Design and Synthesis of a Robust Power Supply for Harsh Environments

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It all starts here ™

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Declaration

I, Gert Benadé hereby declare that this dissertation titled “Development and Synthesis of a Robust Power Supply for Harsh Environments” is my original work and has not been submitted elsewhere.

GJJ Benadé
5 February 2019
Potchefstroom

Acknowledgements

To Legh,

One of the last modern-day heroes….

Abstract

Research and control applications often takes place in harsh environments where equipment is exposed to less-than-ideal environmental conditions. This dissertation relies on a proven engineering process to design and synthesise a robust artefact suitable for deployment in harsh environments such as scientific and industrial applications.

Part of the design for this artefact is the flexibility in application it provides. More specifically does it provide continuation of research such as that which has been conducted at the Centre for Space Research at the North West University. This research programme on cosmic rays has been in operation since the late 1950s. It utilises neutron monitors as far south as Antarctica and with the highest latitude monitor located in the semi-desert of Namibia. Long term scientific data pertaining to space weather provides a sound scientific understanding of the environment in which our technology is required to operate.

Powering research and industrial equipment under harsh environmental conditions is a challenge to any design and requires a thorough understanding of both the environment as well as the engineering solutions required. The outcome of this research is the fully verified and validated design and synthesis of a power supply prototype suitable for deployment in a range of harsh conditions and accordingly, makes a significant contribution to, *inter alia*, neutron monitor-based research.

Keywords:

Harsh Environment, Power Supply, Robust Design, Adaptable Application, Cosmic Rays, Neutron Monitor, Long Term Stability, Scientific and Industrial Applications, Flexible Implementation.

Definition of Terms

Cold Boot

When a circuit, typically a micro-controller or computer circuit is powered up from a completely non-powered state. This is in contrast to a "warm boot" where an initialisation signal or instruction is passed to the processor or controller to reset all registers and clear all buffers/caches. During a warm boot, all power to the system is maintained. A cold boot entails switching the mains supply off, disconnecting all battery backup and after a required time, reconnecting the supply. This can clear stuck bits in memory cells caused by static discharge on sensitive components, memory clocking problems or interference.

Designed Life-span

All electronic components have a finite life-span based of factors such as hours-at-rated temperature, working voltage, design specification and environmental conditions. This term also refers to devices being superseded by improved technology (i.e. improvements in materials, manufacturing or assembly processes). Therefore, it also refers to outdated technology or practices where a component or system is no longer used since newer (more efficient or cost effective) alternatives exists.

Harsh Environment

Electronic equipment, and specifically scientific apparatus, more often than not operates in less than ideal conditions in terms of power supply stability and other environmental factors such as temperature, humidity and atmospheric conditions. Harsh environment can also refer to electro-magnetic noisy conditions which can adversely affect operation of electronic and electrical equipment.

Redundancy

An engineering term to describe the duplication of a component or sub-system within a device to ensure greater reliability of said device. This term may also refer to the duplication of entire systems for increased reliability in a particular application.

Relative Efficiency

Relative efficiency describes the highest efficiency of a specific topology or lay-out of a system compared to systems of more complex designs; to obtain the highest efficiency for a given level of system complexity.

Relevant Technology

Components, systems or methods pertinent to a specific area of research or application. This term also refers to standard practices relevant to modern day industry.

Topology

Referring to the configuration or layout of the various components of which a power supply for example, consist of. This term is also used to refer to the lay-out or interconnections of sub-systems within a system.

List of Abbreviations

AC – Alternating Current
ADC – Analogue to Digital Converter
ATX – Advanced Technology eXtended
CI – Configuration Item
COTS – Commercial Off-The-Shelf
CSR – Centre for Space Research
DC – Direct Current
DMM – Digital Multi-Meter
ESD – Electo-Static Discharge
EUT – Equipment Under Test
HMB – Human Body Model
HE-PSU – Harsh Environment Power Supply Unit
HF – High Frequency
HVAC – Heating, Ventilation and Air Conditioning
IC – Integrated Circuit
NM – Neutron Monitor
NWU – North West University
PCB – Printed Circuit Board(s)
PSU – Power Supply Unit
PTC – Positive Temperature Coefficient (PTC)
PWM – Pulse Width Modulation
RFI – Radio Frequency Interference
SMD – Surface Mount Device
SMPS – Switch-mode Power Supply(s)
TTL – Transistor-Transistor Logic
UPS – Un-interruptible Power Supply

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CHAPTER ONE

Background

This chapter outlines the parameters and scope of the research project *apropos* the design and testing of an application-specific power supply for harsh environmental conditions. Due to the fact that this research problem originated within a cosmic ray research environment, the proposed low voltage power supply is primarily intended for use with a typical neutron monitor (NM). However, the proposed power supply could equally be employed for a variety of functions including surveillance equipment, data acquisition and even remote monitoring stations etc. Regardless, this entails a design which must operate in a very specific environment; therefore this chapter also provides a background to terrestrial cosmic ray studies, neutron monitors and the environment in which these instruments normally operate.

Following this, a suitable research methodology is established which is wholly applicable to the actual investigation. Lastly, a general overview is presented in order to outline the various chapters that comprise this dissertation.

1.1 Research Context

Modern society is inextricably tied to the continued provision of technological services relying on electronic systems, specifically those operating in space. Examples of these are satellite systems such as the Global Positioning Systems (GPS and GLONASS) and communication platforms such as the Iridium network **[1,2]**. However, all of these technologies rely on radio frequency communication that make use of the electromagnetic spectrum **[3]**. As technology advances, so too does the need for energy efficiency increase, partly due to many systems being battery-powered. Correspondingly, the power levels at which these operate are decreasing. This causes the electronics to increasingly become sensitive to disturbances, especially under harsh conditions.

Typically, all wireless communication are subject to various aberrations including fading, reflections, shadowing and multi-path effects **[4,5]**. This also applies to radio frequency communications that pass between the earth's surface and space **[6]**. Figure 1.1 illustrates the typical operating environment for various technologies.

