears that β -radiation would be the preferred emission. It is not as dangerous as gamma radiation yet can penetrate in air or another dielectric – much further than alpha radiation.

The ideal radioisotope would then offer the following features:

- Emit only β -radiation for a relatively long period of time – that will make the generator a reliable source of electricity.
- Emit β -radiation with sufficient energy to just reach the collector shell. The generator does not exploit or depend on the kinetic energy that incoming β -radiation imparts to the collector shell. In fact, less kinetic energy would also reduce the incidence of secondary emissions and Bremsstrahlung. However, there must be sufficient kinetic energy for incoming charges to force themselves into the face of the collector shell, and hopefully cause outward migration of charges.
- The radioactive decay products must ideally be solid, so as not to interfere with the dielectric medium, and must ideally be stable so as not to cause further emission of possibly non- β -radiation (α or γ radiation).
- Ideally the source must be a waste product from previous nuclear processing. Tritium (^3H) and carbon-14 (^{14}C) appear to be possible candidates, although tritium's waste product is helium-3 and carbon-14's waste product is nitrogen-14. In both cases the waste products are by Grace stable, but are then gasses and might impact on the dielectric's functioning. Nitrogen-14 might be funnelled upwards and out via a chimney, and in so doing remove the charge that would build up on the source, impeding later release of β -radiation and the proper functioning of the generator. Tritium is also a gas but it might be fixed into the electrode material as per Kavetsky *et al.* (2008), allowing the same strategy to be used to remove helium-3. These decay product gasses are typically charged, and their removal might thus be promoted by using an oppositely charged "target". The problem is then to maintain the opposite charge.

2.13.4 Distance between emitter source and collecting shell

Madame Curie already recognised that radioactive decay could imply the build-up of charge of two opposing polarities (R J Strutt, 1903). Moseley (1913) tried to prevent the negatively charged β -particles from leaving the source by increasing source potential difference to 1 million Volt. However, charge build-up on the collector electrode also causes problems:

Next, we consider the effect on η of the accumulated voltage between the electrodes. This voltage will appear as a result of negative collector charging

resulting in repulsion of incoming beta particles. If the energy of the beta particles moving through the growing potential field between the electrodes of a capacitor is less than or equal to that field, those beta particles cannot reach the collector. If the particle energy is greater than the product of the voltage on a collector and an elementary charge, and the particle is moving under an angle to the source surface, then under action of the electric field, it will deviate from its initial rectilinear trajectory. Increasingly fewer beta particles will reach the charging collector compared to the collector at its zero starting voltage. (Kavetsky *et al.*, 2008).

It is reasonable to expect that the arrival rate of charged particles will reduce as the amount of charged particles on the collector increase. This stems from the action exerted by Coulomb's force. The voltage is, however, probably more a symptom than a direct cause of the rate reduction. Now, if the quantity and distribution of charged particles are taken as a determinant – then the incoming particle will also exert force on the resident particles. This will open an additional coping mechanism of moving excess resident particles to the outer surface of the electrode. The push of charge to the outer surface is probably already a contributing factor to the leakage current as identified by Kavetsky *et al.* (2008).

As the core element of the system would be a capacitor formed between the source emitter and the collecting sphere, it is vital to create distance between the electrodes. This would reduce the incidence of spontaneous discharge between the electrodes. Longer distance would also reduce the kinetic energy of emitted particles, thus reducing the creation of Bremsstrahlung. The generator would only require the electric charge of the particle. The kinetic energy must only be sufficient to ensure a landing.

2.13.5 Dielectric

The dielectric must:

- ideally be easy to attain and maintain – even over long lifetimes, like 20 years;
- ideally allow β -radiation to pass unhindered;
- ideally not lead to creation of Bremsstrahlung with β -radiation interacting with dielectric molecules; and
- ideally not ionise, such that it will allow corona and arc discharges at low potential differences.

2.13.5.1 Hard vacuum

Hard vacuum is very difficult to attain and maintain and would become especially infeasible when the size of the containment sphere is increased for greater distance between the emitter source and the collecting sphere. Moseley (1913) demonstrated the difficulty in attaining hard vacuum.

The problem is that air is known to ionise and thus leak charge. According to R. J. Strutt (1903): “It is now well recognised that the air in any ordinary-vessel possesses the power of conducting electricity, although to a very slight extent. It has been usual to refer to the effect as the ‘spontaneous ionisation’ of the air.” This effect led to the attempt to create hard vacuum round the radioactive setup.

The tritium capacitor experiment also used vacuum below 10^{-5} Torr (Kavetsky *et al.*, 2008). However, given that the intent is to produce a power source for long term use, vacuum creates a risk.

2.13.5.2 Sulphur hexafluoride

Sulphur hexafluoride (SF₆) comes to mind as it is frequently used in switchgear. However, the reason for its popularity there is because of its high electronegativity, implying that it quenches or absorbs electrons. Thus it would likely prevent beta (electron) radiation from reaching the collecting sphere.

2.13.5.3 Carbon dioxide

Carbon dioxide (CO₂) might be a candidate, and should be considered.

2.13.6 Proposed concept

The following figure provides a plan view of the generator layout (supposing a static Faraday shell can be developed; else the concept of Figure 2-78 is to be used):

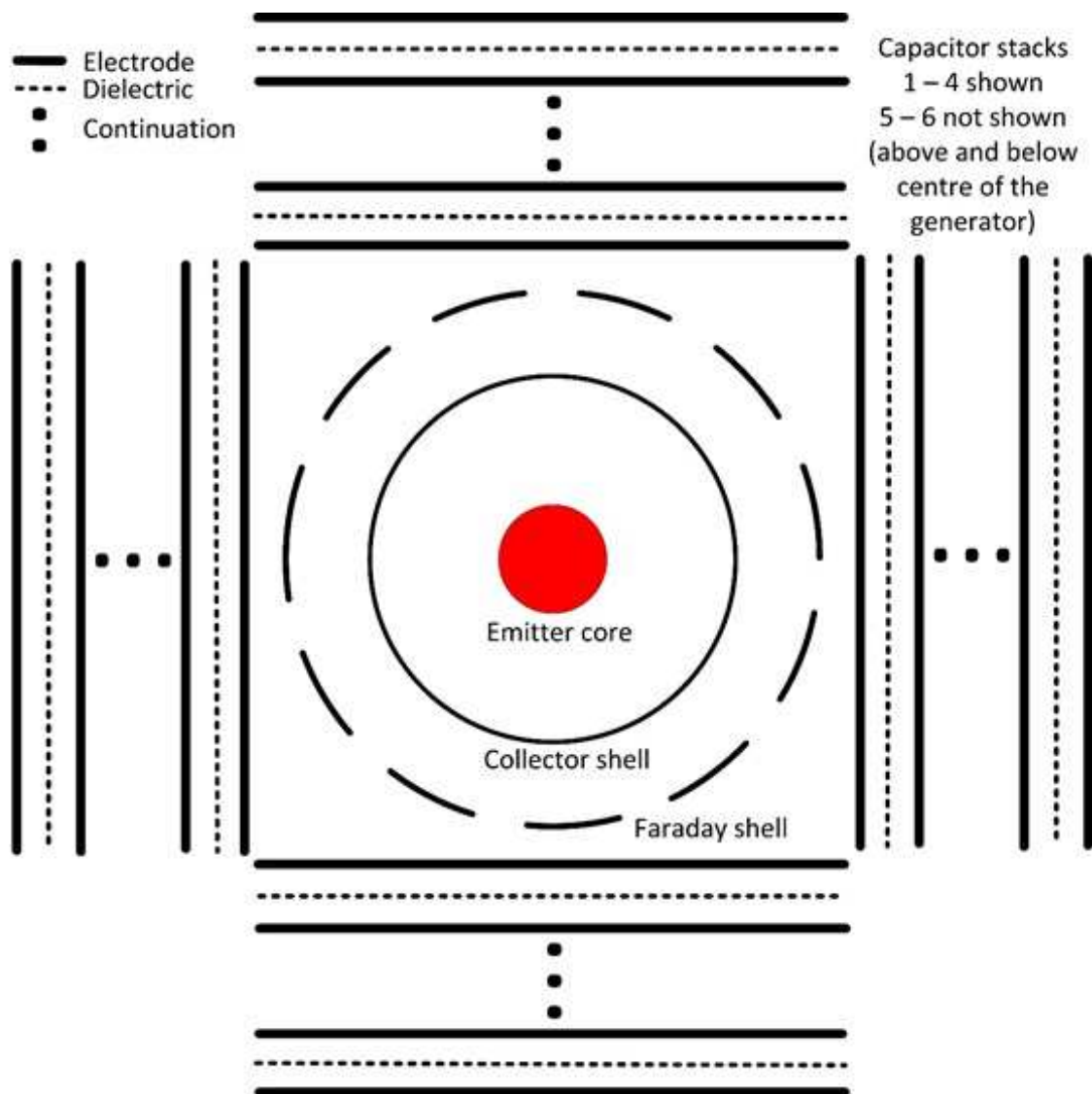


Figure 2-80: Plan view layout of the generator.

The emitter core would radiate β -particles towards the collector shell. The collector shell must be at such a distance from the emitter core that the Coulomb attraction between charges on the core and on the inside of the shell can be overcome by Coulomb repulsive forces amongst charges on the inside of the shell. This must then push excess charges outwards.

There is a possibility that some excess charges might even be pushed outwards due to fly-bys of particles that cannot land on the collector shell.

2.13.7 Essential safety considerations

2.13.7.1 Gamma radiation

No gamma radiation could be tolerated, even if the effective exposure is very low. The socio-political risk of any association of this product proposal with gamma radiation would be too dangerous. Select a radioisotope that will not emit gamma radiation in the intended lifetime of the generator.

2.13.7.2 Effective radiation levels

Ensure that the effective radiation from the generator will be below the background radiation of most places in nature. Use shielding to ensure a low radiation exposure for the user.

2.13.7.3 Bremsstrahlung

Prevent creation of Bremsstrahlung which would emit photons. The Bremsstrahlung is more likely to occur in collisions of the β -radiation's electrons with dense materials like lead or steel than in collisions with low-density materials.

2.13.7.4 Cerenkov radiation

Cerenkov radiation – must be contended with, even though it does not appear to pose a risk to users in the current application.

2.13.7.5 Heat build-up in radioisotope source

Heat in source, to be removed via a heat removal conduit. Linder (1950) identifies returning emitted particles as a cause of heat in the source and offers some solutions, including using a hollow source through which a coolant may be circulated. A convection pipe connected to an external heat sink might also remove excess heat. However, the actual level of heat generation must be established to determine whether it will have significant impact.

2.13.7.6 Other safety features

Required other safety features:

- Continuous earthing of source emitter via the heat removal conduit. Do this if the heat generation in the source is a significant problem. The amount of nuclear decay heat generated may for instance be below the levels the system can absorb, in which case no heat removal mechanism is required.
- Bridging between source emitter and the collector shell, including a double switching arrangement to prevent arcing.
- Voltage control spike between emitter core and collector shell, including a double switching arrangement to prevent arcing. Switches might be closed intermittently or continuously – depending on experimental outcomes. Voltage control spike to prevent spontaneous arcing.
- Voltage control spike between collector shell and Faraday shell, including a double switching arrangement to prevent arcing. Switches might be closed intermittently or continuously – depending on experimental outcomes. Voltage control spike to prevent spontaneous arcing.
- Voltage control spike outside Faraday shell and before inner faces of the capacitor stacks, including a double switching arrangement to prevent arcing. Switches might be closed intermittently or continuously – depending on experimental outcomes. Voltage control spike to prevent spontaneous arcing.
- The voltage control spikes described above require a connection to earth – which is not always possible or advisable. However, spontaneous discharge must be prevented in three instances, namely:
 - between the emitter core and the collector shell; as well as
 - between the collector shell and the Faraday shell; and finally
 - between the Faraday shell and the inner faces of the capacitor stacks.

Each of these instances constitutes a capacitor. Capacitors may be discharged partially, to some desired level where the charge will be at a required level – by bridging the capacitor for a set amount of time via a specific resistance. This arrangement may be set to automatically discharge a capacitor to a desired operating level, and keep it within limits. Also, then the generator does not require an earth connection. The voltage control spikes may be replaced by the capacitor-controlled discharge mechanisms.

- Earthing connection for the Faraday shell.
- The metallic collector shell might be shielded on the inside by lower density material, such as plexiglas that will reduce the speed of the emitted particles before they hit higher density material and cause Bremsstrahlung.

2.13.8 Performance comparison with a tritium capacitor

Kavetsky *et al.* (2008) described their experiment in such detail that a comparison might be attempted.

Table 2-14: Modelling of the tritium capacitor experiment (Kavetsky <i>et al.</i>, 2008)			
Item	Value	Unit	Reference
Source activity	5.90E+10	Bq	p 327
Number of sources	24	each	p 327
System activity	1.42E+12	Bq	Calculated
	38.27	Ci	Calculated
Capacitance	3.34E-09	F	Calculated
	3.34E+00	nF	Calculated
Permittivity of free space	8.85E-12	m ⁻³ kg ⁻¹ s ⁴ A ²	-
Relative permittivity	1	-	-
Area	0.19	m ²	p 327
Distance offset	0.0005	m	Note 1
Charge			
Activity	1.42E+12	Bq	Calculated
Electrons per coulomb	6.24E+18	e per C	-
Charge addition	2.27E-07	C/sec	Calculated
Charge time	10	min	p 328
	600	sec	Calculated
Released charge (max)	1.36E-04	C	Calculated
Potential difference (max)	40 780	V	Calculated
Efficiency	12.50%	-	p 329
Captured charge	1.70E-05	C	Calculated

Potential difference (calculated)	5 097	V	Calculated
Capacitance (measured)	3.00E-09	F	p 328
Potential difference (calculated)	5 672	V	Calculated
Potential difference (measured)	5 300	V	p 329
Peak power	1.60E-04	W	p 329
Note 1. Modified the distance between electrodes to bring the calculated capacitance in the same ballpark as the measured and fitted values. It is reported as 5 mm, but 0,5 mm brings it in the correct ballpark.			

The performance of the proposed generator is now modelled, using the main parameters from the tritium capacitor experiment. Charging and leakage is retained at the same values. An elementary layout is followed with all the charging capacitors consolidated into one, with the same area. The stack is then positioned on the away side of the collector electrode.

Table 2-15: Modelling of the proposed generator			
Item	Value	Unit	Reference
Harvesting capacitor			
Charge in tritium capacitor	1.70E-05	C	Calculated
Charge recovery multiple	1	-	Assumption
Effective charge recovery efficiency	12.50%	%	Calculated
Charge	1.70E-05	C	Calculated
Area	0.19	m ²	p 327
Stack offset	1	m	Assumption
Stack capacitance	5.01E-12	F	Calculated
Internal energy	2.89E+01	J	Calculated
Harvesting frequency	1 000	Hz	Assumption
Internal energy per second	2.89E+04	J	Calculated
Power	28 911	W	Calculated
Improvement	180 696 085	%	Calculated

Note that the total radioactive source was tritium with an activity of $1,4 \times 10^{12}$ Bq. Using a value for specific activity of $3,57 \times 10^{14}$ Bq/g for tritium, the experiment actually used only 0,004 g

tritium. Only 0,004 g tritium could thus enable the generation of 28 911 W for at least 10 years – without any radiation hazards. Tritium is, in fact, a nuclear waste product – thus this generator enables effective utilisation of nuclear waste until it is safe.

2.13.9 Performance comparison with a ^{235}U Uranium battery and nuclear fission

Kumar (2015) analysed the performance of ^{235}U both as a nuclear battery and also in nuclear fission:

Table 2-16: Modelling of nuclear battery and nuclear fission applications		
Item	Value	Unit
Nuclear source	Uranium-235 (^{235}U)	
	1000	Kg
Alpha decay	1.600E+11	protons per second
Nuclear battery	0.06	W
Nuclear fission		
Fission release	200	MeV
Total energy over lifetime	8.21E+16	J
Half-life	7.04E+08	Year
	2.22E+16	Seconds
Average energy release	1.85	J/s or W
<u>Usage 27 ton ^{235}U per year in 1000 MWe reactor (World Nuclear Association):</u> (The reference refers to a complex mixture of ^{238}U and ^{235}U . For simplicity of comparison and as a very conservative case – the whole 1 000 kg is regarded as ^{235}U , and impact of additional ^{238}U is disregarded).		
Actual lifetime	1 168 000	Seconds
Actual energy release	1 168 000 000 000 000	J
Actual power	1 000 000 000	J/s or W

The same amount of radioactive material, 1000 kg of ^{235}U is then used in a generator:

Table 2-17: Modelling of generator application		
Item	Value	Unit
Generator		

Charge build-up rate	1.600E+11	protons per second
	2.564E-08	C/s initially for 1 sec only
Electrode area	1000	m ²
Stack depth	20	m
Stack capacitance	1.33E-09	F
Stack internal energy	2.476E-07	J
Harvest frequency	500	Hz
Energy harvesting rate	1.238E-04	J/s or W
<u>Now, let charge build up for 30 days:</u>		
Final charge	6.646E-02	C
Stack internal energy	1.663E+06	J
Harvest frequency	1000	Hz
Energy harvesting rate	1 663 446 600	J/s or W
<u>Feasibility check on the 30 days' charge:</u>		
Electrode radius	35.68	m
Capacitance of single disk	2.53E-09	F
Voltage	26 305 610	V
Safe distance in air	8.77	m
Various dielectrics can be used to enable safe use at the calculated safe distance		

The relative performance, using 1 000 kg of ²³⁵U can be summarised as:

Table 2-18: Summary of performances of various modalities		
Energy generation modality	Power	Lifetime
Nuclear battery	0,06 W	Half-life 7.04E+08 years
Nuclear fission	1 000 MWe	1/27 year => 13,5 days
Generator	1 663 MWe	Half-life 7.04E+08 years

The generator, using electrostatic inductance charging of capacitors, will thus outperform nuclear batteries as well as nuclear fission – even at an accelerated usage rate – where the energy is depleted in 13,5 days. The generator will supply energy for 704 million years, given that the switches last. Imagine the present value of such an income stream?