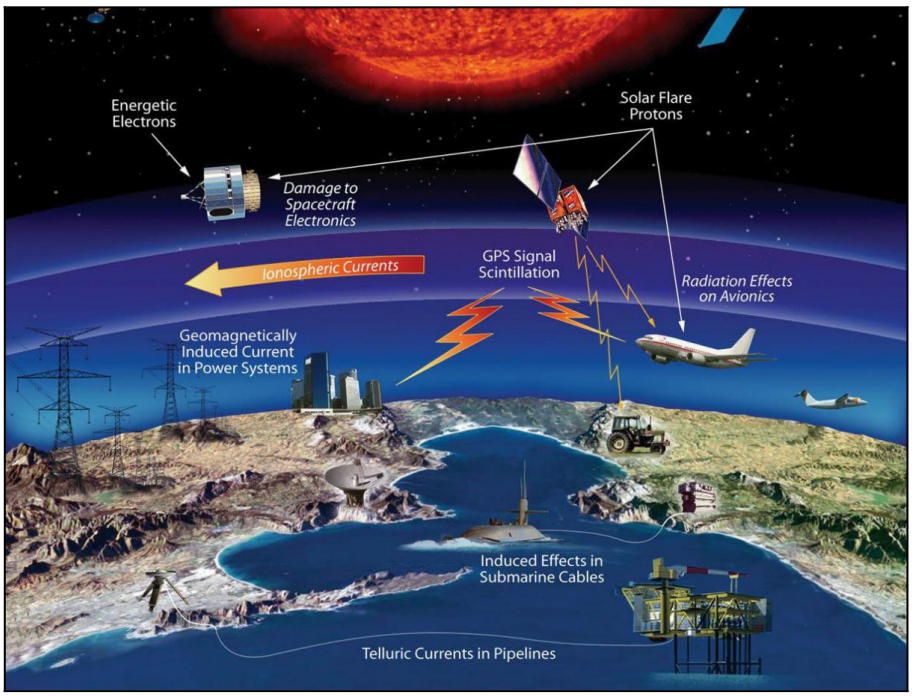


Figure 1.1 Typical Wireless Environment **[3]**

Figure 1.1 indicates typical equipment and signal paths that comprises the wireless environment. From this figure it can be surmised that technology operates under a wide range of environmental and electro-magnetic conditions.

The electro-magnetic conditions in space surrounding earth are commonly referred to as space weather **[7]**. In order to ensure reliable operation of the technology deployed on and around the earth, prevailing space weather must be predictable and the associated effects on equipment quantifiable. It therefore follows that studying space weather and its effects on technology helps to increase the stability and improve the operation of various technologies. Due to the scale of the prevailing conditions, amongst other factors, it is important to develop technology and especially research instrumentation of high quality. These must have stable, long-term performance characteristics to ensure that reliable data is obtained, thus enhancing the understanding of space weather.

Part of space weather studies are devoted to the study of cosmic rays. These high-energy particles travel through the cosmos and strike the earth's atmosphere. Such interactions produce, *inter alia*, neutrons **[8]**. These neutrons penetrate the atmosphere and by detecting and counting these particles with terrestrial-based neutron monitors an indirect measurement of the incident cosmic rays are made. The number of detected particles are proportional to the number and energy of cosmic rays interacting with the upper atmosphere of the earth **[9]**.

Figure 1.2 indicates global research stations where cosmic ray research using fixed neutron monitors is performed.

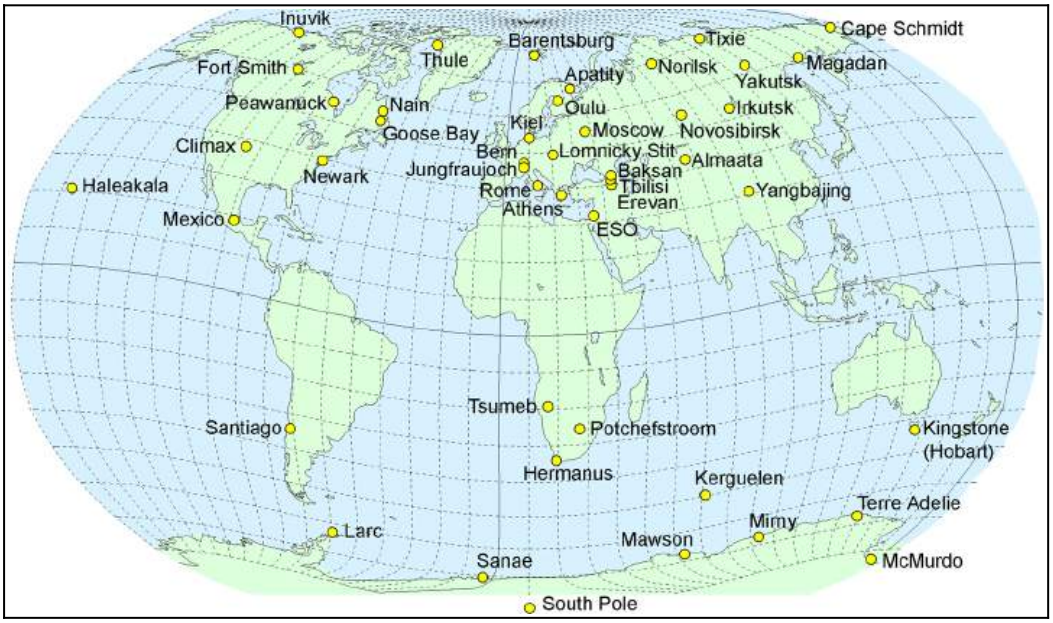


Figure 1.2 Global Neutron Monitor Sites for Cosmic Ray Studies **[10]**

The above map indicates the number of global research locations where neutron monitors are deployed. As these sensitive instruments are being operated in environments ranging from the Namib desert to the Antarctic, their design-criteria must take vastly different environments into consideration in order to ensure reliability of the equipment.

The Centre for Space Research (CSR) at the North-West University (NWU) has been involved in cosmic ray research since the 1950s **[10]**. It has employed a number of neutron monitors of different designs throughout the years in order to detect and count neutrons. The CSR directly operates stations in Tsumeb (desert), Potchefstroom (high altitude), Hermanus (coastal area) and Sanae (Antarctic). The resultant research data is hosted on their website **[10]** as well as on the International Neutron Monitor Database (NMDB) **[11,12]**.

In this context, two distinct types of neutron monitors are discerned. The first and most common are fixed neutron monitors for permanent installation and typically within a controlled environment such as a research facility. The second type of neutron monitors are portable and used for smaller short term monitoring and calibration purposes. Fundamentally, the construction and operation of the fixed type neutron monitor is similar to that of the portable system. The inceptive portable neutron monitor is known as the Calibration Monitor. This was developed in ca. 2002 with later versions of the same instrument known as the Mini Neutron Monitor developed during the period from 2009 to 2015 **[13,14]**.

Figure 1.3 shows the 2002/2003 portable neutron monitor known as the Calibration Monitor in contrast to the 2015 version of the portable version known as the Mini Neutron Monitor. Both these instruments consist of a detector “body” with an attached electronics “head”.

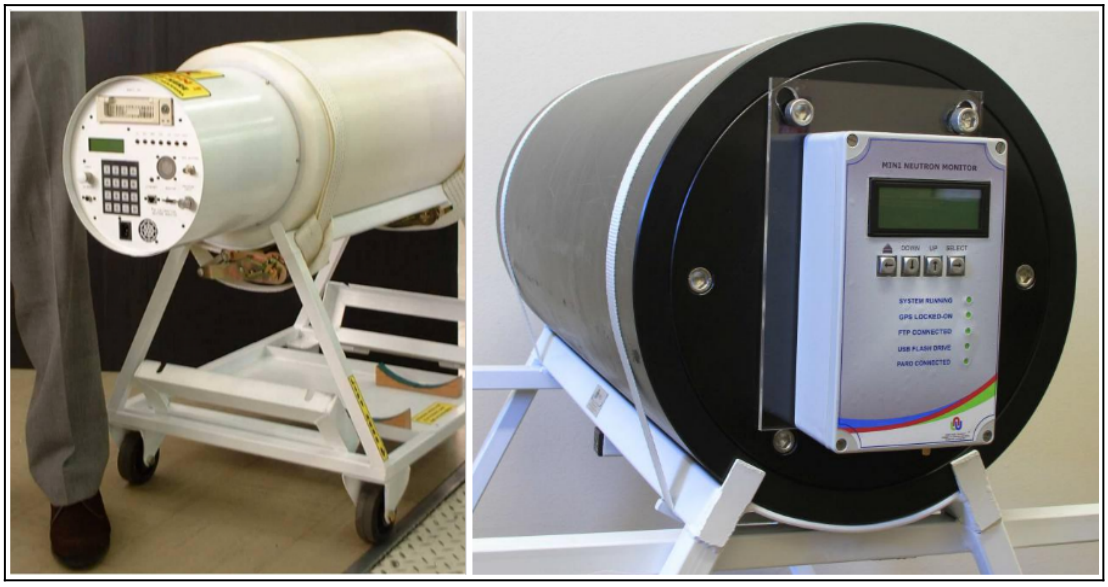


Figure 1.3 Calibration Monitor (ca. 2002) and Mini-Neutron Monitor (2015) **[9,13,14]**

Figure 1.4 represents the functional layout of a typical neutron monitor as described in **[9,13,14]**.

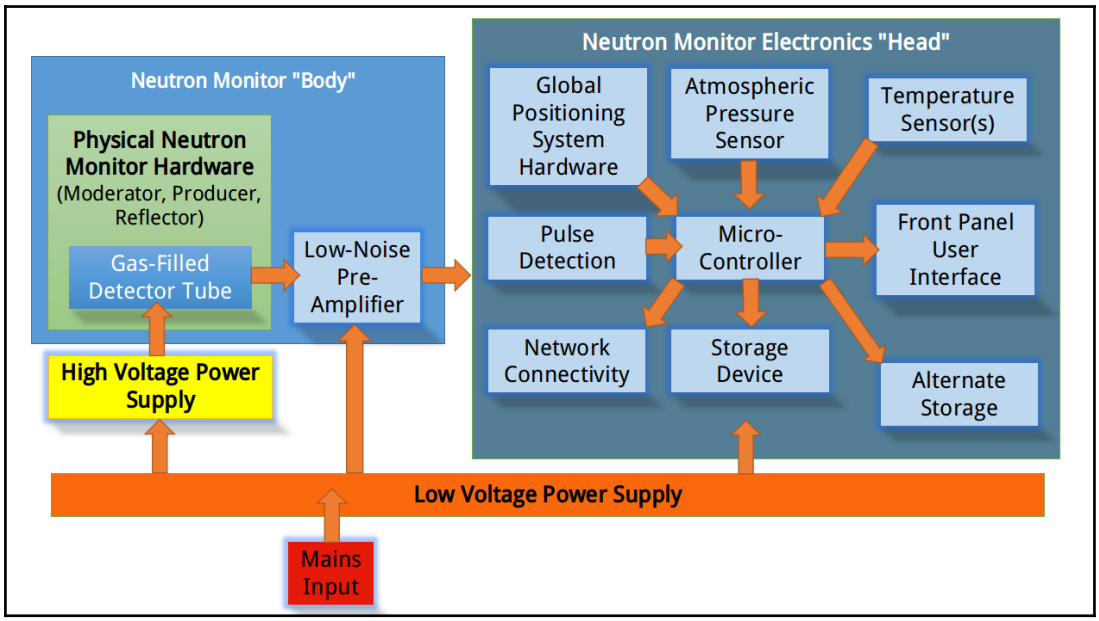


Figure 1.4 Functional Lay-out of a Typical Neutron Monitor **[14]**

The cut-away view of the mini neutron monitor is depicted in the following diagram.

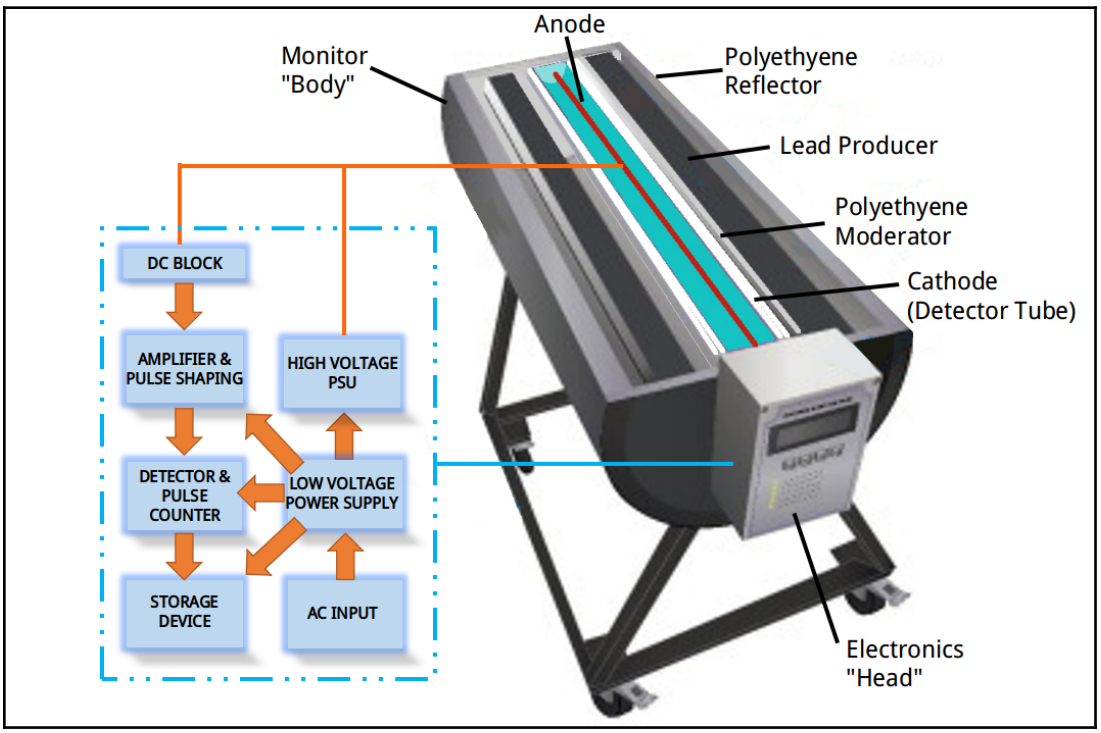


Figure 1.5 The Mini Neutron Monitor Cut-Away View **[9,13,14]**

In this dissertation, the physical mechanism by which neutron monitors operate is largely of secondary concern. Indeed, this predominantly constitutes an appropriate understanding of the physics involved in neutron monitoring and cosmic ray studies. The electrical operational parameters of a typical portable neutron monitor are set out in Table 1.1 below:

Table 1.1: Typical Mini Neutron Monitor Operating Parameters **[14]**

Operating Parameter	**Value**	**Tolerance**
Detector Operating Voltage	~1400 V_{DC}	±10 V_{DC}
Pulse Height	±500 μV_{DC}	±50 μV_{DC}
Pulse Duration	±7 µs	±1 µs

Considering the architecture and operational parameters of a typical neutron monitor as set down in Figure 1.4, 1.5 and Table 1.1, it is evident that the power supply plays a critical role in these instruments since the magnitudes of the operating parameters are minute. The development of a power supply for operation under ideal conditions would be a relatively simple task. However, electronic systems and specifically scientific and industrial instruments are deployed in geographically diverse and often harsh conditions. Therefore, it is important to establish a power supply capable of stable operation in not only clement environments but also extremely harsh and demanding environmental conditions such as deserts and the Antarctic.