The generator will, by Grace, not create any nuclear waste products that would not have been created due to natural decay anyway. In fact, the recommended approach is to select previously generated nuclear waste, such as tritium or carbon-14 – and use their β -emissions effectively.

2.13.10 Other applications

Vibration Energy Harvesters (VEH) (Boisseau *et al.*, 2012) are developed, typically as small scale power systems – including also microelectromechanical systems (MEMS) (Toshiyoshi *et al.*, 2019) and (Wada *et al.*, 2016) and (Zhang *et al.*, 2007). The energy available as vibration energy might also be used in the present application, perhaps in a different configuration, to power the shutters of a Faraday shell, enabling higher efficiency energy extraction from radioisotopes.

Wind or water energy might similarly be used to drive the shutters of a dedicated Faraday shell application. The generator is thus not at all limited to micro and nanoscale devices.

CHAPTER 3 RESEARCH METHODOLOGY

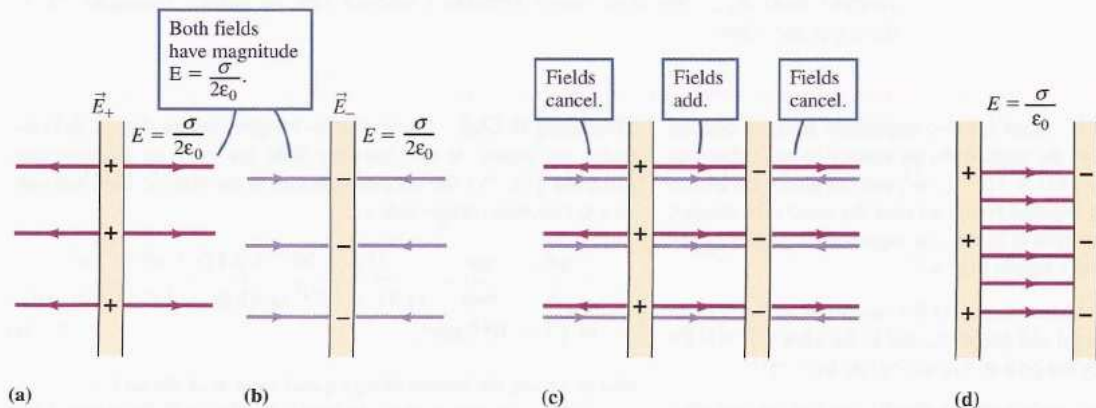
3.1 Introduction

As work commenced on this research, it was realised that there are serious challenges:

- Energy generation from electrostatics was not considered a viable solution, prior to current research (God willing). The closest relevant subject matter research investigates triboelectric nano generators (TENG), but the prime strategy of varying the gap between electrodes would not constitute a viable strategy for larger volume electricity generation.
- There were thus no local experts available, specifically on energy generation from electrostatics. Normally this should have terminated the research, but the research was not viewed as just disciplinary research but as a multi-disciplinary approach toward establishing a possible solution for energy generation. Fortunately, some local experts did assist, particularly Professor Serfontein and Mr Visser.
- Several attempts have been made to consult with international experts, none of which are working on the current topic, yet to no avail.
- There were no suitable laboratory facilities at Vaal University of Technology, nor at the time in the Engineering Faculty of North West University. The criterion was the generation and detection of electrostatic charge with a potential difference to ground in the order of 10 000 Volts.
- By Grace, the co-supervisor offered research facilities at Walmet Technologies (Pty) Ltd. Resources included a DC generator with a capability of 50 000 Volts and an electrostatic voltmeter with an effective range of 600 – 2 000 Volts.
- As the topic at the time was not viewed as a feasible solution, it was not considered viable to seek research funding towards better equipment.
- A critical literature review offered the possibility of gaining expert and peer-reviewed opinion on required issues.
- Literature is, unfortunately, not infallible. The electric field between the plates of a parallel-plate capacitor is discussed to demonstrate the challenge:

The Electric Field Between Two Uniformly Charged Planes with Opposite Charge

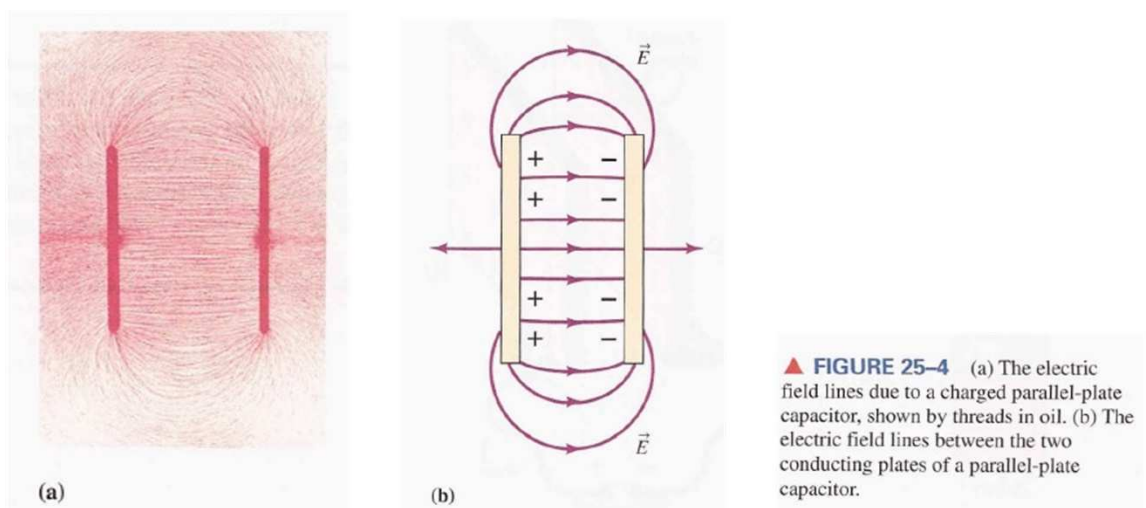
Example 22–8 shows that the electric field for a positively charged plane of uniform surface charge density σ is uniform and perpendicularly directed away from the plane (Fig. 22–19a). If the plane were negatively charged, the field would be similar but would be directed *toward* the plane (Fig. 22–19b). What happens if we place the two planes, oppositely charged but with the same magnitude of charge density σ , parallel to each other? (This forms a capacitor.) As shown in Fig. 22–19c, the fields outside the



▲ **FIGURE 22–19** (a) The electric field due to a positively charged plane is directed away from the plane; (b) that due to a negatively charged plane is directed into the plane. (c) With two parallel planes carrying equal but opposite charge, the electric field cancels to zero outside the planes but is additive inside. (d) The field inside is σ/ϵ_0 and is directed from the positive plane to the negative plane.

Figure 3-1: Initial discussion of electric fields in capacitors (Fishbane *et al.*, 2005: 647).

Later on the discussion is:



▲ **FIGURE 25–4** (a) The electric field lines due to a charged parallel-plate capacitor, shown by threads in oil. (b) The electric field lines between the two conducting plates of a parallel-plate capacitor.

Figure 3-2: Second discussion of electric fields in capacitors (Fishbane *et al.*, 2005: 716).

The problem is that the discussion does not correspond with the visualised electric field lines, shown in part (a) of Figure 3-2, which seems to correspond to the following two visualisations:

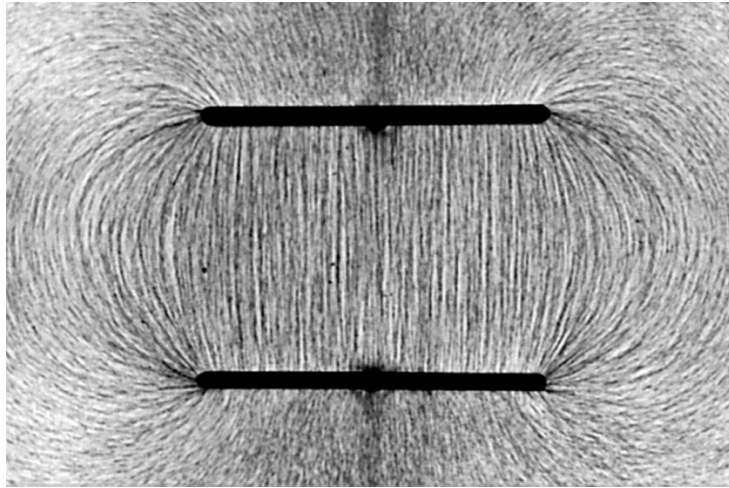


Figure 3-3: Second view of actual electric fields in capacitors (Fägerholt, 1999; Energy Content and Electromagnetic Force, 2019).

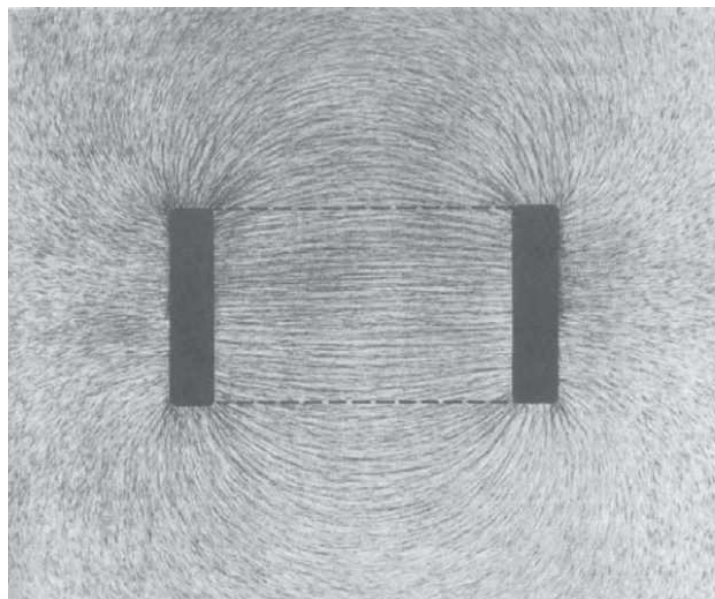


Figure 3-4: Third view of actual electric fields in capacitors (Waage, 1964).

All three of the visualisations of electric field in and around capacitors show electric fields outside the capacitor plates. Fishbane *et al.* (2005: 716) published a diagram showing no field lines just next to the visualisation showing field lines (Figure 3-2). Figure 3-1

shows the reasoning by Fishbane *et al.* (2005: 647) as to why there cannot be field lines outside a capacitor.

Electric fields outside a capacitor is vitally important for the current research, as it would imply that adjacent capacitors would be self-charged if a centre capacitor is charged. Consider the following set-up with four electrodes separated by three dielectric sheets, this constituting three serially connected capacitors:

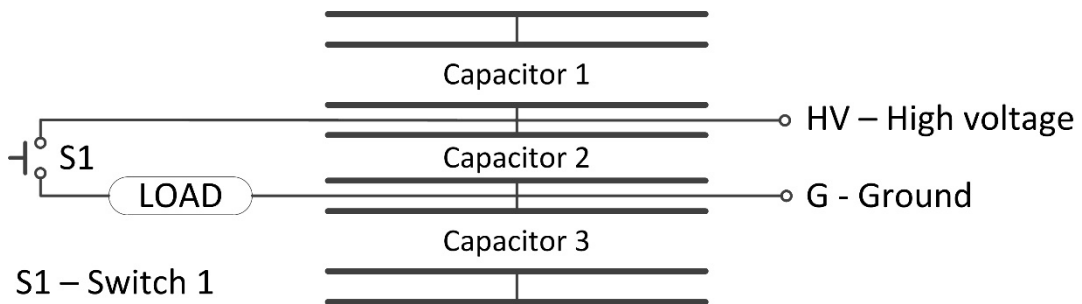


Figure 3-5: Experiment testing electric fields in capacitors.

This experiment was conducted. Capacitor 2 was charged, but no potential difference was found in capacitors 1 and 3. According to the electric field visualisations, there should have been something. However, given the limitations of the instruments at hand, the:

- potential difference might have been too low for the sensitivity of the instrument; or
- the “charge leakage” from the charged capacitor might take time. Measurement did not allow for a time delay.

Given the review as reflected in Chapter 2, there is a possibility that current theory, as explained by Fishbane *et al.* (2005) might be incorrect:

- Electric fields cannot exist in nor radiate through conductors, otherwise there would have to be a potential difference inside the conductor.
- Refer to Figure 3-1. It reflects electrostatic induction, and not conduction current charging. Parts (a) and (b) are separately charged, at opposing polarities. When these are brought closer together as shown in part (c), the electric fields would, with plates rather than planes, induce charges on both sides of the opposing electrodes. It is uncertain how electrostatic induction would function with a plane. With a plate, there would then be charges of opposing polarities on the external

faces of the electrodes. These would eliminate each other, but if there is a disparity, electric field lines would appear outside.

Due to the importance of the research objective and the paucity of research facilities, literature review was a vital part of the research, despite challenges even there.

The literature review is approached as a valuable part of research. This methodology is based on a concept of reflective writing. Driscoll (1994) adapted the three stem questions by Borton (1970) to create the Driscoll Borton framework of reflection (Dabell, 2018; Frameworks for Reflective Writing, 2019). The Driscoll Borton framework has now been adapted for literature survey research:

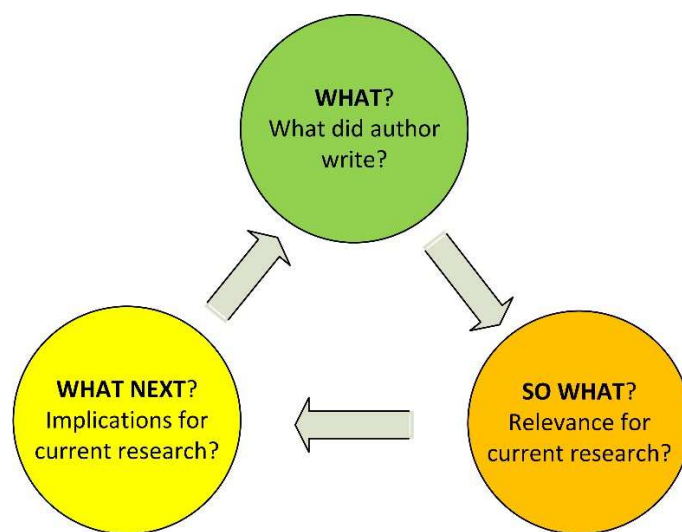


Figure 3-6: Driscoll Borton framework adapted for literature survey research.

Each new piece of information is then interrogated according to the three aspects. It was not written as per such subheadings, as that would have resulted in disjointed writing which is difficult to follow.

Walker (1985) described reflective writing for internalisation of experiences during events. His statements are equally applicable to pieces of information from authors:

- “The use of writing also captures the initial event in a way that enables it to be the basis of continuing and more developed reflection.” (Walker, 1985: 63)

- “The experience is also preserved in such a way that the learner can return to it when further knowledge has been gained which might help to interpret it more fully.” (Walker, 1985: 63)
- “Another significant element in reflection is the association of ideas: the bringing together of new and old in a way that can be the basis of working to integrate them.” (Walker, 1985: 64)
- “The portfolio helped participants to integrate existing and new knowledge.” (Walker, 1985: 65)
- “It can prevent the situation arising where new knowledge lies on top of old knowledge, without integration taking place.” (Walker, 1985: 65)

Paré and Kitsiou (2017) reviewed literature survey methodology in detail. Seven types of literature review are identified, one of which is the current approach, the critical review: “Aims to provide a critical evaluation and interpretive analysis of existing literature on a particular topic of interest to reveal strengths, weaknesses, contradictions, controversies, inconsistencies, and/or other important issues with respect to theories, hypotheses, research methods or results.”

One of the building blocks of a critical review would be screening. This occurred in the background, from a database of 6 450 files consuming 23,5 Gigabytes of memory.

After the critical literature survey, viable routes towards a solution must be found. As these routes must be viable but also valid and reliable, the research paradigm must change from qualitative research to quantitative research.

3.2 True experimentation

The research methodology design to be used in the current research is true experimentation, seeking to establish “the cause-effect relationship among a group of variables of the research.” (Sloboda, 2019)

Given the research objective, an experiment is designed to include independent and dependant variables. Ideally one independent variable is manipulated to impact on one dependent variable.

Sloboda (2019) explained: “This type of research design is called true experimentation because this research design establishes the **cause-effect relationship** among a group of variables of the research. In a truly experimental design, an effort is made to identify and impose **control over all other variables except for one variable**. An independent variable is manipulated to determine the effects on the dependent variable.” An attempt is thus made to:

- establish with rigour (requiring replication) and consistency a specific cause-effect relationship, formulated as a hypothesis; and
- control as far as possible, all variables except the independent variable under investigation.

True experimentation would also have to satisfy the demands on internal and external validity:

- Internal validity, especially given research resource constraints, imply that a significant and repeatable impact is caused on the dependent variable.
- External validity require that the outcome can be generalized. Experiments will be designed such that the outcomes would be generalizable, should the effect be proven.

It appears as if Gerald Milburn said: “Scientific research is a chaotic business, stumbling along amidst red herrings, errors and truly, creative insights.” (Rajasekar *et al.*, 2006) That is then the road ahead.

CHAPTER 4 EXPERIMENTS

4.1 Introduction

The first experiments started in 2016, and many hours were invested. The study supervisor cautioned that work must be written up, and it was, but in a laboratory notebook. Twenty-five notebooks and four years later the write-up on a laptop occurred. At that time, the thesis was approaching 250 pages, and it would be cumbersome to take readers through the struggle of four years.

The empirical investigation posed many challenges. It is of interest for future research to document the empirical journey, including both successes and failures. When an objective is valuable enough, documented failures will assist the ongoing journey to attain the objective.

To thus respect the reader and to provide an account of the journey, and overview will first be provided, followed by selected reviews of experiments.

4.2 Research journey

This research was very much a chaotic business as per Millburn (Rajasekar *et al.*, 2006) rather than a strategically planned project. The problem is obviously that this research is into the unknown, like travelling through a maze. Multiple dead-ends were encountered.

The actual journey involved six major stages, with multiple experiments per stage:

- Static capacitor stage. Certain lessons were learnt at this stage, including:
 - High voltage electrodes should have rounded corners to prevent arcing.
 - Polarity reversal was detected.
 - With a sectional capacitor, it appeared that charge moved between capacitors.
- Sliding electrode stage. Various lessons and achievements included:
 - Difficulty of operating when instrument reliability is uncertain.
 - Difficulty of measuring relatively small energies with an analogue electrostatic voltmeter whilst the capacitor charge is leaking away, perhaps through the instrument. Readings were filmed on a cellular phone and the values transcribed afterwards, measured against the second reading of the film.

- Another problem with the instrument is that the needle obviously jumps when an electrode is moved. The jump causes oscillation of the needle. Then, while waiting for the needle to stabilise, charge seems to leak away.
- The experiments initially comprised charged outside electrodes, with uncharged inner electrodes moved in.
- Later the protocol was changed to charge the inner electrodes and particularly to then apply charge to the outer faces of a parallel plate capacitor. This charged capacitor was then withdrawn from the outer electrodes, all energy in them removed and then the charged inner capacitor was returned to the uncharged outer electrodes. They were then charged.
- At a critical point, the supervisor was invited for a demonstration, and on that day the Coulomb attraction forces refused any movement of the inner electrodes. This never occurred during the almost twelve months prior to the demonstration.
- Hollow electrode stage. Various lessons and achievements included:
 - The atmosphere appears to be the enemy of electrostatic charge. Humidity and even high energy particles from outside our galaxy continuously discharge all charge.
 - Transformer oil protects charge, as long as it is itself free of absorbed moisture.
 - The strategic intent of the hollow electrode stage was informed by the feature of a hollow electrode that as a charge is inserted into the cavity, an opposing polarity charge is automatically electrostatically induced inside the hollow electrode and a similar polarity charge outside. Capacitor stacks were affixed outside the hollow electrode. The charge appearing on the outside of the hollow electrode was then supposed to electrostatically induce charge throughout the capacitor stack, until charge is also induced on the outside face of the capacitor stack. That charge was then relayed back into the inside of a hollow electrode to recycle the charge.

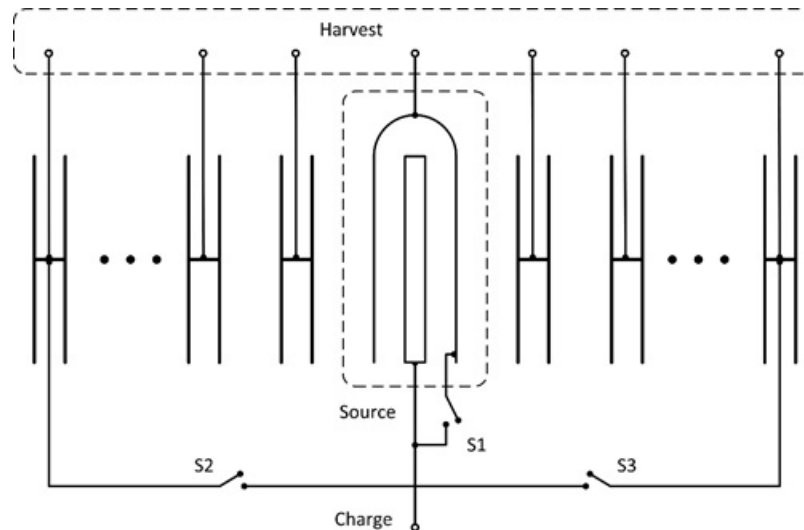


Figure 4-1: An electrostatic generator concept.

In principle the idea should work, but the layout was problematic. Closing switch 2 to relay a fraction of the charge on the outside face of the capacitor stack to the electrode inside the source hollow electrode automatically discharges all energy in that side of the stack. It was then attempted to circumvent this problem by charging a small sphere on the outside face of the capacitor stack and then physically inserting the charged probe into the hollow electrode. No success, but the lack thereof might signify some experimental error rather than a problem with the physics.

- What actually causes charge to redistribute when two conductors are connected? The experimental objective was to move charge, which by implication becomes a current flowing, via a cable. At times even a co-axial cable was used to improve reliability. It appears that charge will move when one conductor is at a higher potential than the other, or when the geometry of the two conductors necessitate redistribution. This then constitutes charge movement without a circuit being completed.
- Connecting conductors via cabling imply switches. When does a switch with charge start to transmit charge via corona discharge, as one example of various risks? The following switch was conceptualised for application inside a hollow electrode. When charge is initially moved to sphere A, it electrostatically induces charge on the inside and outside faces of section F of the hollow electrode. Solenoid D can then be activated to neutralise the inside charges and fix the charge on the outside face of the electrode.

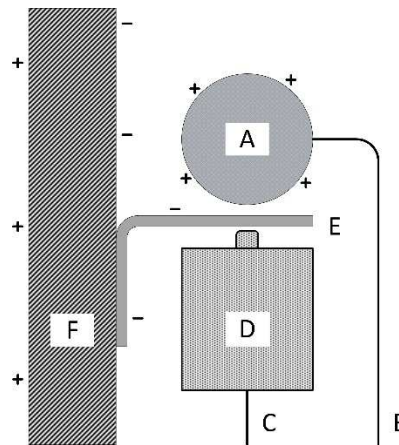


Figure 4-2: An electrostatic switch.

The switch seemed to work, but it would have helped tremendously if proper instrumentation could have been available to track charge movement.

- How to get charge inside a hollow electrode? The previous discussion illustrates that charge insertion could be a vital part of a solution. However, it is a difficult endeavour although it is easy in theory.
- How to protect a cable entering a hollow electrode such that the electrode will remain a hollow electrode? Working with high voltage is problematic in that the Van de Graaff seems to charge everything in the surrounding area. When an attempt was then made to transport charge into a hollow electrode via a cable, there would inevitably be flash-overs. This could not be resolved, despite several attempts.
- Rotating electrostatic generator stage. Attempted to create a machine that will generate measurable amounts of electricity.
- Square ice pail within square ice pail stage.
- Capacitor stack stage. Various lessons and achievements included:
 - It was by Grace proven that the concept of a stack of several parallel plate capacitors does convey charge better than two electrodes with the same amount of air gap between them.



Figure 4-3: Capacitor stack versus void experiment.

Significant more charge was detected on the outside of the filled stack than outside the void stack.

- The Van de Graaff electrostatic generator would charge everything in the surrounding area and it becomes difficult to establish the role played by the observer, for instance when the observer touches a capacitor face with an isolated (1 m wood) sphere.
- It was attempted to mount the sphere so as to isolate it, and prevent contact with the observer. Unfortunately, the sphere then just becomes part of a capacitor and no immediate arc was observed at the energies detected. It might be better to initially keep the sphere away and only later bring it in contact with the outside face. This seemed to work.



Figure 4-4: Isolated sphere for arc detection.

In this application, an arc signifies the presence of charge, signifying that the stack was charged.

- The Van de Graaff charged all surroundings, including the glass flask of the electroscope. It was thus enclosed in a bespoke Faraday cage, with gauze for observing and mounted in such a way as to be shielded from the Van de Graaff:



Figure 4-5: Isolated and shielded electroscope.

This seemed to work.

- An instrument was purchased, but it did not work. The supplier indicated that it was to be expected of a product for that price.
- Another attempt to verify charge inside the capacitor stack was to mount two arc horns from the sides. This, unfortunately, resulted in corona discharges from the outset, and is only useful at night when the discharge can be seen. It was hoped that discharge may be inherently delayed until the potential difference is large enough for an arc:



Figure 4-6: Arc horns on top of capacitor stack.

4.3 The electrostatic voltmeter

The electrostatic voltmeter, with a 2 000 V range, was manufactured by Sensitive Research, a subsidiary of the Singer Company. Without this instrument, none of this research would have commenced. Access was provided due to the kindness of the co-supervisor, Professor Walker.



Figure 4-7: The electrostatic voltmeter.



Figure 4-8: Closer view of the electrostatic voltmeter.

This electrostatic voltmeter enabled the research to proceed, yet there were some challenges:

- Was the instrument reliable? It was last calibrated on 11 March 1985.
- It could only read effectively between 600 V and 2 000 V.
- It is an analogue instrument. Recording readings was thus a challenge. It was done via cellular phone videoing, which was later transcribed.
- The voltmeter does not indicate polarity. This brought uncertainty into the experiments.

4.4 Static capacitor stage

Previous research and development towards a section insulator highlighted a need for a DC equivalent of the functioning of a transformer in an AC circuit. The transformer can transfer energy from a source circuit to a destination circuit, while isolating the source circuit from certain events in the destination circuit. It is for instance possible to encounter a short circuit in the destination circuit, without direct transfer of the fault to the source circuit. Research indicated that a capacitor within a capacitor would allow energy transfer in a DC circuit, whilst possibly offering circuit isolation. The capacitor within a capacitor was initially conceptualised as a capacitor which is charged, and then isolated:

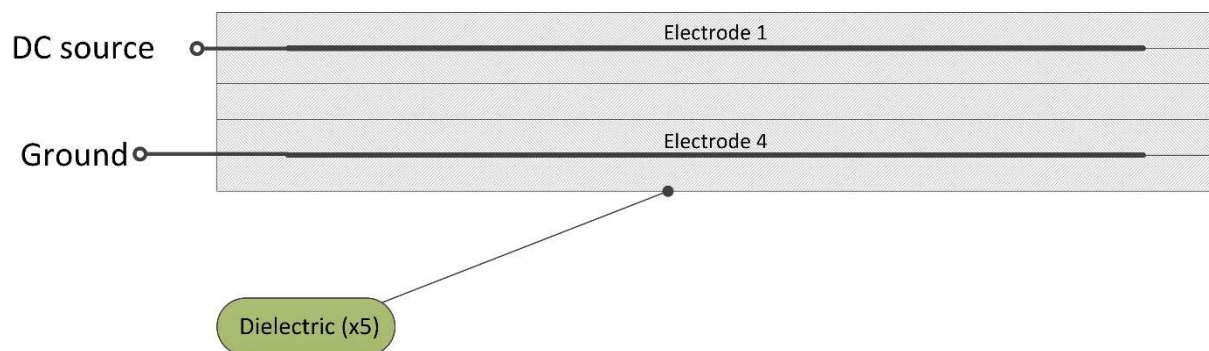


Figure 4-9: Initial capacitor.

Another capacitor, comprising two electrodes and a sandwiched dielectric, is then inserted into the charged capacitor. With the new capacitor inserted, the layout is as follows:

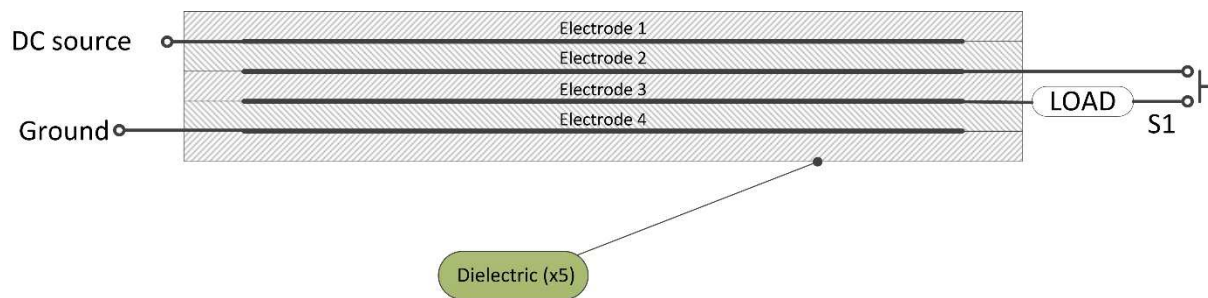


Figure 4-10: A second capacitor inserted into the first.

Consider the circuit from DC source to ground as the primary circuit, and the circuit with the load as the secondary circuit. Then, given that the primary circuit is open (interrupted), closing S1 to send energy through the load should not impact the primary circuit electrostatics permanently. Once capacitor 1-4 has been charged, electrostatic energy is redistributed to capacitors 1-2, 2-3 and 3-4 after insertion of electrodes 2 and 3. However, once the energy in capacitor 2-3 has been harvested and electrodes 2 and 3 removed, the energy in capacitor 1-4 should return to the original level. Experiments have been hampered by parasitic leakage of charge, creating doubt as to whether capacitor 1-4 did in fact attain original energy levels. There is also the possibility that some capacitive energy gets stored in dipole moments in the dielectric, and that energy is then lost when the intermediate capacitor is discharged.

A concern with the dipole moment view, is that:

- Capacitor electrostatics is determined by the relationship $Q = C.V$.
- When an intermediate capacitor is discharged, the overall potential difference (V) drops.
- This is logical in a static capacitor set-up, as the discharge of the intermediate capacitor effectively increases the overall capacitance. It appears that a discharged intermediate capacitor acts as a short circuit for the overall circuit. The overall charge was not depleted, yet the potential difference dropped. This signifies that the overall capacitance had to have increased.
- Note there was no reliance on dipole moments in the dielectric thus far.

The capacitor within a capacitor, as shown here with four electrodes, actually constitutes three capacitors in series:

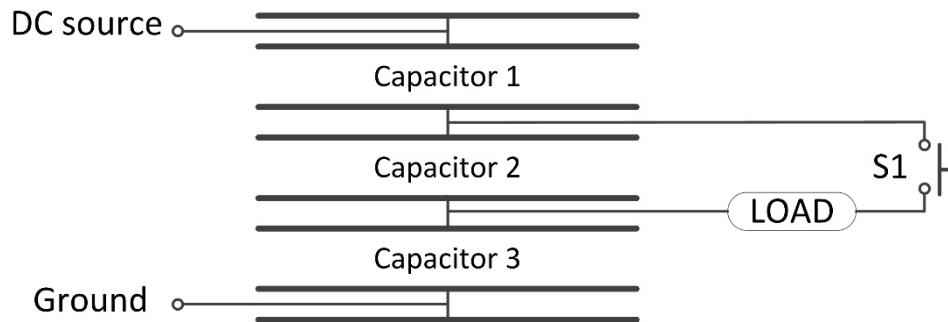


Figure 4-11: Equivalent circuit of the capacitor within a capacitor.

Closing S1 thus drains the energy in capacitor 2, without impacting the energy levels in capacitors 1 and 3, provided that they are isolated at the time. If capacitors 1 and 3 are not isolated, closing of switch S1 will merely create a compound circuit – where energy from the DC source will flow through to the load.

Working with the capacitor in a capacitor concept – led to an appreciation that the internal capacitor can be charged electrostatically, as opposed to conventional charging through electromagnetic current flow.

These early experiments encountered several problems:

- The layout was a static layout. Once the intermediate capacitor's charge was removed, it could only be recharged via the overall system. Refer to Figure 4-11. Capacitor 2 will not automatically recharge from capacitors 1 and 3.
- Parasitic leakage brings a lot of uncertainty into experimentation.

Two highlights from this stage were the polarity reversal experiment and the sectional capacitor experiment.

4.4.1 Polarity reversal in serially connected capacitor

A standard experiment was done to charge a set of three serially connected (four electrodes and three dielectric sheets inside and two sheets outside for protection):

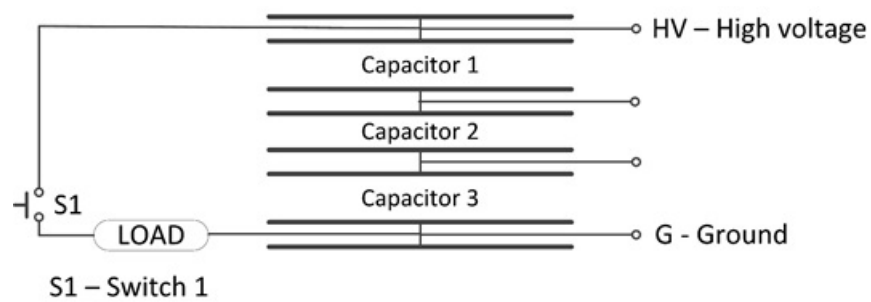


Figure 4-12: Equivalent circuit for three serially connected capacitors.

When the switch S1 was closed, polarity reversal was detected.

4.4.2 Sectional capacitor

If a capacitor was constructed as a hybrid serial and parallel capacitor, charged, then partially discharged, would the discharged section recharge?

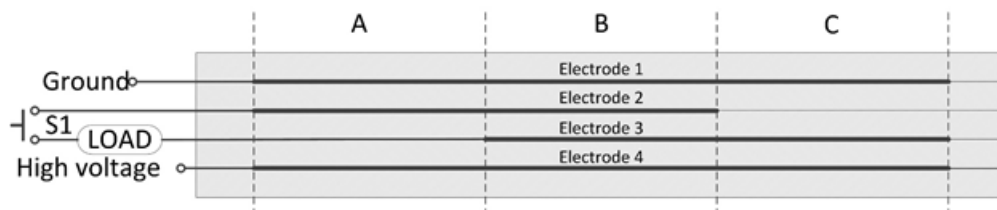


Figure 4-13: Layout of the sectional capacitor.