1.1.1 Neutron Monitor Application

Neutron monitors are constructed and tested within the development and manufacturing environment and tested to conform to the required standards for cosmic ray research. This is performed alongside a fixed neutron monitor of known standard to ascertain factors such as count-rate and stability **[9]**. Upon completion, the monitor is transported by various means to the research location and commissioned.

Upon completion of the research objective (typically after sufficient data has been acquired), the monitor is transported to a new location or returned to the originating station. Both fixed as well as portable neutron monitors are deployed in geographically diverse environments as illustrated in Figure 1.2 and on many occasions, require a combination of transport methods for it to be installed at the research location. The typical transport life-cycle of neutron monitors is illustrated in Figure 1.6.

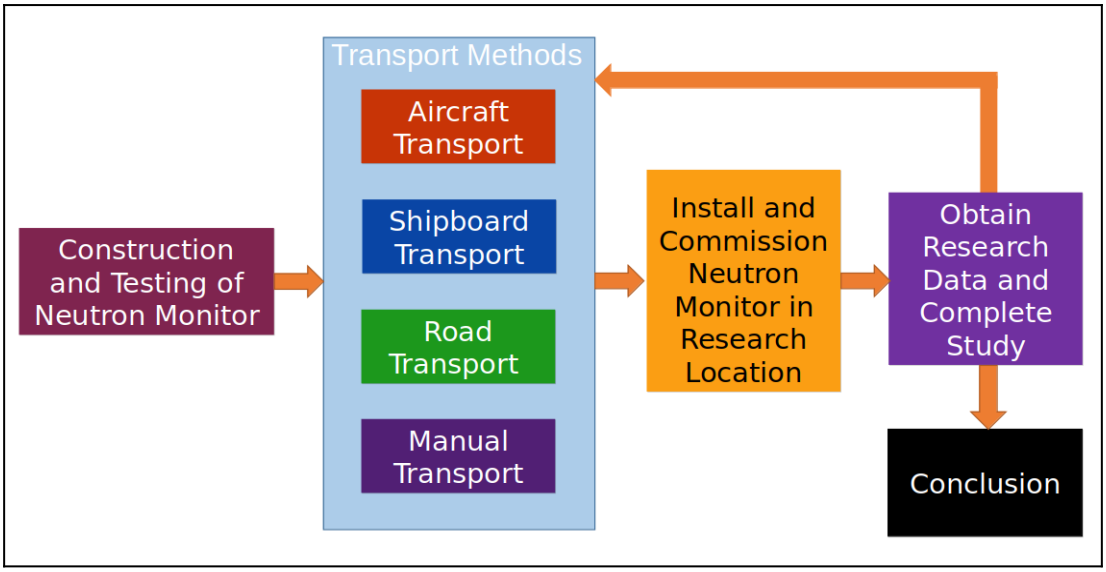


Figure 1.6 Typical Mini Neutron Monitor Transport Life-Cycle **[9,13,14]**

On many occasions the monitor is flown to the closest airport, transported by road and lastly, carried by hand to the point of installation. Thus, apart from the harsh environment found at a typical research location, the power supply design also needs to be able to withstand the impact of various forms of transportation.

Logistically challenging scenarios such as the distances between management stations and research installations, inclement weather conditions and transport costs are some of the factors that complicate maintaining a global neutron monitoring network. In order to reduce the impact of configuration management on the development, operation and maintenance of instruments, it follows that it is preferable to deploy only a single configuration item to all relevant locations.

The problem, therefore , is how best to design and synthesis of a power supply based on a single configuration item approach, capable of operation under a multitude of environmental extremes present during the transport and deployment of electronic equipment related to neutron monitors.

1.2 Problem Statement

With the foregoing background information in mind, the following research problem becomes evident:

> *Is it possible to design and synthesise a single configuration item (i.e a robust, low voltage, power supply) capable of being deployed in all environments in which neutron monitors are deployed?*

1.3 Objectives

The above research problem can be addressed by meeting the following objectives:

1. *Is it possible to design and synthesise a robust power supply which can withstand a range of specified harsh environments?*
2. *Can this envisaged PSU be designed with a view to ease manufacture by modular construction (including identification of readily obtainable components)?*
3. *How best may the envisaged artefact (PSU) be validated and verified in order to determine if the research parameters have been adequately addressed?*

1.4 Proposed Research

The focus of the proposed research is the design and synthesis of a power supply capable of operating effectively in a wide range of anticipated harsh environments.

This will be undertaken through a thorough literature study whereby harsh environments are clearly defined, how the synthesised artefact can be tested for reliable operation in these environments and against which international standards such testing should be performed.

Furthermore, an artefact will be synthesised based on a requirements analysis to establish the full span of physical requirements. Finally, the artefact will be validated and verified and conclusions drawn.

1.5 Research Methodology

The research presented in this dissertation follows a research methodology similar to that conducted by Krige **[15]** and is outlined below in Figure 1.7.