The equivalent electrical circuit would be the following:

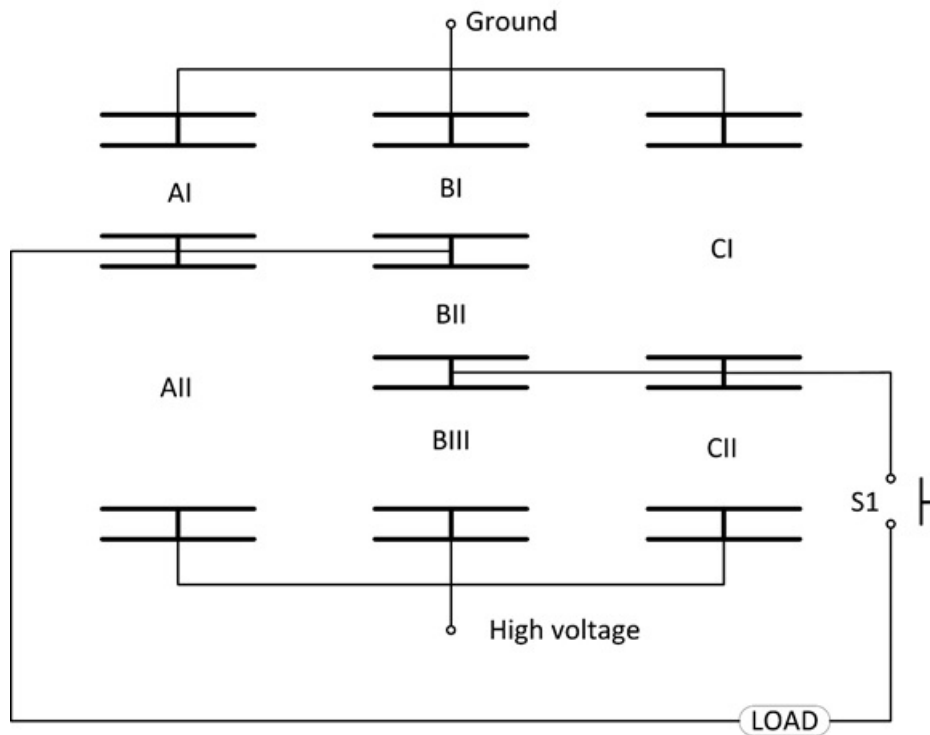


Figure 4-14: Equivalent circuit of the sectional capacitor.

It is a challenge to construct parallel plate capacitors and then keep the surfaces in close contact, so as not to change the capacitance values. The route selected was to construct a concave structure over which the sectional capacitor components were draped and tensioned:



Figure 4-15: Supporting structure for the sectional capacitor.

A switch was made to enable manual switch-over of live high voltage:

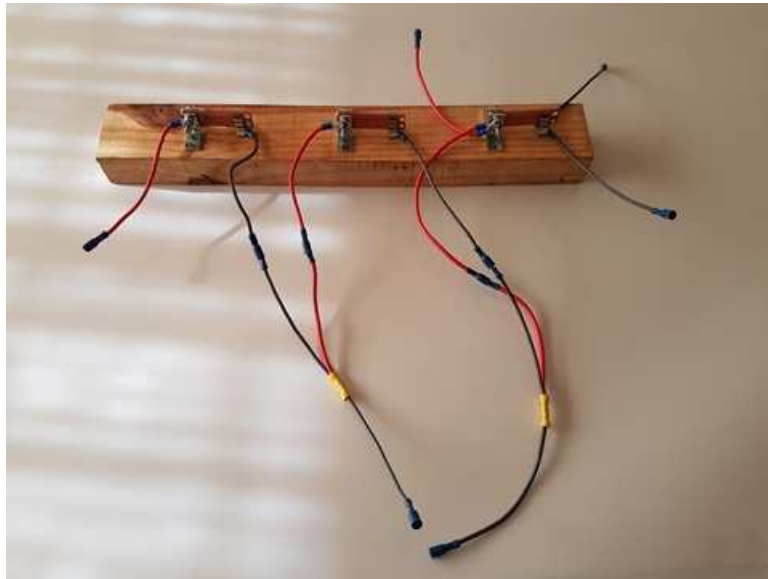


Figure 4-16: Switch for working with high voltage.

Some of the tools made and used, ensuring safety:

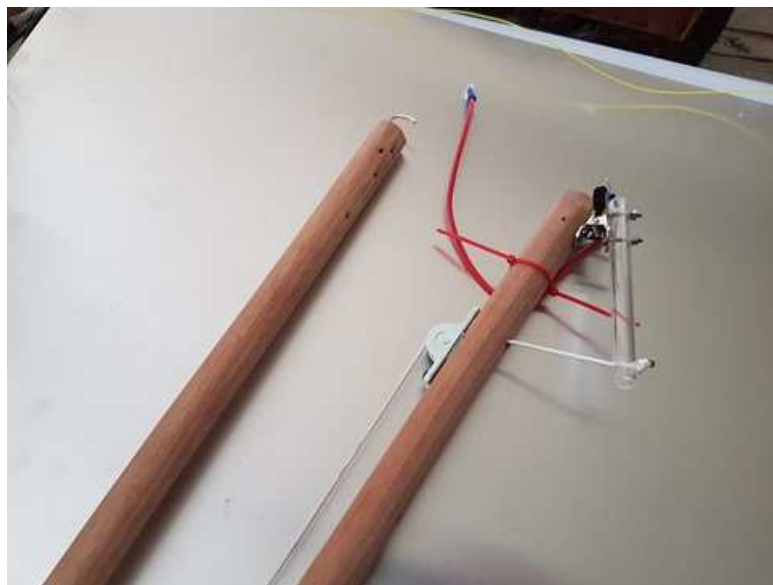


Figure 4-17: Isolated tools for working with high voltage.

The constructed sectional capacitor under test:



Figure 4-18: Testing the sectional capacitor.

4.5 Sliding electrode stage

This set of experiments attempted to demonstrate that the basic capacitor equation $Q = C.V$ would dictate that, whatever happens inside a capacitor, as long as the charge has not been disturbed and the capacitance is the same again, the potential difference would also remain the same. To this end, a sliding capacitor was built:



Figure 4-19: Sliding electrode apparatus during construction.

The sliding electrode comprises the following electrostatic elements:

- An aluminium sheet 650 mm x 350 mm x 0,9 mm thick as stationary electrode
- Fixed protection by a 250 micron Mylar® sheet
- M1 mobile protection by a 130 micron Mylar® sheet
- M1 electrode in the form of an aluminium foil 650 mm x 350 mm x 0,1 mm thick
- M1 mobile protection by a 130 micron Mylar® sheet
- M2 mobile protection by a 130 micron Mylar® sheet
- M2 electrode in the form of an aluminium foil 650 mm x 350 mm x 0,1 mm thick
- M2 mobile protection by a 130 micron Mylar® sheet
- Fixed protection by a 250 micron Mylar® sheet
- An aluminium sheet 650 mm x 350 mm x 0,9 mm thick as stationary electrode

One of the stationary sheets is fixed into position, while the other is spring-loaded to maintain the closest distance through all the material between it and the fixed sheet:



Figure 4-20: Spring-loaded support of movable electrode.

It was attempted to reduce capacitor leakage by using cable with silicon insulation, and enclosing it inside a PVC-tube:



Figure 4-21: Cabling protocol.

4.5.1 Revival of charge on uncharged electrode

Experiments were conducted to establish whether an uncharged electrode would be recharged by a charged electrode. The experimental protocol included:

- Charge the two outer electrodes.
- Slide in an intermediate electrode.
- Discharge one of the two electrodes created by the insertion of the intermediate electrode.
- Remove the intermediate electrode.
- Monitor the potential between the remaining outer electrodes.

4.5.2 Charge on outside of sliding electrodes

The initial experiments always entailed charged outer electrodes and then the insertion of uncharged electrodes which then become charged. Could the experiment succeed the other way around?

The experimental protocol involved:

- Insert both the intermediate electrodes.
- Charge the three capacitors now created in a particular sequence, to ensure that the electrodes of the intermediate capacitor would have the same polarity charges on both

faces. Initial experiments indicated faster decay of charge when opposite polarity charges reside on opposite faces. The problem was, as soon as the intermediate capacitor (both electrodes) is withdrawn, the outside charges become free and can move at will. When such free charges move to the other face, it neutralises opposite polarity charge. It was thus deemed prudent to charge such that each electrode carries the same polarity charge on both sides.

- Withdraw the intermediary capacitor.
- Bridge the remaining outer electrodes, such that no charge remains.
- When the intermediary capacitor is reinserted, establish if the outer electrodes are charged via electrostatic induction.

Figure 4-22 shows the polarity order, as discussed before:

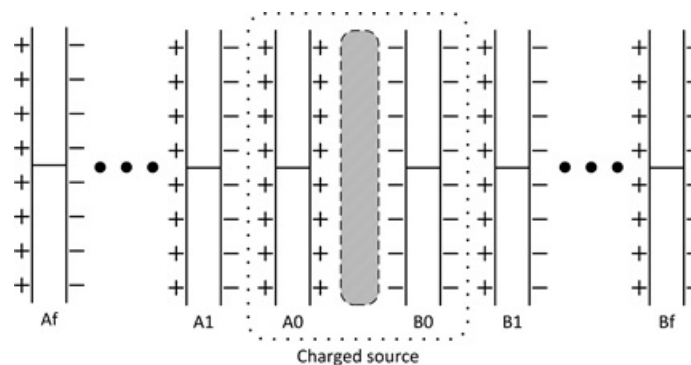


Figure 4-22: Polarity order for charges on the outside of a capacitor.

4.5.3 Sliding electrodes without frictional contact

The experiment would demonstrate two charged electrodes (of respectively positive and negative polarity) being inserted between two stacks of serially connected plate capacitors. The hypothesis is that:

- while the insertion will involve a fixed and constant amount of energy,
- a linearly increasing amount of energy may be electrostatically induced in the stacks. If so, more energy can be created by adding more capacitors – without increasing the energy of insertion.

Movement is induced by releasing a mass – initiating a gravity-driven movement. Energy at the start would comprise:

- the potential energy of the mass; and
- the electrostatic energy between the charged electrodes and the first electrodes of the adjacent stack capacitors (starting position).

Final energy status would comprise:

- the potential energy of the mass, remaining in the final position;
- the electrostatic energy between the charged first electrodes of the opposing stack capacitors (starting position);
- the electrostatic energy between the charged electrodes and the first electrodes of the adjacent stack capacitors (final position); and
- the electrostatic energy in the adjacent stack capacitors (final position).

Gravitational potential energy has now been traded for mechanical energy moving the charged electrodes into a new position, where the incoming charge initiated electrostatic induction in all adjacent conductors. Movement would have had to overcome frictional forces, which should be quantified.

The experiment would allow work with sliding electrodes to occur and also assist in defining the electrostatic force as well as the relevant frictional forces.

4.6 Hollow electrode stage

Experiments with hollow electrodes were conducted primarily to establish if the charge that should appear on the outside of a capacitor stack, that has been charged via electrostatic induction, can be reintroduced into another hollow electrode. This would recycle the charge, albeit with some losses.

4.6.1 Charge storage

It became apparent very early on that electrostatic charge does not last when exposed to the atmosphere. Transformer oil was tested, where the whole entity is then submerged.

4.6.2 Charge redistribution

Charge does not automatically move, as does a potential difference, due to the fact that one end is at a higher potential than the other. A new charge distribution is defined by the electric fields as well as a geometrical feature such as the radius of curvature over the conductors.

4.6.3 Charge redistribution via cable

Attempts were made to connect cabling directly to the inside of hollow electrodes:



Figure 4-23: Cable connected hollow electrode.

After failure, intermittent connection to the inside of the hollow electrode was attempted:



Figure 4-24: Hollow electrode with intermittent cable connection.

This method relies on adjacent capacitor stacks to provide the free charge on the outside:

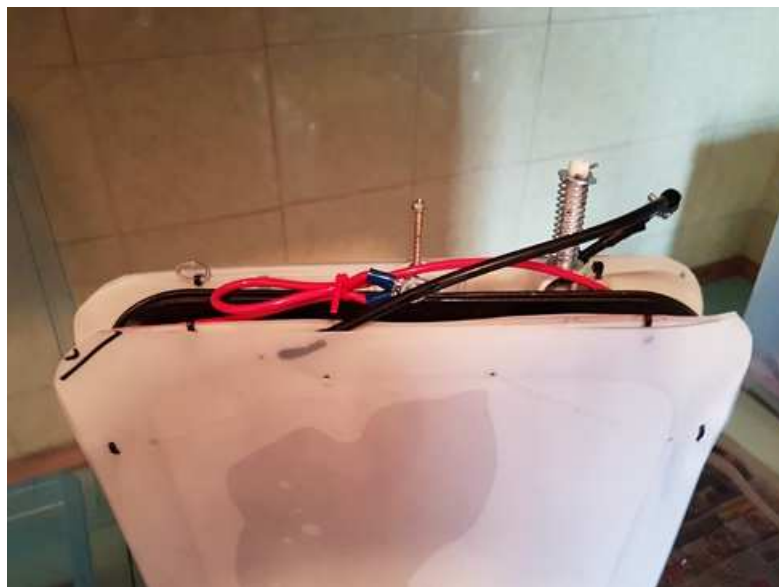


Figure 4-25: Hollow electrode with intermittent cable connection, with adjacent capacitor stack.

It became apparent that it is difficult to bring a cable into a hollow electrode without compromising its functioning as a Faraday cage. The cable would short to the hollow electrode, where it enters:



Figure 4-26: Cabling into hollow electrode.

It was then decided to create a segmented Faraday cage, to prove that a Faraday cage will protect charge from entering, despite a non-continuous shell:



Figure 4-27: First attempt at a segmented Faraday cage.

By Grace, the second attempt worked:



Figure 4-28: Second attempt at a segmented Faraday cage.

It was then attempted to extend this success into segmented cabling:



Figure 4-29: Attempt at a segmented Faraday cage cable, in construction.



Figure 4-30: Attempt at a segmented Faraday cage cable.

4.6.4 Charge redistribution via charged entities

It proved very difficult to use cabling to reintroduce charge into a hollow electrode.



Figure 4-31: Charge into hollow electrode via charged entity

The concept entails:

- A small sphere inside a PVC conduit, can be pulled up or released.
- Pulling it up, brings it into contact with two wires carrying charge from elsewhere.
- Inside the hollow electrode, the charged sphere must then electrostatically induce charge inside and outside the hollow electrode.
- The sphere bottoms against two more wires, connecting it to the inside of the hollow electrode. As it then bottoms, the electrostatically induced charge on the inside of the hollow electrode is neutralised, and the charge outside is fixed.

4.7 Rotating electrostatic generator

The experimental intent was to create machine that will generate enough energy to enable measuring and evaluation.

A machine may now be constructed, with a segmented rotor – and capacitor stacks containing serially connected parallel plate capacitors on both sides thereof. The rotor has radial segments – with similar segmentation in the stacks. Rotor segments are alternately charged and not charged (remain neutral).

As charged rotor segments rotate by stack segments, corresponding stack segments are electrostatic inductively charged. While the rotor segment is still in place, maintaining the charge in the stack segment – the energy from that stack segment is harvested. As soon as a neutral segment is then rotated in line with the discharged stack segment – the faces closest to the rotor and furthest from the rotor – is discharged. The stack segment is then ready for a next charging cycle.

The timing of discharge is crucial, as rotation must not be interrupted, for the sake of an energy efficient operation. Energy might easily be wasted by the unnecessary stopping and starting of rotation. Allow possibly only for discharging the energy for only two or three time constants (τ). This would ensure that the effective energy yield remains higher. After two time constants, only 1,8% of the original energy is still available, and after three time constants, only 0,3%.

Current thinking considers it imperative to conclude discharge prior to the charged rotor radial segment moving out of position. The discharge cycle may thus commence while the charged segment is only about 90% aligned. The discharge cycle may also continue while the charged

segment is rotating beyond alignment – in order to capture any available energy, preventing waste. Experiments should inform the optimal discharge management strategy.

Electrostatic induction charging specifically offers the possibility of increasing the energy density of the source, by:

- Increasing the potential difference between the electrodes (higher initial charge voltage as well as increased off-set between electrodes).
- Increasing the harvesting frequency, which is possible given that charging occurs at the speed of light.
- Higher harvesting frequencies imply rotary motion – which may occur at constant velocity, without acceleration and deceleration.
- Segmentation can now be used, especially as a mechanism to increase the harvesting frequency without increasing the rotary speed. Segmentation would imply that the effective capacitor area (for both linear or rotary applications) be parted into two or more segments. The same number of segments should normally be used for both the rotary and the static portions of the unit. However, half of the rotor segments should remain unused – to enable switching of the static segments between CHARGE and HARVEST.
- Increasing the stack depth – to increase harvestable energy.

The stack is proposed as a series of parallel plate capacitors. In terms of physics, such a series would be equivalent to one capacitor with the same capacitance. Why then is a series of capacitors recommended?

- High voltages are recommended as a strategy to improve energy yields. When a single equivalent capacitor is then applied, the harvesting voltage might impose a burden on the energy transformation circuit. Such a circuit would transform the high voltage pulsed energy to a user-effective format.
- Plate capacitors are recommended as the electrostatic field propagates perpendicular to the electrodes and thus longitudinally with the stack direction. Fringing would yet occur and cause a loss of electrostatic field – although the magnitude of loss would be reduced by locating the target electrode very close to the source electrode. A single capacitor might necessitate a substantial offset between electrodes, increasing fringing losses.

High rotation speeds are envisaged, faster than normal for rotating equipment, but as the rotor does not counteract substantial torque and it is light – special high-speed bearings (air or magnetic bearings) might meet the requirements. Such special bearings would be advisable, as an energy source might operate at 100% duty cycle for extended periods.

The harvested energy must be transformed into electrical current at the appropriate potential difference. Experiments must be conducted to establish whether it might be feasible to supply electricity in a highly pulsed (even 10 000 Hz) DC or AC mode. The pulsed nature of the input might allow optimal wave profiles that are not currently feasible.

4.8 Square ice pail within square ice pail

To demonstrate the possible Faraday second law of electrostatic induction:

- An inner ice pail is charged, and so it charges an outer ice pail.
- Stop the Van de Graaff generator from rotating, and thus adding new charge to the inner pail.
- Remove energy and thus the charges between the two ice pails.
- Remove the ice pail assembly from the Van de Graaff generator, or earth its dome. No more charge must remain at the Van de Graaff, and this will allow the charge inside the inner ice pail to migrate outwards.
- The outer ice pail should become charged again.

In this experiment, the ice pails are actually an aluminium box for the inner and an aluminium clad plastic box (wood reinforced) for the outer.

It was realised early in construction that the pulley system must be replaced to handle mass. A replacement could not be purchased and was made up from off-the-shelf components:



Figure 4-32: Bespoke heavy duty pulley system.

The frame, showing the inner ice pail:



Figure 4-33: The ice pail frame.

The completed assembly, suspended over the Van de Graaff generator:



Figure 4-34: The ice pail assembly over the Van de Graaff generator.

A view from inside:



Figure 4-35: The ice pail assembly from inside.

It was attempted to use an arc horn assembly as an automatic indicator of energy presence inside the two ice pails:



Figure 4-36: Arc horn assembly.

4.9 Capacitor stack stage

This part is vital in attaining the research objective, as it deals with the mechanism for multiplying electrostatic induction over many capacitors.

4.9.1 Empty versus stack – d_0 versus $n * d_1$

Is there any value in a stack of multiple capacitors versus two dispersed sets of electrodes with air as intermediate dielectric? This experiment must provide the answer.



Figure 4-37: Stack versus void experiment.

4.9.2 Capacitor stack holding mechanism

A stack will not maintain its integrity without a holding mechanism. Research has indicated that electrodes must probably be well aligned to assist effective propagation of electrostatic induction, with minimal fringing losses.

Stacks contain high energy, and special care must be taken to prevent leakage and arcing.

A first attempt:



Figure 4-38: First stacking mechanism tested.

Second stacking mechanism tested:



Figure 4-39: Second stacking mechanism tested.

Third stacking mechanism tested:



Figure 4-40: Third stacking mechanism tested.

4.9.3 Charge polarity reversal after arcing

During testing, it appeared as if charge reversal occurs after arc flashover.

4.9.4 Isolate the operator

It appears as if the operator also gets charged within the surroundings of the Van de Graaff generator, and then imparts uncertainty to experimental findings. Specifically, resource constraints mandated that an isolated sphere be used to test for the presence of energy at the away face of the capacitor stack. However, if the operator is highly charged, an arc might occur from the sphere staff held in the operator's hand to an uncharged away electrode?

It would be best to eliminate causes of false readings. One of the solutions was to mount the test sphere on a string to eliminate the risk of human contamination of results:



Figure 4-41: Sphere on a string without operator.

A special arcing plier was also constructed to test the energy content of capacitors.

4.9.5 Van de Graaff static potential control and termination and earthing the dome

The possibility of arc flashover implies that a method must be found to maintain a set potential on the dome of the Van de Graaff generator. It was attempted to provide sufficient distance between the dome and the target electrode, but this proved to be infeasible also with the effect that charge capture is significantly reduced. The dome must thus be as close as possible to the target electrode but without arc flashovers occurring.

It must also be possible to terminate the Van de Graaff generator without human contact, and the charge on the dome must be removed. Table 4-1 details the specifications for the required controller for the Van de Graaff generator:

Table 4-1: Specification for Van de Graaff controller		
Sequence	Action	Timing
1	Maintain Van de Graaff dome potential below a set value.	Continuously.
2	Terminate running of the Van de Graaff generator.	As required.
3	Remove charge from the Van de Graaff generator's dome.	Almost immediately <u>after</u> action 2.

The constructed Van de Graaff controller:



Figure 4-42: The Van de Graaff controller.

4.9.6 Detecting charge

Detecting charge is the core of all work on electrostatics. The full requirement is actually more than detecting, and must include measuring the quantity of charge, determining the polarity and recording the measurements. Professional instruments meeting these requirements might exist, but there were no more funds left for instrumentation.

An instrument was purchased but it delivered questionable results. Perhaps incorrectly, this predisposed the researcher against self-built electronic solutions. However, a colleague, Riaan Greeff, recently indicated that he built a measurement unit that can detect lightning activity over more than 60 kilometres.

One way that was tested to detect charge was via the sphere on a string, to eliminate the risk of human contamination of results. It is shown in Figure 4-41.

It was tested to suspend the electroscope behind the capacitor stack, such that it should be shielded from the electric field emanating from the Van de Graaff generator:



Figure 4-43: Hanging electroscope

Other strategies:

- Protecting the electroscope inside a Faraday cage.
- Slow motion video graphing of activity, particularly to attempt to get clarity on the charge reversal phenomenon.
- Mounting a small torch inside the enclosure. Might have to be removed due to the possibility of charge transmission to the electroscope via the conducting body of the torch. It was mounted with the switch outside the enclosure.



Figure 4-44: Enclosed electroscope

4.10 Experiment to demonstrate electromagnetic waves from a changing electric field

4.10.1 Background

As James Clerk Maxwell started reformulating the core equations for electromagnetism, which was published in 1865 as “A Dynamical Theory of the Electromagnetic Field” (Maxwell, 1865), he encountered a problem with Ampère’s law. He realised the equation does not remain valid when there is a capacitor in the loop (Selvan, 2009). Thus he created the concept of a displacement current which constituted a breakthrough (Selvan, 2009), (Maxwell, 1865: 462). However, the displacement current has been in dispute since then – especially as it is not a real current.

The Ampère-Maxwell equation predicts that the magnetic field is created by either or both of a conduction current and a changing electric field (displacement current):

$$\nabla \times \mathbf{B} = \mu_0 \mathbf{J} + \mu_0 \epsilon_0 \frac{\partial \mathbf{E}}{\partial t}$$

Current research to investigate the impact of electrostatic sources on capacitors creates a new opportunity. Previous research attempted to charge capacitors within a controlled and isolated environment, typically within a Faraday cage, to exclude other signals. The magnetic field, if it exists, within the capacitor is then measured, for instance by Paulus and Scheler (2015).

The new opportunity focusses on the following:

- No conduction current is used to charge the capacitor.
- There are no conduction currents present that should impact on the Ampère-Maxwell equation.
- Only an electrostatic source is used to charge the capacitor.

It has been indicated that a magnetic field must be established due to a changing electric field – even in the absence of a conduction current (“The presence of the term $\delta D/\delta t$ in the right-hand side of Ampère's law literally means that a changing electric field causes a magnetic field, even when no conduction current exists.” (Selvan, 2009: 41)). Furthermore: “According to Roche [5], the investigations by Purcell, Zapolsky, and Bartlett demonstrated that ‘the displacement current of a rapidly changing induced electric field will generate a significant magnetic field.’” (Selvan, 2009: 42).

This is the first experiment, as far as could be established, where the relationships are tested in the absence of a conduction current. The experiment should thus, God willing, provide interesting insights into Maxwell's displacement current. Also, another of Maxwell's core predictions that an electromagnetic wave will be created as an electric field and a magnetic field mutually interact, will be investigated.

4.10.2 First experiment

We have, by Grace, been able to establish that changing electric fields from a Van de Graaff generator will create electromagnetic waves. The following experimental setup was used:

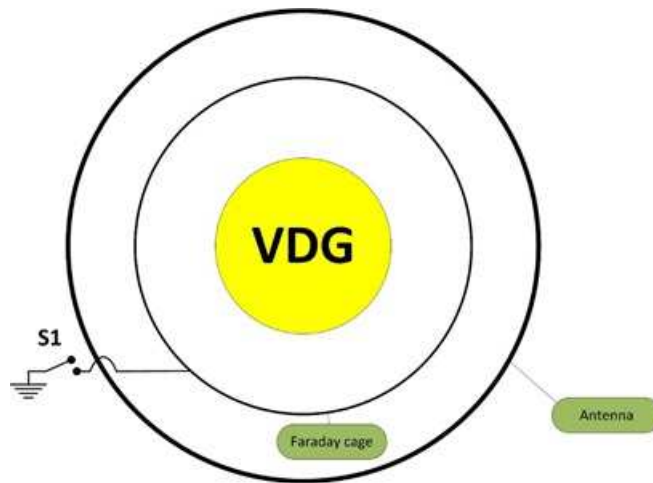


Figure 4-45: First experimental set-up (plan view).

The prime experimental parameters were:

Table 4-2: Set-up experiment 1	
Van de Graaff dome diameter	270 mm
Faraday cage cylinder diameter	680 mm
Faraday cage cylinder height	1 250 mm
Antenna dipole diameter	4 m

The dipole antenna was connected to a network analyser (Agilent 8712 ET – 300 kHz tot 1 300 MHz) and many pulses were observed around 17,5 MHz (quarter wave frequency), less by 35 MHz (half wave frequency) and seldom by 70 MHz (full wave frequency).

The basic mechanism of the Ampère-Maxwell is thus confirmed; in that:

- a magnetic field has by inference been created by the changing electric field;
- electromagnetic waves were observed, which implies the interaction between changing magnetic and electric fields.

The next photograph shows the experiment:



Figure 4-46: Experiment 1.

A snapshot of activity on the network analyser:

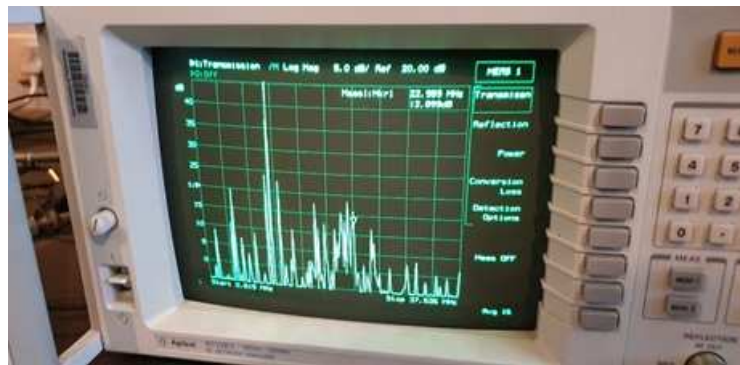


Figure 4-47: Snapshot of network analyser results for experiment 1.

4.10.3 Second experiment

In recognition of the important role of capacitors during the formulation of the Maxwell equations – it will be attempted to observe electromagnetic waves while charging the capacitor via electrostatic induction. The following set-up will be used:

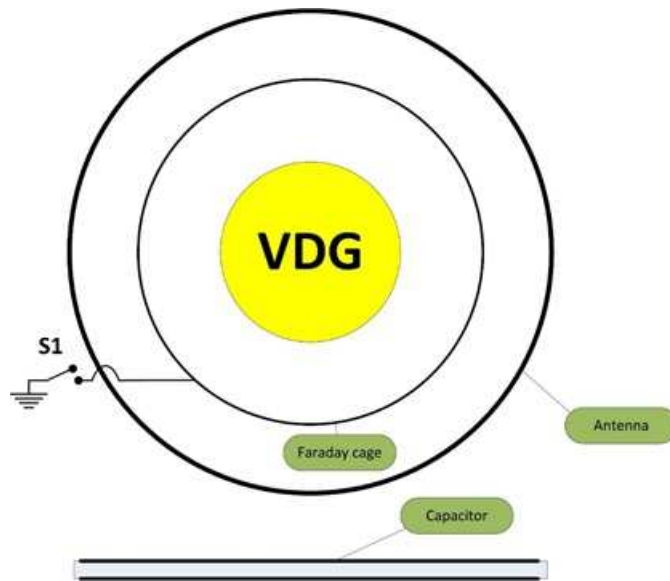


Figure 4-48: Set-up for experiment 2.

Experiment 1 showed electromagnetic activity around 17,5 MHz (quarter wave frequency), less by 35 MHz (half wave frequency) and seldom by 70 MHz (full wave frequency). The capacitor electrode dimensions were thus designed to create activity elsewhere.

4.10.4 Future experiments

Repeat this experiment with a radioisotope source, offering a stable and predictable emission rate and thus a relatively constant change to the electric field. Furthermore, with such a source there could be no argument about electromagnetic currents contaminating the experiment.

CHAPTER 5 FINDINGS

5.1 Significant outcomes

The following outcomes are significant:

- Polarity reversal in set of three serially connected capacitors movement – although experiment will have to be repeated.
- Sectional capacitor with charge movement – although experiment will have to be repeated.
- Applying charge on the outside of a sliding capacitor, and using the charge in the enclosed capacitor to prolong the lifetime of the charge outside.
- Submerging a charged conductor in transformer oil to prolong the life of the charge there-on.
- Polarity reversal after an arc struck the nearest electrode of a capacitor stack.
- Shielding of the electroscope.

5.2 Major lessons learnt

The lessons learnt are building blocks that may be used in future research. These included:

- The process of inserting and extracting an electrode from between two other charged electrodes forming a capacitor, appeared to be essentially reversible with respect to the electrostatic energies involved. However, attempting to extract any energy on a sustainable basis proved very difficult, to an extent due to capacitor leakage and instrument uncertainties. The biggest question on this approach centres on the actual mechanism for energy storage in a capacitor. The mechanism is not fully understood, and it appears that at least part of the energy is stored via dipole rotation in the dielectrics. This energy should then be “returned” to the electrodes upon exit, but it is uncertain whether this is happening.

This uncertainty about the actual mechanism of energy storage is echoed by (Lin *et al.*, 2016: 21): “First, the fundamental mechanism of contact electrification remains to be investigated extensively. This phenomenon has been researched for a long time, which refers to the charge generation on the surface of the materials when they are brought into contact with different materials; several theories about the contact electrification have been proposed; however, there is no substantial conclusion achieved. Thus, the

deepened understanding of contact electrification is vitally important to achieve a higher output of the TENG.”

- Electrodes are perhaps not supposed to be moved in and out of capacitors, at least until there is exact understanding of the process, sufficient to allow proper design and monitoring of the process.
- Once a capacitor has been charged through electrostatic induction, it must ideally be discharged as soon as possible before leakage can reduce the yield. This holds for laboratory capacitors. Despite care, it appears no built capacitor attained better than 50% of the designed capacitance. Leakage was a serious problem.
- Rotation of electrode discs proved a major problem. A disc of 500 mm diameter was laser cut, so should have been well balanced. Serious vibration occurred even at 1 000 revolutions per minute, causing the cancellation of that experiment, although roller bearing supports at the edges might have allowed the experiment to proceed. Such bearing support might have limited the rotational speeds.
- High voltage, as generated by a Van de Graaff generator, seems to be ever present. The theory obviously supports that all conductors in an electric field will have a potential and all dielectrics will become polarised. Everything in the vicinity thus seems to become charged.
- The person conducting the experiment then also becomes charged, and the difficulty is that it makes interpretation of the results difficult. By way of an example, a capacitor stack is electrostatically charged by a Van de Graaff generator, and the operator attempts to discharge the free charge on the outside face of the capacitor stack. When a spark is detected, does it mean:
 - the higher potential charge on the outside face of the capacitor stack arced to the hopefully uncharged sphere held by the operator; or
 - the higher potential charge on the sphere held by the operator discharged to a lower potential or neutral outside face of the capacitor stack.

Proper instruments could alleviate this difficulty.

- Without proper instruments, it becomes very difficult to establish what is happening, especially as electric fields cannot normally be seen. It would be difficult to conduct all experiments in an electric field visualisation apparatus, but perhaps that is an option. One difficulty was to establish whether charge did in fact transfer to an intermediate sphere upon contact. At times, to improve reliability, the transfer was even conducted submerged under transformer oil. Afterwards it was then tested with an electroscope, but

this proved an unreliable instrument. The problem with an electroscope in the vicinity of a Van de Graaff generator, was that the glass flask becomes polarized and thus seemed to remember previous fields.

- The electroscope was eventually enclosed within a Faraday cage to shield it from all undue influences.
- Transformer oil proved to be excellent for protecting electrostatic charge against atmospheric discharging. The transformer oil must, however, in itself be protected from absorbing moisture. Furthermore, it should also not be disturbed, as it appears the energy in charged dipoles might be lost.

5.3 Static capacitor stage

Two highlights from this stage were the polarity reversal experiment and the sectional capacitor experiment. It was noted that high voltage incurs risk. Two incidents of cross-over arcing were encountered:



Figure 5-1: Cross-over arcing in a capacitor.

5.3.1 Polarity reversal in three serially connected capacitors

Three capacitors were connected in series, by being constructed one above the other. They were charged to 3 000 V for the set. The potential difference was measured to be 1 000 V per capacitor, indicating equivalent construction:

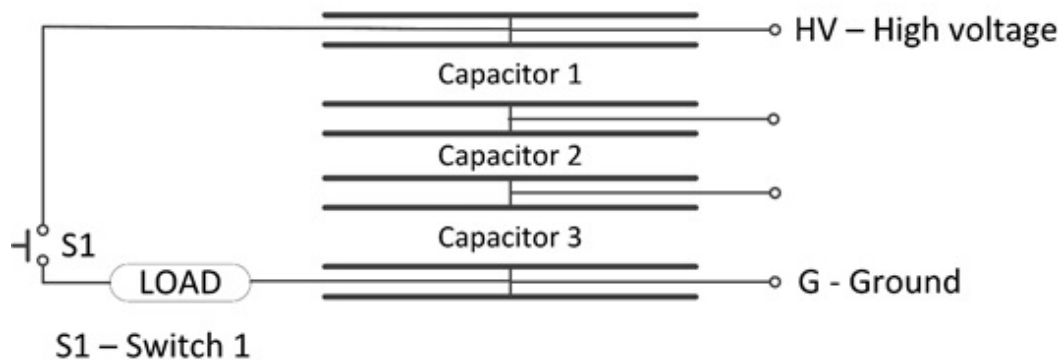


Figure 5-2: Electrical layout of three serially connected capacitors.