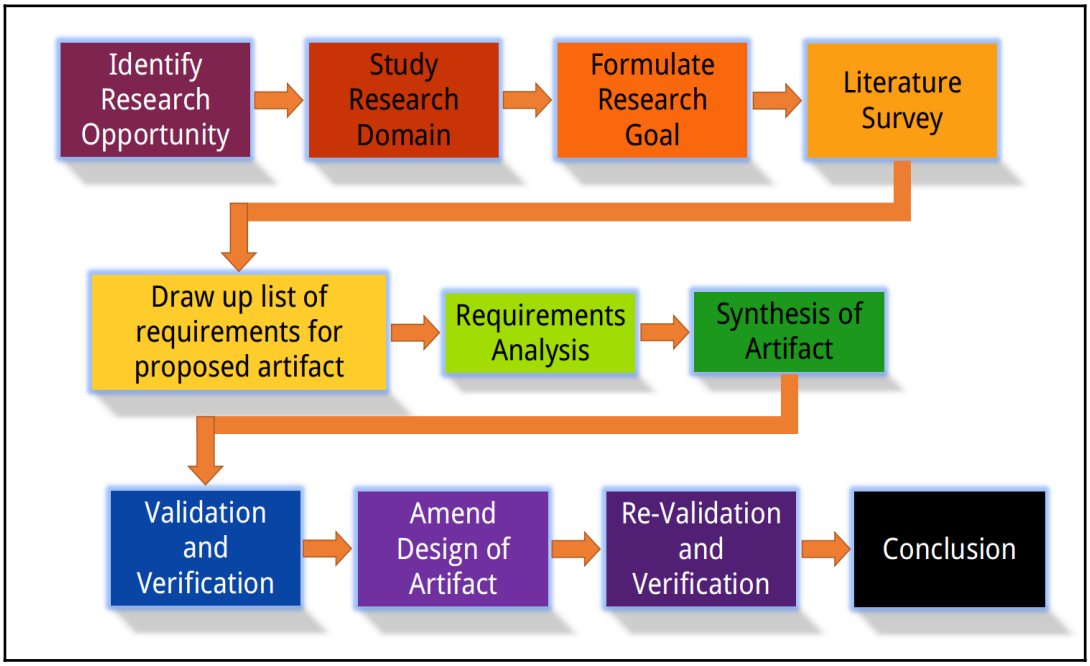


Figure 1.7 Methodology of Research [16]

In order to answer the research question satisfactorily, the following actions will be undertaken:

- A requirements analysis will be conducted to ascertain the requirements of a neutron monitor power supply suitable for deployment in geographically diverse locations ranging from desert locations to Arctic/Antarctic conditions. Once the requirements, both electronic as well as mechanical have been established, the various power supply topologies will be investigated for suitability vis-a-vis harsh environments as well as other pertinent neutron monitor requirements;
- These requirements will be used to synthesise an artefact, satisfying the research question and objectives identified in sections 1.2 and 1.3;
- A process of validation and verification will be used to quantify the artefact's design and performance. The validation process will confirm the functionality of the synthesised power supply whereas the verification process will ensure its operation over the entire range of environmental parameters. All relevant data will be reported in the form of graphs and tables reflecting the artefact's performance under the defined harsh environmental conditions;
- A concluding chapter will summarise the research performed in this dissertation. In this context, recommendations will be made for future research and enhancements to the design will be suggested.

1.6 Delimitation of Research

This research does not intend to explain the fundamental physics involved in space weather, nor the detailed operation of neutron detection or neutron monitors specifically in cosmic ray studies. Information provided thereto serves only as background to the problem statement as laid out in section 1.2.

The high voltage required by the neutron detector tube **[13]** is provided by a separate high voltage power supply and does not form part of this investigation.

As part of the verification process, the artefact will be subjected to temperature, vibration and electro-static discharge tests in order to quantify its conformity to the pre-defined specifications of the requirements analysis. Where possible conformance to international standards will be sought. However, similar testing schemes may be utilised based on the availability of test and measurement equipment.

However, because the synthesis of the artefact is purely a proof-of-concept design, the effect of altitude and humidity on the artefact will not be investigated. During the design process, will components however be selected to the highest of specifications in order to maximise the artefact's robustness. The artefact is only a proof of concept design and will require conversion into a final artefact suitable for production within a suitably rated and appropriate enclosure.

1.7 Assumptions of Research

It assumed that the reader is familiar with the process of computer aided design and manufacturing techniques. Chapter 4 provides technical information regarding the design and synthesis of the artefact.

It is also assumed that all technical information (e.g. data-sheets) as supplied by reputable manufacturers of commercial off-the-shelf (COTS) electronic components have been correctly verified and are valid and may be employed directly in the synthesis of the proposed artefact without having to retest the supplied parameters.

1.8 Overview of Research

This dissertation is laid out in six chapters and is outlined in the following section:

Chapter One – Background

Provides a short background on cosmic rays and neutron detection, specifically concerning cosmic ray studies. This is done purely as background to the research problem also defined in this chapter.

Chapter Two – Literature Study

The literature study reflects research on what constitutes harsh environments as well as harsh environments for typical neutron monitors and their power supplies. Chapter 2 also researches various types of stresses found in harsh environments as well as a number of power supply topologies. Furthermore, corrective and preventative actions against these stresses are researched in order to form a full understanding of designing a power supply for harsh environments.

Chapter Three – Power Supply Design

This chapter deals with the Requirements Analysis where the individual components for a harsh environment power supply such as required by neutron monitor are evaluated. The final list of requirements for said power supply will be reviewed and motivations for the chosen layout will be given. It takes practical power supply design into consideration and an initial block diagram/functional layout is drawn up in order to move toward a synthesized artefact that is based on the specified requirements.

Chapter Four – Power Supply Synthesis

From the preceding research, a block diagram is drawn up, suitable components selected and a physical artefact is synthesised using industry standard procedures such as Spice, Computer Aided Design and Manufacturing processes. Full information including circuit diagrams are provided in order to facilitate the future synthesis of this artefact.

Chapter Five – Validation and Verification

This chapter details the validation and verification process followed in order to determine if the research question has been answered successfully. Results that were obtained during this process are summarised. The chapter ends with a conclusion based on the obtained data.

Chapter Six – Conclusion, Recommendations and Contribution

This final chapter summarises the research done in this dissertation and suggests improvements of the artefact through further research. Furthermore are the contribution of this research to the body of knowledge discussed.

CHAPTER TWO

Literature Study

This chapter provides an in-depth literature study and addresses the problem statement as formulated in the previous chapter by researching various aspects of power supply design, testing and real-world application. Harsh environment stress factors are identified in order to describe what constitutes a harsh environment, and describes which international standards can be used to test against. Furthermore, preventative actions are investigated to mitigate effects of the identified stresses. Different types of power supplies and topologies will be analysed and suitability for scientific equipment and deployment in harsh environments established. Finally a neutron monitor power supply (as used in a harsh environment) will be discussed to identify its strengths and weaknesses.

2.1 Neutron Monitoring

The majority of neutron monitoring equipment around the globe is, at the very least, in excess of a decade old, although some upgrades have been initiated. For example, the neutron monitoring network of the Centre for Space Research (CSR) of the North West University (NWU), has been in operation since the 1950s **[10]**. As with all electronic systems, these instruments have a finite life-span and are slowly approaching the end of their original design life. The fact that these instruments have operated on a continuous basis with no or few interruptions for more than six decades attests to the high build-quality and thorough engineering practices that went into both the design and manufacture of the individual components, sub-systems and systems as a whole. Another factor contributing to the longevity of these systems is the good maintenance practices which have been employed in the upkeep of these instruments and stations.

Since many of these instruments operate in harsh environments, the ageing tempo is dramatically accelerated **[17,18]**. Factors such as temperature, humidity, vibration and electro-magnetic interference (radio frequency, static electricity and irregular power supply) **[19]** all contribute significantly to the ageing and subsequent failure of these instruments.