Then switch S1 was closed, and the potential differences changed as follows:

Table 5-1: Evaluation of polarity reversal experiment					
Capacitor	Electrode	Initial		Final	
		Potential difference	Potential gradient	Potential difference	Potential gradient
1	Top	3000 V	-1000 V	1500 V	500 V
1	Bottom	2000 V		2000 V	
2	Top	2000 V	-1000 V	2000 V	-1000 V
2	Bottom	1000 V		1000 V	
3	Top	1000 V	-1000 V	1000 V	500 V
3	Bottom	0 V		1500 V	

Polarity reversal occurred in capacitors 1 and 3. The experiment was repeated with similar results. In hindsight, the time for closure of switch 1 must have a significant impact on the experiment. Two aspects are interesting:

- Polarity reversal inside a capacitor would require energy. The capacitor is initially discharged and then recharged.

- The final potential gradients in the capacitor set sums to 0 V, which is intuitively correct as the connections were bridged. Nevertheless, there is still energy in the individual capacitors.

It would be useful, for the broadening of understanding of capacitors, to repeat the experiment. There is the possibility that alternating current may be generated from direct current via high frequency switching and capacitors. It was not considered a vital part of the present research.

5.3.2 Sectional capacitor

The electrical layout for the sectional capacitor is as follows:

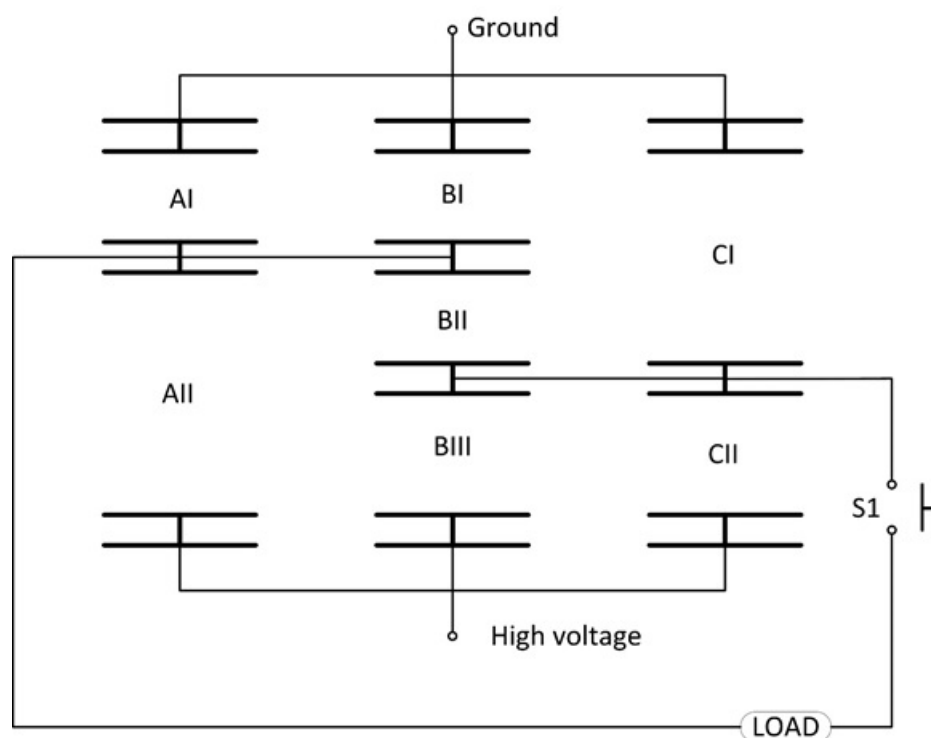


Figure 5-3: Electrical layout of sectional capacitor.

The initial measurements were:

- | | | |
|--------------------------|--------|---------|
| • First electrode at top | Ground | 0 V |
| • Second electrode | | 500 V |
| • Third electrode | | 1 100 V |

The final calculated overall capacitance was 17,84 nF against the measured value of 17,9 nF, which was deemed acceptable (error of 0,34%).

Table 5-2: Evaluation of sectional capacitor experiment						
Capacitor	Capacitance	Capacitance check	Initial		Final	
			Potential difference	Charge	Potential difference	Charge
AI	15.00 nF	3.35 nF	500 V	7.50E-06 C	800 V	1.20E-05 C
AII	4.32 nF		1 080 V	4.67E-06 C	600 V	2.59E-06 C
BI	32.20 nF	10.73 nF	500 V	1.61E-05 C	800 V	2.58E-05 C
BII	32.20 nF		600 V	1.93E-05 C	0 V	0.00E+00 C
BIII	32.20 nF		480 V	1.55E-05 C	600 V	1.93E-05 C
CI	4.32 nF	3.75 nF	1 100 V	4.75E-06 C	800 V	3.46E-06 C
CII	28.50 nF		480 V	1.37E-05 C	800 V	2.28E-05 C
Overall	17.90 nF	17.84 nF	1 580 V	2.83E-05 C	1 400 V	2.51E-05 C
Sum				8.15E-05 C		8.59E-05 C
Error		0.34%		-188%		-243%

The evaluation indicates that the experiment should have been redone:

- The basic experimental setup was problematic, in that it did not perform symmetrically with respect to capacitances.
- A convex support structure was used, which might have been problematic with the 0,9 mm aluminium sheet used as electrodes as they might not drape properly. This would include uneven air gaps in the electrodes. A repeat of the experiment can rather be done on a flat surface, using a combination of vacuum and air pressure to ensure close contact.
- Manual calculations at the time indicated charge movement between the sections. Unfortunately, recalculation now indicated massive errors, making any conclusions as to charge movement unreliable.

5.4 Sliding electrode stage

The intent of this stage was to demonstrate that a capacitor will have all its energy restored, despite what happened inside the electrodes, given that the charge and the capacitance is restored to its initial conditions.

This could never be proven 100%.

5.4.1 Evaluation of capacitor capacitance

Testing with the sliding capacitor commenced with measuring the attained capacitances in the various positions possible with the equipment. Table 5-3 shows the possible positions as well as the codes used for them in Table 5-4.

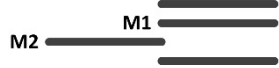
Table 5-3: Various operational stages of the sliding capacitor		
Code	Illustration	Explanation
A		Both M1 and M2 electrodes inserted. Capacitors from top: C1, C2, C3 and C0 overall
B		M1 electrode extracted.
C		M2 electrode extracted.
D		Both M1 and M2 electrodes extracted.

Table 5-4 show the comparison, as per the stages defined in Table 5-3:

Table 5-4: Comparison between calculated and measured capacitances					
Item	Unit	Stage			
		A	B	C	D
ϵ_0	F/m	8.85E-12	8.85E-12	8.85E-12	8.85E-12
ϵ_R	-	3.30	3.30	3.30	3.30
A (0,65 m x 0,35 m)	m ²	0.23	0.23	0.23	0.23

d₁	calculated	mm	0.26	0.52	0.26	
		m	0.00026	0.00052	0.00026	
C₁	calculated	F	2.56E-08	1.28E-08	2.56E-08	
	calculated	nF	25.57	12.78	25.57	
	measured	nF	7.59	4.83	7.59	
	yield	-	30%	38%	30%	
d₂	calculated	mm	0.26		0.52	
		m	0.00026		0.00052	
C₂	calculated	F	2.56E-08		1.28E-08	
	calculated	nF	25.57		12.78	
	measured	nF	6.47		4.43	
	yield	-	25%		35%	
d₃	calculated	m	0.26	0.26		
		mm	0.00026	0.00026		
C₃	calculated	F	2.56E-08	2.56E-08		
	calculated	nF	25.57	25.57		
	measured	nF	7.29	7.22		
	yield	-	29%	28%		
d₀	calculated	mm		0.78	0.78	0.78
		m		0.00078	0.00078	0.00078
C₀	calculated	F	8.52E-09	8.52E-09	8.52E-09	8.52E-09
	calculated	nF	8.52	8.52	8.52	8.52
	measured	nF	2.3	2.87	2.78	3.04
	yield	-	27%	34%	33%	36%

Note the very low yields attained. This applied for a very simple dielectric-electrode-dielectric sandwich.

5.4.2 Initial results of the sliding electrode experiments

The following diagram illustrates the impact of the various manoeuvres conducted with the sliding electrode apparatus. Three repetitions were typically conducted per value:

SUMMARY OF ALL OBSERVATIONS OF CHANGES IN OVERALL POTENTIAL DIFFERENCE								
FROM	TO							
	A	B	C	D	E			
								
A		-	23%		43%	26%	-18%	-14%
B		-	-16%		34%	13%		
C			-26%	-15%		-25%	-21%	
D		-25%	-22%		38%	22%		
E		4%	-13%					

Figure 5-4: Summary of results from sliding electrode apparatus

The yellow highlighting indicates that the apparatus was charged with both intermediary electrodes inserted. In the alternative, just the outer electrodes were initially charged. The apparatus was initially charged as close as possible to 2 000 V, the upper limit of the electrostatic voltmeter's range.

Note that these results were primarily compiled before the capacitor leakage became very suspect. Hysteresis can thus still be observed, for instance:

- Inserting the M2 electrode into a yellow charged apparatus (move from C to B) causes a loss of 15% in potential difference.
- Retracting the M2 electrode from the yellow charged apparatus (move from B to C) causes a gain of 13% in potential difference.

The potential difference squared, relates to the internal energy.

At this stage it appeared as if the electrostatic energy is actually restored, when the starting conditions are reinstated, at least with respect to combinations where no energy was removed. As an example, energy is removed in E. To move from E to A, costs 13% of the potential difference. Then to move from A to E, costs another 14%.

5.4.3 Evaluation of capacitor leakage overall

Early on it was established that the capacitors are losing energy very quickly, either via capacitor leakage or through an internal leakage in the electrostatic voltmeter. The internal resistance of the voltmeter is above 10^{12} ohm, so it should not have posed a problem. The problem became very visible around November 2016, to the extent that specific tests were conducted to find a remedy.

5.4.4 Capacitor leakage check: 25 November 2016

The test was conducted three times. Herewith the first test:

Table 5-5: Experiments on 25 November 2016 - 1				
Objective	V ₀		V ₀	
	[V]	[s]	[V]	[Δs]
Characterise capacitor leakage	2010	101	2010	0
(M1 in & M2 in)	1950	105	1950	4
	1900	109	1900	8
Sam20161125 003 cap leak 1.mp4	1850	114	1850	13
	1800	119	1800	18
	1750	125	1750	24
	1700	131	1700	30
	1650	137	1650	36
	1600	145	1600	44
	1550	151	1550	50
	1500	158	1500	57
	1450	166	1450	65
	1400	175	1400	74
	1350	184	1350	83
	1300	194	1300	93
	1250	204	1250	103
	1200	215	1200	114
	1150	227	1150	126
	1100	239	1100	138
	1050	252	1050	151
	1000	265	1000	164

	950	281	950	180
	900	295	900	194
	850	312	850	211
	800	329	800	228
	750	349	750	248
	700	369	700	268
	650	392	650	291
1/Tau (1/τ)	3.83E-03			
Tau (τ)	261		s	
	4		min	
C	2.33E-09		F	
R	1.12E+11		Ω	

Results were plotted to establish the delay constant:

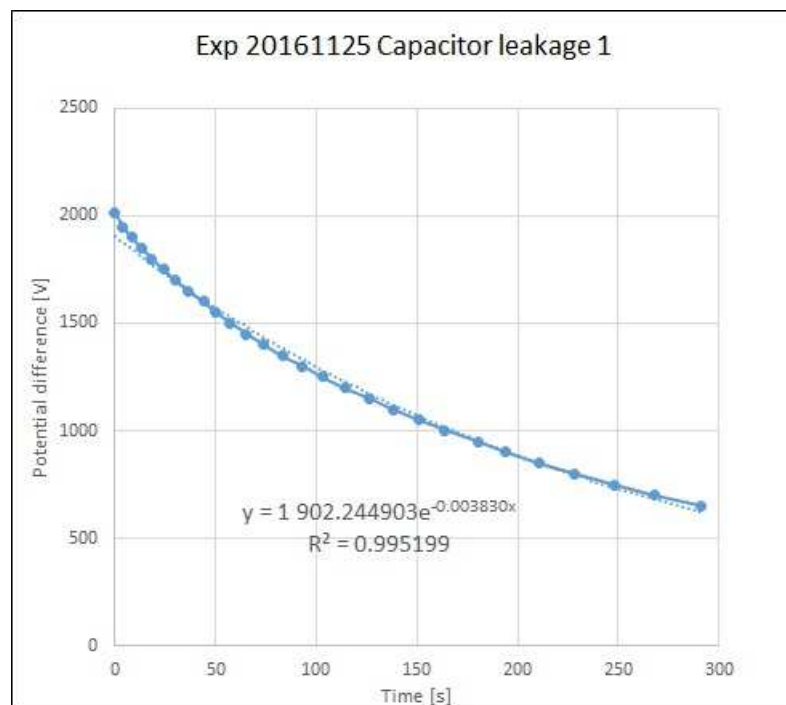


Figure 5-5: Capacitor leakage test 1 on 25 November 2016.

The second test on 25 November 2016:

Table 5-6: Experiments on 25 November 2016 - 2				
Objective	V₀		V₀	
	[V]	[s]	[V]	[Δs]
Characterise capacitor leakage	1990	53	1990	0
(M1 in & M2 in)	1950	55	1950	2
	1900	58	1900	5
Sam20161125 005.mp4	1850	62	1850	9
	1800	67	1800	14
	1750	74	1750	21
	1700	81	1700	28
	1650	89	1650	36
	1600	98	1600	45
	1550	107	1550	54
	1500	117	1500	64
	1450	128	1450	75
	1400	139	1400	86
	1350	151	1350	98
	1300	164	1300	111
1/Tau (1/τ)	3.70E-03			
Tau (τ)	270		s	
	5		min	
C	2.33E-09		F	
R	1.16E+11		Ω	

Results were plotted to establish the delay constant:

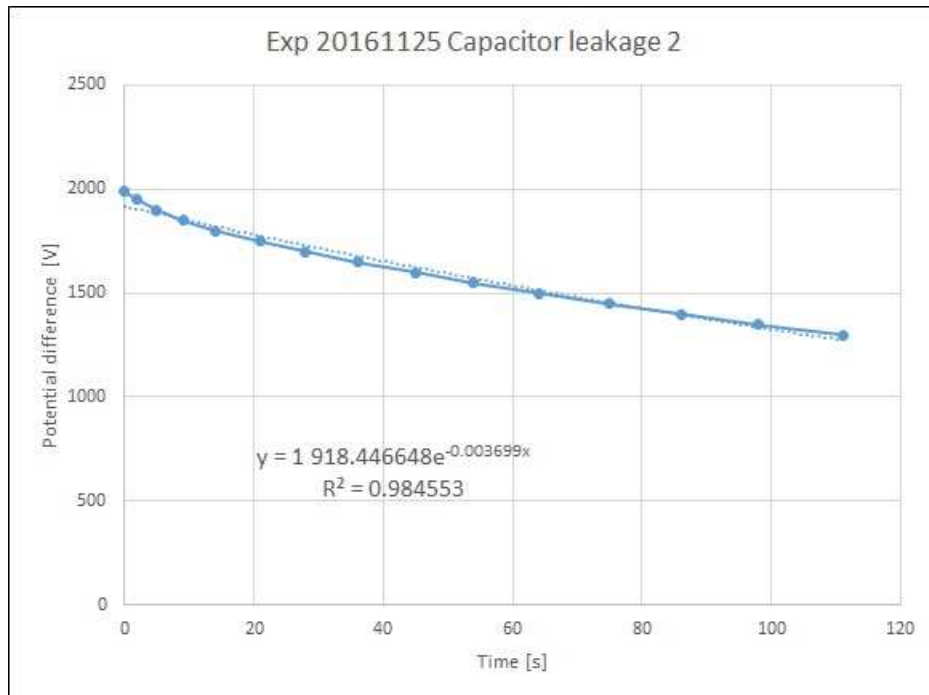


Figure 5-6: Capacitor leakage test 2 on 25 November 2016.

Third test on 25 November 2016:

Table 5-7: Experiments on 25 November 2016 - 3				
Objective	V₀		V₀	
	[V]	[s]	[V]	[Δs]
Characterise capacitor leakage	2000	267	2000	0
(M1 in & M2 in)	1950	271	1950	4
	1900	276	1900	9
Sam20161125 005.mp4	1850	281	1850	14
	1800	287	1800	20
	1750	293	1750	26
	1700	301	1700	34
	1650	310	1650	43
	1600	319	1600	52
	1550	329	1550	62
	1500	340	1500	73
	1450	352	1450	85
	1400	364	1400	97
	1350	375	1350	108

	1300	389	1300	122
	1250	403	1250	136
	1200	417	1200	150
	1150	433	1150	166
	1100	448	1100	181
1/Tau (1/τ)	3.20E-03			
Tau (τ)	313		s	
	5		min	
C	2.32E-09		F	
R	1.35E+11		Ω	

Results were plotted to establish the delay constant:

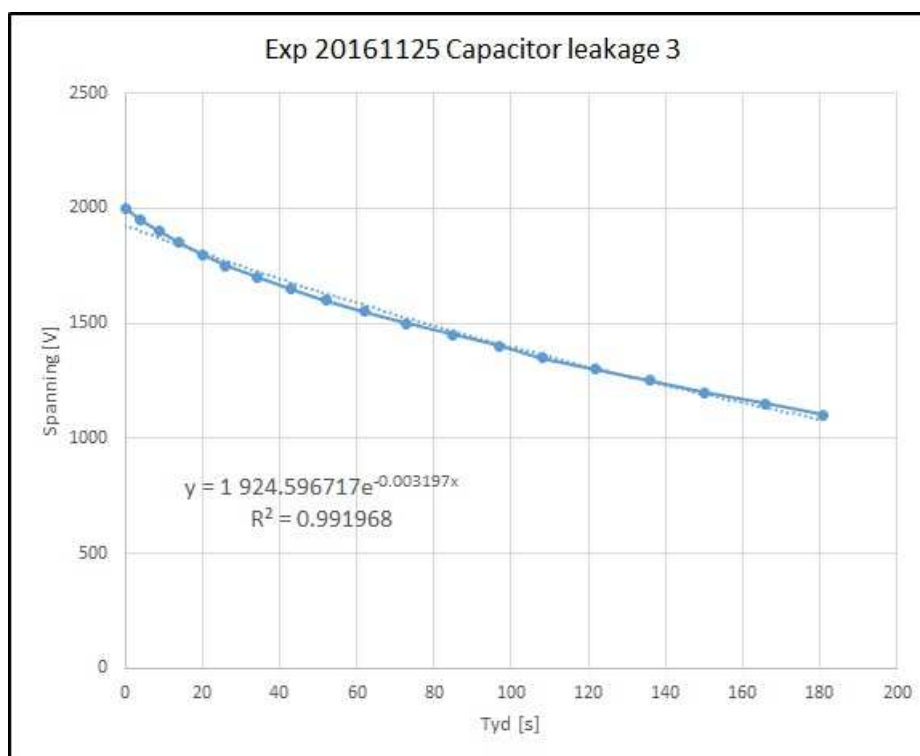


Figure 5-7: Capacitor leakage test 3 on 25 November 2016.