Experience has shown that these instruments, although originally intended to operate in a stable environment, are sometimes used in less-than ideal conditions. Researchers often need to alter one specific facet of an experiment, such as humidity or temperature to study its effect on terrestrial cosmic ray counts. As discussed in Section 1, the physical processes taking place inside a neutron monitor are minute. In this

context, reactions happen on an atomic level and sensitive electronics are used to detect, amplify and count cosmic rays reaching the detector from space. If an instrument is subjected to less-than ideal environmental factors, or a harsh environment in general, the operation and data integrity of the instrument can be severely affected. Often the researcher may have only a have single chance to observe a specific event, requiring equipment to be absolutely reliable.

External factors such as humidity or temperature that typically affect neutron monitor hardware can be limited or controlled to a certain extent. Certain research scenarios do not offer this and causes undue strain on equipment. This can be classified as harsh environmental conditions.

Because the whole neutron monitor system is dependent on a well-regulated power supply to perform its various functions, many experiments have failed completely or incomplete data were captured due to problems relating to poor power quality or prevailing harsh environmental conditions **[20-23]**.

2.2 Typical Operating Conditions

The large number of cosmic ray monitoring stations globally (Figure 1.2) are placed in regions where environmental conditions vary considerably. As an example, the cosmic ray research group at the NWU directly operates neutron monitors as far north as the northern parts of Namibia, and as far south as the SANAE IV research base on Antarctica **[10]**.

Heating, Ventilation and Air Conditioning (HVAC) systems are generally used to maintain a constant temperature inside research stations. However, the deployment of neutron monitors often requires these instruments to be exposed. An example of such a scenario was during the 2006/2007 take-over period when the SA Agulhas research vessel visited Antarctica for the yearly relief mission. A calibration neutron monitor was placed outside the SANAE IV base and cosmic rays were counted for a period of two weeks. Average instrument temperatures of -15°C were recorded outside the station where the instrument was operating **[22,23]**.

Similarly a mini-neutron monitor was sent to Thailand on loan to a research group. The unit was deployed at the Princess Sirindhorn research station on the Doi Inthanon mountain at an altitude of 2560 meters **[20]**. It operated in temperatures reaching 50°C with an ambient relative humidity of 90%. Due to the use of high voltage **[13,14]** in the neutron monitor, the extremely high humidity also had a negative impact on the reliable operation of equipment. Typically, moisture enters the system, through ventilation ports and forms

conductive paths on components and printed circuit boards (PCBs). This causes leakage currents and unreliable operation due to high voltage flash-over **[24,25]**.

Neutron monitors have also been used to measure cosmic rays on-board aircraft at high altitudes. Because aircraft-borne equipment experiences rapid changes in pressure and temperature, from ground level to high altitudes in a short time-span, such changes can have negative effects on components such as aluminium capacitors **[26]**. Likewise storage and transport conditions of an inactive unit also greatly affect the long term reliably of devices **[27]**. These should not be over-looked when specifying packaging, storage or transport parameters.

As stated previously, the typical operating conditions for neutron monitors are quite varied. Based on experience with neutron monitor power supplies, the preceding information can thus be summarised into the following environmental stress factors. These are listed in order of severity and all play a role in the performance of neutron monitors and especially power supplies of neutron monitors:

1. Electrical / Electronic / Electrostatic stresses;
2. Temperature stresses;
3. Mechanical stresses;
4. Humidity;
5. Altitude.

The design and synthesis of a harsh environment power supply as set out in this dissertation must therefore be cognisant of these factors.

2.3 Power Supply Metrics

Power supplies must be tested against a number of standards for proper performance evaluation. These standards are important to define the performance and capabilities of a power supply intended for a particular application and, by way of example, allows engineers to compare power supplies of different topologies.

In order to evaluate the performance of a particular power supply, or compare different power supplies, a number of standard parameters are defined **[28]**. Table 2.1 lists the typical power supply metrics.

Table 2.1 Power Supply Metrics and Descriptions **[28-33]**

Metric	Description
AC Inrush Current	The instantaneous current drawn when the power supply is turned on from a un-powered state
Line Regulation	The change in output voltage over the entire input range while the output load is constant
Load Regulation	The change in output voltage of a power supply while the load is varied of its entire range. Input voltage is constant during this test
Drop-out voltage	Minimum input voltage that is require to maintain output voltage(s) at nominal values
Full Load	The maximum continuous output current or wattage a power supply is rated for at the nominal output voltage(s)
Galvanic Isolation	The input and output of a power supply has no ohmic connection and can be achieved by means of a transformer or opto-coupler
Power Factor/Apparent power (V_{RMS} x A_{RMS})	Phase angle between voltage and current on input of power supply expressed as Cos θ. Used to express the ratio between input voltage and current and how closely it matches a perfect load's i.e. pure resistive load
Switching Frequency	Used for determining noise/interference such as harmonics and Radio Frequency Interference
Total Harmonic Distortion (THD)	The quantity of multiple harmonics of the fundamental switching frequency present on the output of a power supply
Power Supply Noise	All other frequencies not part of the specified output voltages of the power supply
Standby Power	Required for IEC62301 and Energy Star Compliance – Consumption during standby. Used to quantify energy saving while plugged in but not actively powering a load
Operating Temperature	Temperature span in which a power supply can be operated safely without risk of damage or malfunction
Operating Junction Temperature Range	Specify maximum silicon temperature of switching element for safe-area operation
Storage Temperature Range	Indicates temperature range for safe storage of power supply. Generally has a wider range than operating temperature
Altitude	The maximum altitude at which a power supply can be operated without derating due to cooling or component restriction
Lead Temperature (Soldering, 10 seconds)	Maximum solder temperature during manufacture or repair of components or sub-systems

The metrics listed in the above table allow comparison of specific characteristics of various power supplies to establish suitability for a particular application, or the determining of factors such reliability and efficiency in a specific application.

2.4 Power Supplies

All electronic equipment is supplied by electrical power in some form. In this regard, the power supply plays a critical role. Power supplies transform the supplied power to that required by the load or target device. Without a stable, well-regulated power supply, no instrument can perform to its full specification and malfunction or permanent damage becomes possible. As already stated, the high voltage required by the neutron detector tube **[13,14]** is provided by a separate high voltage power supply and need not be investigated in the context of this dissertation.

Since neutron monitor (NM) micro-controller and storage systems require direct current (DC), low voltage power **[13]**, the following section elucidates the functioning of the different types of such power supplies. This is done to establish a foundation for the later design of the artefact.

2.4.1 Direct Current (DC) Power Supplies

In terms of fundamental operation, are three main types of direct current power supplies distinguished **[34-36]**:

- Unregulated;
- Linear;
- Switch-mode.

2.4.1.1 Unregulated Power Supplies

An unregulated power supply is the most basic type of power supply and merely converts one voltage level to another, without any control over the output. This type of power supply is typically used in applications where secondary control or regulation is provided and where the output of the unregulated power supply is of little consequence to the system being powered. Figure 2.4 shows a basic unregulated power supply with optional rectification.