Results were compared with previous results:

Table 5-8: Review of capacitor capacitances on 25 November 2016												
#	M1	M2	Description	15 November 2016			22 November 2016			25 November 2016		
				Meas (nF)	Calc (nF)	Error	Meas (nF)	Calc (nF)	Error	Meas (nF)	Calc (nF)	Error
1	Out	Out	HV - G	2.04			2.71			2.32		
2	In	Out	HV - G	2.12	2.05	3%	2.70	2.59	4%	2.33	2.29	2%
3			HV - M1	4.55			6.86			5.62		
4			M1 - G	3.74			4.17			3.87		
2	Out	In	HV - G	2.10	2.05	2%				2.43	2.36	3%
3			HV - M2	3.10						3.61		
4			M2 - G	6.06						6.84		
5	In	In	HV - G	2.12	2.04	4%	2.83	2.67	6%	2.4	2.31	4%
6			HV - M1	5.07			7.52			5.98		
7			M1 - M2	7.23			8.84			7.91		
8			M2 - G	6.49			7.78			7.21		
				44.6 2			43.4 1			50.5 2		

5.4.5 Capacitor leakage check: 16 January 2017

First test on 16 January 2017:

Table 5-9: Experiments on 16 January 2017 - 1				
Objective	V ₀		V ₀	
	[V]	[s]	[V]	[Δs]
Characterise capacitor leakage	1860	212	1860	0
(M1 in & M2 in)	1800	227	1800	15
	1750	242	1750	30
20170116_141916 Cap decay 1.mp4	1700	259	1700	47
	1650	280	1650	68
	1600	300	1600	88
	1550	322	1550	110
	1500	348	1500	136
	1450	374	1450	162
	1400	400	1400	188

	1350	429	1350	217
	1300	461	1300	249
	1250	495	1250	283
	1200	531	1200	319
	1150	568	1150	356
	1100	608	1100	396
1/Tau (1/τ)	1.30E-03			
Tau (τ)	768		s	
	13		min	
C	3.29E-09		F	
R	2.33E+11		Ω	

Results were plotted to establish the delay constant:

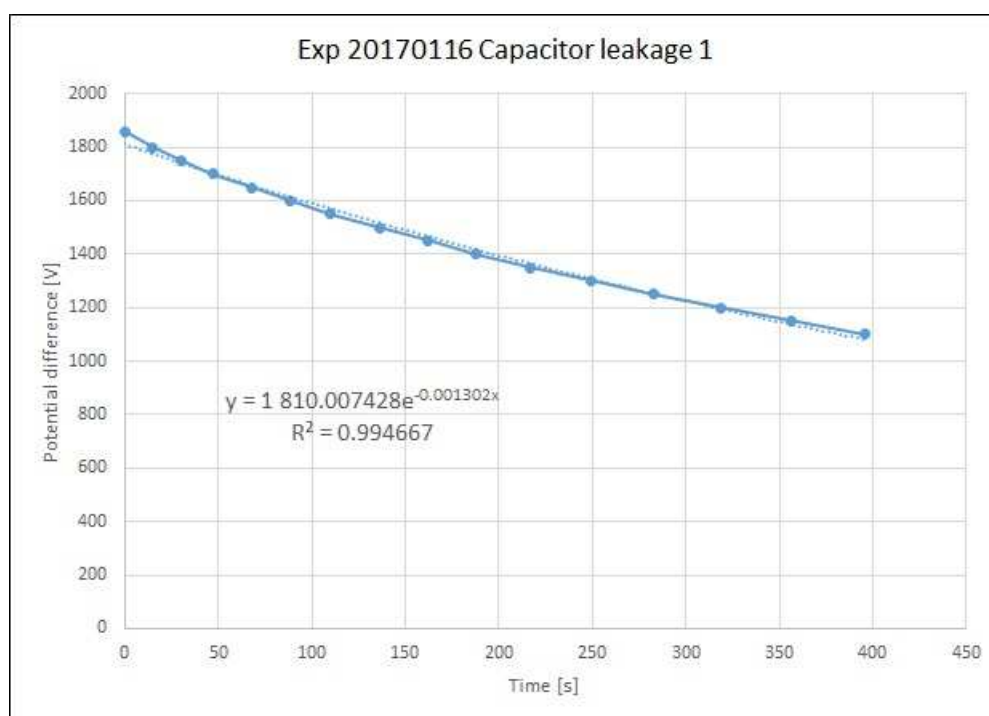


Figure 5-8: Capacitor leakage test 1 on 16 January 2017.

Second test on 16 January 2017:

Table 5-10: Experiments on 16 January 2017 - 2				
Objective	V₀		V₀	
	[V]	[s]	[V]	[Δs]
Characterise capacitor leakage	1880	33	1880	0
(M1 in & M2 in)	1850	39	1850	6
	1800	52	1800	19
20170116_143610 Cap decay 2.mp4	1750	67	1750	34
	1700	84	1700	51
	1650	102	1650	69
	1600	121	1600	88
	1550	141	1550	108
	1500	164	1500	131
	1450	188	1450	155
	1400	211	1400	178
	1350	236	1350	203
	1300	264	1300	231
	1250	290	1250	257
	1200	319	1200	286
	1150	352	1150	319
	1100	383	1100	350
	1050	416	1050	383
	1000	455	1000	422
1/Tau (1/τ)	1.48E-03			
Tau (τ)	676		s	
	11		min	
C	2.38E-09		F	
R	2.84E+11		Ω	

Results were plotted to establish the delay constant:

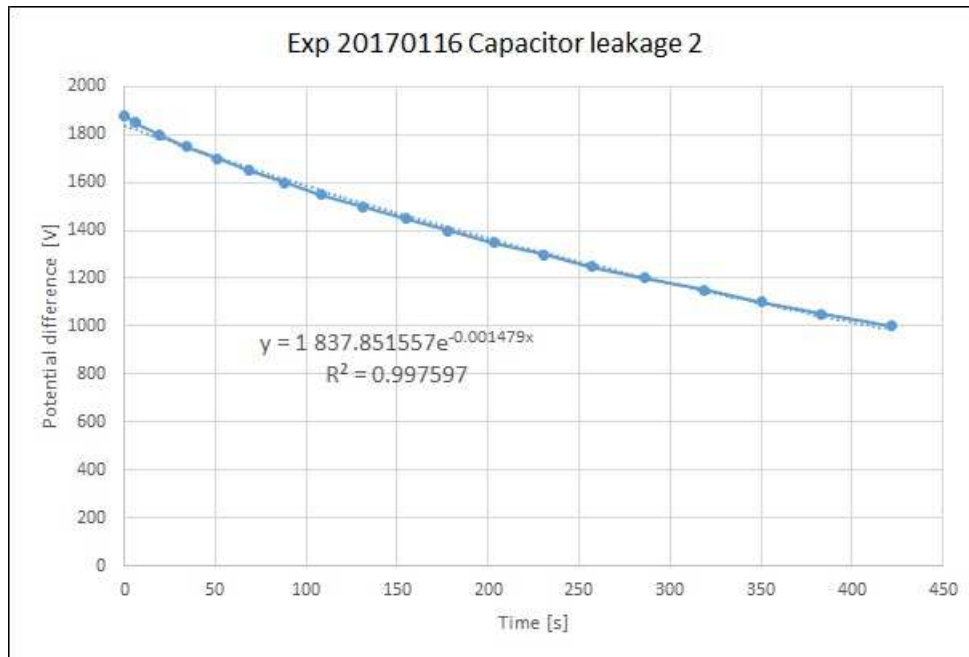


Figure 5-9: Capacitor leakage test 2 on 16 January 2017.

5.4.6 Overall evaluation of capacitor leakage

The results of various leakage tests were compared. There was an excellent result on 23 November 2016, which has somehow deluded the experimenter. Various attempts were made to improve the delay constant, all to no avail.

Table 5-11: Evaluation of capacitor leakage			
Date	Resistance	Capacitance	Time constant τ
20161115	$1,89 \times 10^{11} \Omega$	2,05 nF	389 s
20161123	$1 \times 10^{12} \Omega$	2,71 nF	2 719 s
20161125	$1,12 \times 10^{11} \Omega$	2,33 nF	261 s
20161125	$1,16 \times 10^{11} \Omega$	2,33 nF	270 s
20161125	$1,35 \times 10^{11} \Omega$	2,32 nF	313 s
20170116	$2,33 \times 10^{11} \Omega$	3,29 nF	768 s
20170116	$2,84 \times 10^{11} \Omega$	2,38 nF	676 s

5.4.7 Interpretation of the sliding electrode experiments

It was always noted that, once the intermediate capacitor is inserted into the charged outer electrodes and the charge removed from the intermediate capacitor, the overall potential difference drops. This can be understood in terms of the explanation compiled for the static capacitor case. Now, when the intermediate capacitor is removed from the outer electrodes, the potential difference does not return to the initial value. This observation might be explained as follows:

- Capacitor electrostatics is determined by the relationship $Q = C.V$.
- When an intermediate capacitor is discharged, the overall potential difference (V) drops.
- This is logical even in a sliding capacitor set-up, as the discharge of the intermediate capacitor effectively increases the overall capacitance. It appears that a discharged intermediate capacitor acts as a short circuit for the overall circuit. The overall charge was not depleted, yet the potential difference dropped. This signifies that the overall capacitance had to have increased.
- When the intermediate capacitor is withdrawn, the actual withdrawal comprises two electrodes and three sheets of dielectric. The construction of the sliding capacitor set-up also means that the withdrawal of the two electrodes and three sheets of dielectric implies the immediate insertion of three “new” or “uncharged” sheets of dielectric.
- While it was expected that the potential difference must return to the initial value, it actually reduces further upon insertion of the new dielectric. It is to be expected that insertion of a dielectric would cause a drop in potential difference. However, the actual situation is not just the withdrawal of dielectrics followed by the insertion of dielectrics. It is a continuous and seamless replacement of a dielectric thickness with the same dielectric thickness. Even as the removal of the electrodes imply a small reduction of approximately 100 microns in the amount of material between the two outer electrodes, one of the outer electrodes is flexibly supported by compression springs to absorb any change in thickness.
- The overall capacitance should thus have remained the same, and because the electrodes were isolated and no charge could have been removed, the potential difference should have returned to the original value.
- However, what did change is that charged dielectric was replaced by uncharged dielectric, even though the capacitance remained the same (gap between electrodes did not change). The potential difference dropped, and it might have been due to the ever-

present leakage. If not, it would indicate that something more than $Q = C \cdot V$ is at play when new dielectric is inserted.

- A possible explanation of the “something more” could be:

Charge in the beginning	$Q = C \times V$
-------------------------	------------------

Discharge	$Q = C^+ \times V^-$
-----------	----------------------

Replace dielectric	$Q = C^{++} \times V^-$
--------------------	-------------------------

During discharge, the capacitance must increase as if the intermediate capacitor is bridged out and does not exist. With replacement of the dielectric, the capacitance must increase even further to allow a further drop in the potential difference. This last behaviour corresponds to the insertion of a dielectric block into the air gap between electrodes of a capacitor. However, there was already a dielectric in the space now filled by the fresh dielectric. The increase in capacitance as one dielectric is being replaced by an equivalently dimensioned dielectric might seem to indicate that the relative permittivity of the initial dielectric became 1 and is now reverting to the original value. In reality, the increased capacitance C^{++} should be of similar value to the original capacitance C . Then, however, the potential differences would also have remained constant. This appears to be a mystery.

Mitigation strategies followed in an attempt to reduce capacitor leakage:

- There were doubts on the validity of the electrostatic voltmeter readings. Experiments were conducted to establish if the leakage was retarded by only intermittent contact with the electrostatic voltmeter. Results were inconclusive, which may indicate that the electrostatic voltmeter is not the problem.
- Changed connections, reducing the amount of metal.
- Ensured no exposed connection touched anything, not even wood.
- Replaced the tape fastening the aluminium foil electrodes to the Mylar® dielectric sheets.
- Cleaned dielectric surfaces with methanol, attempting to remove any tracking paths.
- Tightened the clamping screws to reduce the gaps inside the capacitors.

5.4.8 Revival of charge on uncharged electrode

An uncharged electrode can indeed be recharged by a charged electrode.

This result should be reconsidered to possibly throw light on the mystery of the previous paragraph 5.4.7.

5.4.9 Charge on outside of sliding electrodes

Charge can be deposited on the outer faces of the electrodes of an intermediary capacitor. When the intermediary capacitor is then inserted between outer electrodes, they become charged.

This result should be reconsidered to possibly throw light on the mystery of the previous paragraph 5.4.7.

5.4.10 Electrostatic forces prevented removal of the sliding electrodes

After many experiments to characterise the behaviour of the sliding electrode apparatus, the supervisor was invited for an on-site inspection. At that demonstration, for the first time ever, electrostatic forces prevented removal of the sliding electrodes from the charged electrodes.

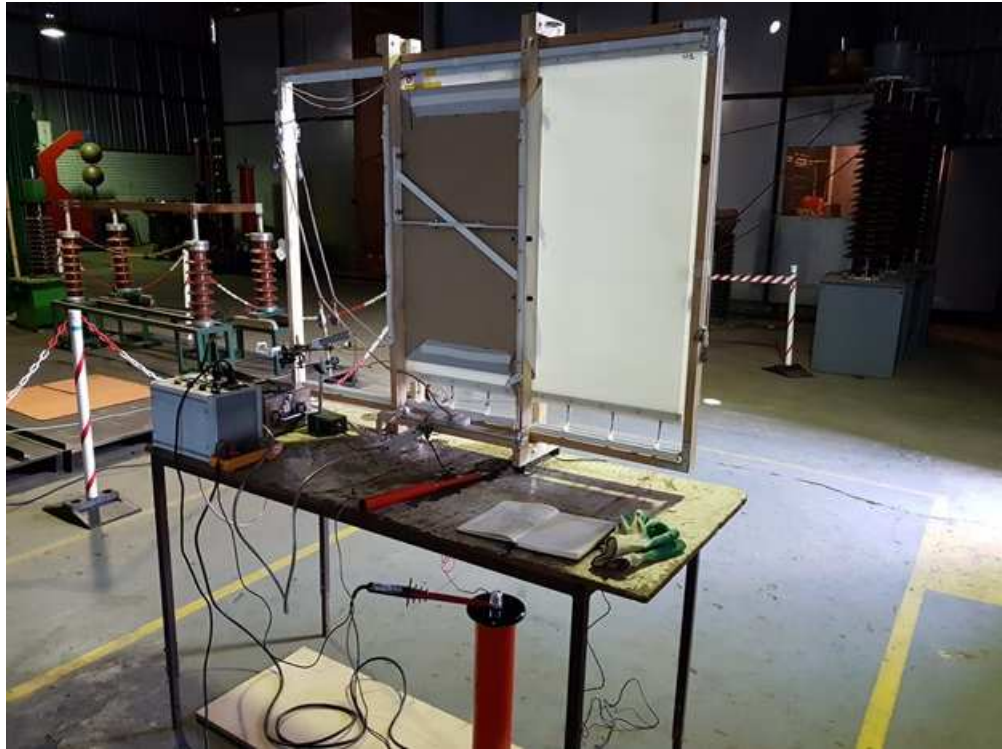


Figure 5-10: Sliding electrode apparatus on day of experiment.

The electrostatic forces involved were considerable:



Figure 5-11: Stuck electrode due to electrostatic forces.



Figure 5-12: Stuck electrode due to electrostatic forces.

The experiment and in fact this part of the experimental programme was reviewed, and the following was decided:

- Humidity in the atmosphere might have played a role on wood used in the apparatus.
- It was appreciated that it would be best to continue experiments without any contact between sliding parts. The electrostatic forces must be established so as to allow proper design of a user system. Redesign and remanufacture the sliding electrode apparatus such that:
 - Forces can be quantified. Establish the sliding force required to pull a charged electrode from a capacitor. Theory is available, and must be locally validated. The hypothesis is that there must be a gap that would allow electrodes to slide in and out, without an undue penalty by the electrostatic forces.
 - The impact of additional capacitors to be charged electrostatically, can be established. The hypothesis is that capacitors in a stack, outside the closest electrode, will have no impact.

This experiment effectively concluded the sliding electrode stage.

5.5 Hollow electrode stage

Experiments with hollow electrodes were conducted primarily to establish if the charge that should appear on the outside of a capacitor stack, that has been charged via electrostatic induction, can be reintroduced into another hollow electrode. This would recycle the charge, albeit with some losses.

5.5.1 Charge storage

Charge was successfully retained for twenty-one days on a plate submerged in transformer oil. The oil must be water-free. It appears transformer oil attracts moisture, destroying its use for electrostatics.



Figure 5-13: Charged plate submerged in transformer oil.

5.5.2 Charge redistribution

Charge does not automatically move, as does a potential difference, due to the fact that one end is at a higher potential than the other. A new charge distribution is defined by the electric fields as well as a geometrical feature such as the radius of curvature over the conductors.

5.5.3 Charge redistribution via cable

Could not succeed in connecting cabling directly to the inside of hollow electrodes. With direct connection, conduction currents will eliminate any potential difference between conductors. Theoretically at least, charge should not enter hollow electrodes via cabling connected to the inside.

Segmented cabling works to protect the inside from external fields. However, even as with a Faraday cage, a force or field inside can only be retained if the shielding is earthed. It was not considered feasible to introduce earthed connections into hollow electrodes.

5.5.4 Charge redistribution via charged entities

It proved difficult to use charged entities to reintroduce charge into a hollow electrode. This experimental approach should work, but available instruments did not allow a step by step validation of the process.

5.6 Rotating electrostatic generator

The motor and control electronics were assembled to the rotor disc.

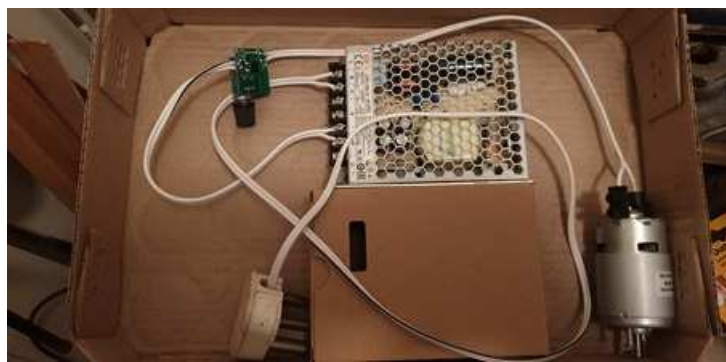


Figure 5-14: Motor and control electronics.



Figure 5-15: 500 mm diameter disc for rotor.

Once it started rotating, it became apparent that the vibration was too much without supporting the rotor at the edges.

This was not considered a good alternative, as the intent was to have the rotor spinning at approximately 10 000 revolutions per minute in order to attain around 1 000 Hz electrostatic

exposures. The motor can only handle 7 500 revolutions per minute and the safe rotation speed for a disc of 500 mm is also approximately 6 000 revolutions per minute. So, with regard to the motor and the disc, the endeavour would be risky, but a useful intermediate step towards the objective.

However, the problem lies with the support. If the disc is rotating at 10 000 revolutions per minute with a 250 mm radius – the supporting bearing will be severely strained. It would be easier to get air bearings, as an alternative, but there was no time in this project to acquire air bearings.

5.7 Square ice pail within square ice pail

This experiment was unfortunately not successful. Later development of the Van de Graaff controller, Faraday shell shutters and a β -radiation source would enable an experiment with a chance of success. The Van de Graaff generator is too bulky and it was not possible to remove charge.

Furthermore, the experiment would be much advanced if a proper means of charge detection can be found. Arc horns deplete energy via corona discharge to the extent that most activity would never be seen.

Also, with proper charge detection instruments, the experiment can first be conducted with table top nested ice pails where it is possible to bring charge in by hand and remove it. The big ice pail assembly was actually a response to two problems: the introduction of charge for which the Van de Graaff generator was used, as well as the difficulty of detecting charge which led to the solution of using a larger scale setup.

5.8 Capacitor stack stage

This part is vital in attaining the research objective, as it deals with the mechanism for multiplying electrostatic induction over many capacitors.

5.8.1 Empty versus stack – d_0 versus $n \cdot d_1$

Substantially larger arcs were detected behind the stack of multiple capacitors against much smaller arcs behind the two dispersed sets of electrodes with air as intermediate dielectric. Even though operator presence has been identified as a possible source of error, in a comparative experiment such as this, both modalities are equally influenced by operator presence.

5.8.2 Capacitor stack holding mechanism

A stack will not maintain its integrity without a holding mechanism. Research has indicated that electrodes must probably be well aligned to assist effective propagation of electrostatic induction, with minimal fringing losses. The third mechanism worked best of all, but still leaks charge. Even the wood feels electrostatically charged, and this may indicate charge leakage.

This work must continue.

5.8.3 Charge polarity reversal after arcing

During testing, it appeared as if charge reversal occurs after arc flashover. This must be investigated further. The phenomenon does seem to occur, and an indication of possible polarity reversal is that while the leaves of the electroscope are extended during charge, the flap closes and then re-extends after an arc. The only explanation at this stage for the electroscope leaves closing and then opening again, is that an excess of the other polarity charge came through the capacitor stack.

A possible explanation may be the following:

- A certain amount of charge is generated on the dome during operation of the Van de Graaff generator.
- A fraction of this is electrostatically induced on the target electrode.
- When an arc occurs, the arc path may be considered as a temporary connection between the dome and the target electrode. All the charge on both conductors is then distributed between the two conductors according to the normal rules of charge distribution.

- The possibility may be that the target electrode was initially populated by an amount of one polarity charge, and will after redistribution have more charge of the opposite polarity.
- This new charge is then cascaded throughout the capacitor stack, causing electrode leaves to close when the initial charge is neutralised and then to re-open due to the net new charge.

5.8.4 Isolate the operator

It is vital to remove sources of uncertainty.

The test sphere on a string does not seem to work.

The special arcing plier also does not seem to work.

5.8.5 Van de Graaff static potential control and termination and earthing the dome

The controller for the Van de Graaff generator does, by Grace, work.

5.8.6 Detecting charge

Detecting charge is the core of all work on electrostatics. The full requirement is actually more than detecting, and must include measuring the quantity of charge, determining the polarity and recording the measurements. Professional instruments meeting these requirements might exist, but there were no more funds left for instrumentation.

Revisit professional instruments. This research is too vital for mediocre resources.

Mostajabi *et al.* (2019) “used machine learning techniques to successfully hind cast nearby and distant lightning hazards by looking at single-site observations of meteorological parameters.” A collaboration might create a local and detailed charge detection capability.

CHAPTER 6 CONCLUSIONS, INCLUDING DELINEATION OF FUTURE RESEARCH

6.1 Generation of electricity from electrostatic induction

This research concludes the following:

- Electricity can be generated via electrostatic induction. It has been happening since long before John Canton in 1753 discovered: “Electrical influence, or the effect which an electrified body exerts upon a body brought into its neighbourhood.” (Thompson, 1888: 569). Examples of electrostatic induction includes Faraday’s ice pail experiments, the Wimshurst electrostatic machine and the electrophorus.
- Electrostatic induction is primarily used in TENG (triboelectric nano generators) and MEMS (microelectro-mechanical systems), where it contributes in converting mechanical energy to electrical energy. As the constituent terms “nano” and “micro” signifies, very small-scale solutions are addressed.
- Electrostatic induction can, however, be used to generate electricity at domestic scale:
 - The physics of electrostatic induction was thoroughly investigated and no limit to domestic scale application was found.
 - It is absolutely possible in theory.
 - Various experiments were conducted in an attempt to construct a laboratory scale demonstrator of electricity generation principles, based on electrostatic induction. It was found:
 - Charge can be propagated through a capacitor stack, which would then induce energy in the stack.
 - Due to research resource constraints, it was not possible to demonstrate the electrostatic energy generated conclusively and unambiguously, such that no other cause might have been possible. Primarily the energy generated is not easily large enough to cause a spark, which would constitute a minimum resource approach towards energy measurement.
 - Regeneration of electrostatic energy in the capacitor stack requires a change in the electric field which can occur via movement of the source, changes in the source or interruption of the electric field between the source and the target electrode. Personal experience thus far with

insertion and withdrawal of electrodes, led to its exclusion, even as it is one of four TENG harvesting modes.

- Movement of source
- Changes in the source
- Interruption of the electric field
- The ultimate electrostatic electricity generator would be one which has a minimal requirement for energy input. Energy costs money but energy input typically implies movement, which incurs a reliability penalty.
- By Grace, towards the end of research the Faraday shell shutters were conceptualised as a means of isolating the electric field emanating from a Van De Graaff generator. It was then realised that this could be combined with a source of β -radiation and capacitor stacks to potentially enable electricity generation from electrostatic induction with minimum energy input and minimum mechanical movement.

6.2 Future research

Primarily, the current research would hopefully lead to renewed interest in electrostatics.

The first priority for future research would be the development and validation of nuclear powered electricity generation via electrostatic induction.

6.2.1 Nuclear powered electricity generation via electrostatic induction

The system comprises the following elements:

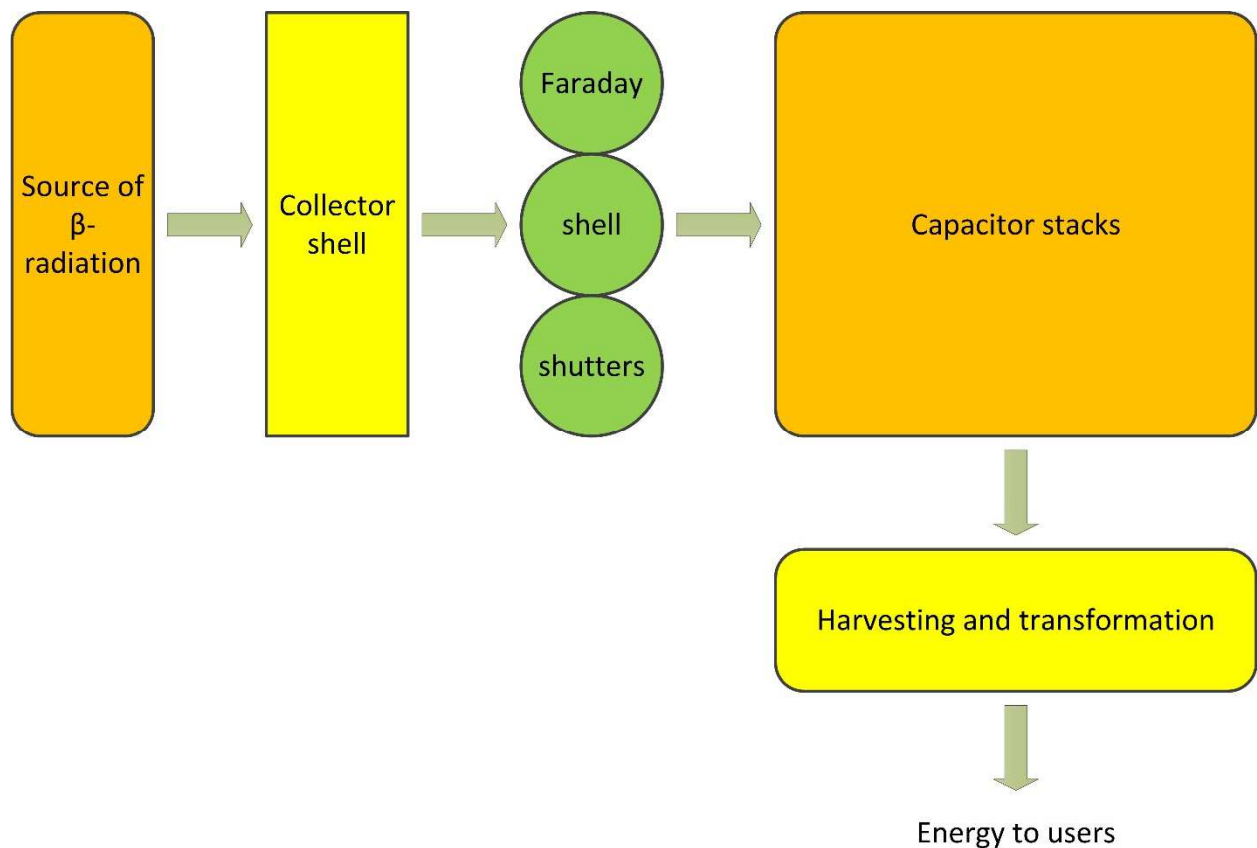


Figure 6-1: Sectional system layout of nuclear powered electricity generator.

There is only one technological hurdle unresolved, namely the migration of negative charge to the outside face of the collector shell. Resolution would require a β -radiation source which was not yet available, although the information assembled in the present report should ease the granting of access to a source and relevant research resources. The following mitigation strategy is envisaged to overcome the technological hurdle:

- The travel distance of β -particles (electrons) is 242 mm (Services, 2012). More accurate travel distances can be sourced. The essence is to ensure that the distance between radioactive source and the inside of the collector shell is as large as possible.
- A large travel distance will reduce the energy with which the particle collides with the collector shell, reducing the incidence of Bremsstrahlung.
- A large travel distance will also reduce the Coulomb attraction forces between the positively charged radioactive source and the negatively charged collector shell. This will assist in two ways:
 - Reduced attraction force will make it easier to eject the nitrogen-14 positively charged ions from the source area.

- The negative charge on the inside of the collector shell will migrate outwards all the more easily, as:
 - The distance to the positively charged source has been reduced, and force magnitude related to the inverse of the distance squared.
 - The quantity of positive charge at the source is being manipulated downwards in two ways. Nitrogen-14 ions are induced to leave, and the remaining positive charge in the source will also encourage newly formed nitrogen-14 ions to leave.
 - The increasing presence of negative charge on the inside of the collector shell will via Coulomb opposing forces cause charges to migrate outwards. The energy of incoming electrons would also assist.

The carbon-14 source also poses a challenge, primarily due to being unknown to the researcher. The required information is the processability of carbon-14, as well as how it should be packaged and suspended to deliver maximum β -radiation and to allow escape of the nitrogen-14 ions.

All the other system components constitute known technology, packaged into a new solution.

The combination of components and the envisaged operational protocol will allow the build-up of electrostatic charge from the radioactive source as well as the re-use of charge. These two features allow a significant performance improvement from previous radioactive batteries.

It is vital that current research continues, and that it will focus on the development and validation of nuclear powered electricity generation via electrostatic induction.

6.2.1.1 Energy balance

Table 6-1 illustrates possible output from a nuclear powered electricity generator:

Table 6-1: Output from a nuclear powered electricity generator		
Aspect	Value	Unit
Source	^{14}C	
Quantity	1 000	g
Specific activity	1.00E+05	Bq/g
Activity	1.00E+08	Bq
Electrons per coulomb	6.24E+18	e per C

Charge addition	1.60E-11	C/s
Efficiency of charge capture	80%	
Effective charge addition	1.28E-11	C/s
Charge time	540 000	s
	6	days
Charge	6.92E-06	C
Permittivity of free space	8.85E-12	m ⁻³ kg ⁻¹ s ⁴ A ²
Relative permittivity	1	-
Electrode square length	0.2	m
Number of electrodes	8	ea
Capacitor area	0.32	m ²
Offset (total stack gap)	2	m
Capacitance	1.42E-12	F
Internal energy	17	J
Harvest frequency	60	Hz
Harvested energy	1 014	J/s = W
Feasibility check		
Capacitance per electrode	6.39E-11	F
Charge	6.92E-06	C
Potential of electrode	108 246	V
Break through distance	0.036	m

Output of around 1 000 W can be gained from a 1 000 g carbon-14 source. The charge inside the collector shell was allowed to build up for six days, resulting in a potential of approximately 110 000 V on the target electrodes. At this potential the arc breakthrough distance in free air is 36 mm, which would be safe if the gap to the electrode is approximately 200 mm.

Vital research is outstanding, which can materially impact the performance of the technology. By way of example, if the charge build-up can be allowed for 13 days, approximately 4 000 W can be harvested with a potential of 216 491 V for an arc break through distance of 72 mm.

It is apparent that too many questions are outstanding for an energy balance to be compiled. However, it should be obvious that the potential of a sustainable energy balance has been created.

6.2.2 Maxwellian radiation from a capacitor

One of the challenges in present research had been to involve internationally renowned researchers. When the topic of Maxwell's displacement currents and the connection with capacitors was identified during the literature review, it was realised that this might offer a strategic opportunity to form a linkage with international experts. Papers and articles on electrostatic induction towards electricity generation struggled for acceptance, while a paper on the generation of Maxwell's displacement current in a capacitor, by using nuclear radiation and electrostatic induction, should find easier entry. This will hopefully open the door for further collaboration.

Bartlett and Corle (1985) used a superconducting quantum interference detector (SQUID) to detect the magnetic field inside a hand-sized circular capacitor with 10 mm plate separation. Using a 1 000 V potential difference the expected magnetic field was only about half a microgauss. Bartlett and Corle (1985: 59) found that, as expected, "the field varies linearly with distance from the axis" and the "measured slope of B vs r agrees with predictions to within 5%".

The authors indicated that the ideal would have been to conduct the research with direct current, but then the capacitor would soon have become highly charged and arced. This experiment can now be repeated with a radioisotope source in conjunction with the Faraday shell shutter mechanism discussed here-in. By removing all additional sources of electromagnetic radiation, clear evidence of Maxwell's displacement current would be observed.

6.2.3 Clarification of microscopic level physics of electrostatic induction

This topic is vital for electrostatic induction, especially as it could generate early warning of problems that may otherwise only be identified after rollout of the technology. The topic requires deep insight into quantum physics, and will have to be addressed by proper experts.

6.2.4 Comparison of conduction current charging of capacitors with electrostatic induction charging of capacitors

The research may be published, particularly to highlight the complexities of conduction current charging of capacitors as well as the importance on energy and exergy considerations.

6.2.5 Two capacitor paradox

Publish current research, primarily with a view of building credibility to enable collaboration with international experts in the field.

6.2.6 Other matters

Other matters that should receive attention, include:

- The possibility of electrostatic induction charging of single plate capacitor.
- The possibility of electrostatic induction charging of super- and ultra-capacitors.
- Arcing from a source to a target electrode may cause charge polarity reversal in the capacitor stack. Investigate the mechanism, impact and mitigation strategies.
- It was realised that capacitor stacks likely function as antennae, and should be treated as such to improve functioning. Investigate and recommend best practices.
- When charge is brought into and removed from a hollow conductor, energy can be generated at entry and at exit. This resonates with Faraday's law of electromagnetic induction. Maybe a Faraday's law of electrostatic induction should be formulated. This matter is an excellent research topic and may offer best practices to significantly increase output from electrostatic generators.

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