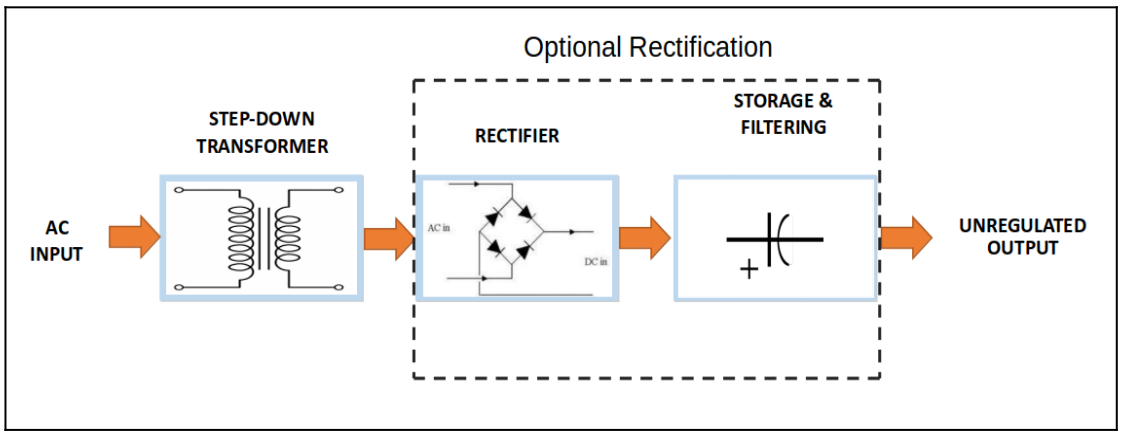


Figure 2.1 Basic Unregulated Power Supply **[34,35]**

This type of power supply is the cheapest, with very low component-count and complexity and generally only performs bulk conversion of mains voltage to low-power alternating current. Depending on the application, a simple rectification scheme might be incorporated to provide low power, unregulated, unstabilised direct current. The output voltage of an unregulated power supply is generally directly proportional to the input voltage.

As such this type of power supply is not suitable for scientific equipment since no regulation is provided. Equipment such as neutron monitors can not be powered by this type of supply since the micro-controller, for example, requires a stable power supply **[13,14,22,37]**.

2.4.1.2 Linear Power Supplies

Linear power supplies, in contrast, consist of a similar configuration as an unregulated supply but contains an additional regulating element and supplemental storage components on the output. The transformer can either be step-up or step down depending on the application. The rectifier is generally made up of a number of diodes, although actively switched MOSFET transistors can also be employed to reduce rectification losses that would otherwise be present in diodes **[38]**. This, however, complicates the design and is generally not used unless the design-criteria requires the rectifier to be an absolutely low-noise and low-loss supply.

Figure 2.5 depicts a typical linearly regulated power supply. The incoming mains is stepped down (or up, dependent on application) and rectified into a pulsating direct current. A large value filter capacitor smooths the pulsating direct current and a linear regulator regulates the voltage to a pre-set value. Additional filtering and storage is provided by another capacitor to improve the transient response of the linear regulator.

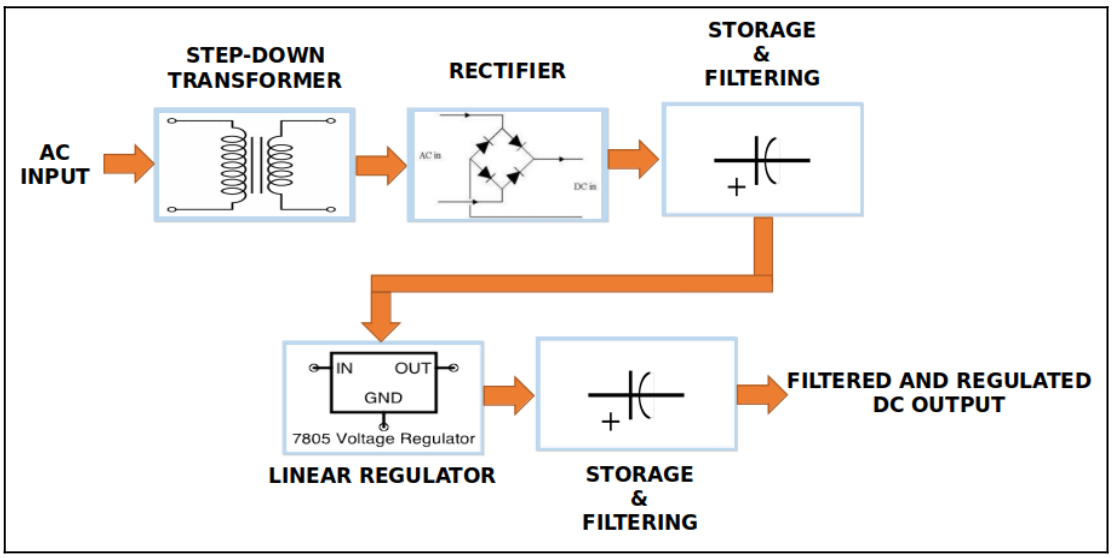


Figure 2.2 Basic Linear Power Supply **[34,35]**

In general, linear power supplies are very simple in design and, therefore, easy to develop and maintain. Since the design has a low component count, these supplies are also highly reliable **[34-36]**. Component values are often over-specified **[34]**, ensuring ample robustness without increasing complexity or cost dramatically. The financial out-lay for the transformer increases dramatically with up-scaling and over-specification and should thus be carefully considered.

The output from a carefully designed linear power supply is generally considered to be well regulated since no switching of stored energy takes place. Noise on a linear power supply output is negligibly small and is typically between 0.005% and 0.2% of the full-scale output **[39]**.

Due to their simplicity and fundamental operation, linear power supplies are not very efficient. The dissipation of excess energy as heat in these types of supplies typically result in an efficiency of only 30% to 60% **[36]**. For this reason linear power supplies are undesirable for battery-or portable powered applications. Linear regulators are only employed in instances where the design requires a low noise power supply or where low-component count is required. Typical applications for linear power supplies are sensors, low-noise amplifiers, data storage devices and radio frequency (RF) applications **[41,42]**.

2.4.1.3 Switch-Mode Power Supplies

Another type of regulator functions through a principle referred to as switch-mode power-control (SMPS) **[33,43]**. These devices make use of a switch, typically a transistor, to switch energy stored in a capacitor or

inductor. The output of this switching device is then filtered and smoothed and can be accurately controlled via a feedback network **[43-45]**.

With increased load conditions, the switch provides more energy during each on-cycle, thereby increasing the output voltage and preventing a drop in the voltage supplied to the increased load. When the load reduces, the average energy supplied by the pulses are accordingly reduced, thereby maintaining precise control of the output voltage **[45]**. This method of switch-mode power control is generally known as Pulse Width Modulation. Figure 2.6 depicts the typical switch behaviour of a switching element of during Pulse Width Modulation (PWM) regulation:

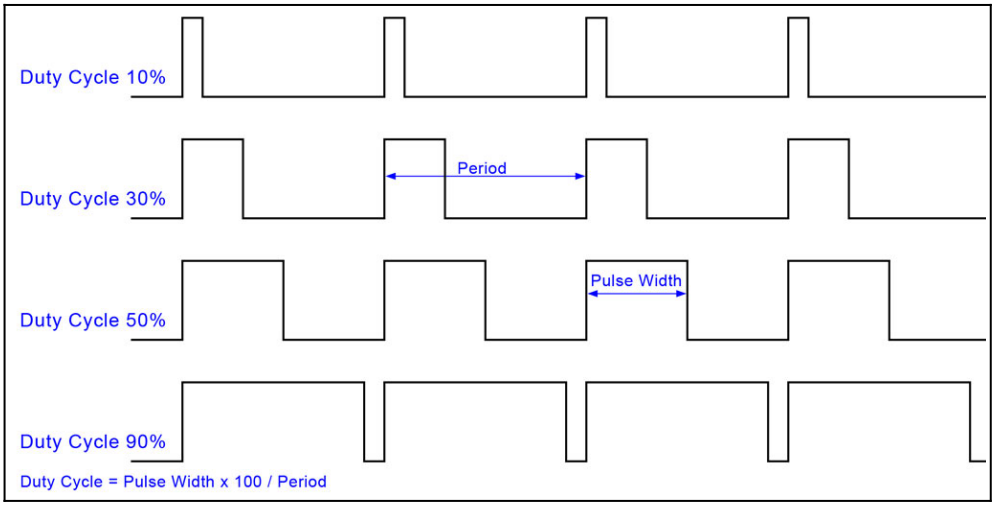


Figure 2.3 Pulse Width Modulation Wave-forms for Different Duty Cycles **[45]**

Various designs exist to transform power using switched power-control. In contrast to linear power supplies, SMPSs are highly efficient and typically operate at 70% or higher efficiency **[46]**. This is advantageous when the power budget of a device is limited, such as is the case with battery powered equipment.

Per Watt-delivered, SMPSs are orders of magnitude smaller and lighter than comparable linear supplies **[46]**. This makes them highly preferable to linear regulator technology in most applications. SMPSs have a high component count, are moderate to highly complex and require special design considerations to increase reliability **[46]**. However, due to modern advances in switch-mode power supply technology, cost has decreased dramatically making SMPSs competitive with linear power supplies in terms of pricing and reliability.

A downside to power supplies of this type is the electrical noise they generate. Since stored energy is switched at high frequency, radio frequency noise is generated which must be handled accordingly. Noise

sensitive equipment might not operate correctly when powered by SMPSs and generally require additional filtering. Figure 2.7 shows a basic switch-mode power supply.

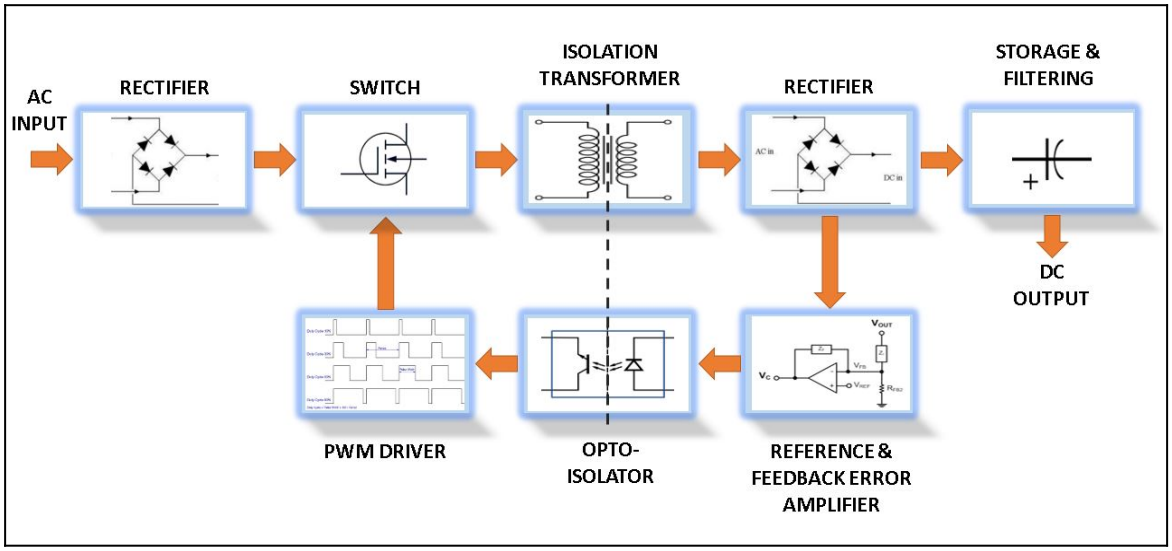


Figure 2.4 Functional Diagram of a Switch-Mode Power Supply **[33,45]**

The basic topology of a switch-mode power supply as depicted in figure 2.7 operate on a macro level as follows **[45]**:

Applied mains voltage is directly rectified by a suitable rectifier and stored in a reservoir capacitor. This capacitor is rated for more than the typical peak value of the rectified mains voltage. A switching element, typically a MOSFET transistor is controlled by a dedicated Pulse Width Modulation (PWM) driver. This transistor switches the stored energy into a suitable high frequency transformer.

The output of the transformer is rectified by a high frequency rectifier such as a Schottky diode. This rectified voltage is then filtered by use of a capacitor and inductor network. The energy delivered by the switch to the transformer is controlled by the reference feedback error amplifier. Factors such as width, frequency or position of the pulses are accurately controlled to vary the output voltage in accordance with load conditions .

2.5 Comparison of Basic Power Supply Types

The preceding information described the basic types of power supplies. Table 2.2 summarises the properties of the three basic types of power supplies:

Table 2.2 Typical Values for Comparison of Basic Power Supply Types **[88,91]**

Power Supply Properties	Unregulated Power Supply	Linearly Regulated Power Supply	Switch-Mode Power Supply
Circuit Design	Simple	Moderately Complex	Complex
Part Count	Low	Medium	High
Load Regulation	±10% (½ load to No Load)	0.005% to 0.2%	0.05% to 0.5%
Line Regulation	Directly Proportional to AC Input Changes	0.005% to 0.05%	0.05% to 0.2%
Ripple (RMS)	0.5V to 5V	0.25mV to 1.5mV	10mV to 25mV
Transient Recovery	Not Available	50-100 microseconds (No Load to Full Load)	300 microseconds (½ Load to Full Load)
Efficiency	90 - 95%	40 - 60%	70 - >85%
Hold-up Time	None	1-2 milliseconds	15-30 milliseconds
EMI	Very Low	Very Low	High
Leakage	Very Low	Low	High
Cooling	Convection	Convection or Fan	Convection or Fan
Weight (Power to Weight Ratio)	Heavy (Low)	Heaviest (Low)	Light (High)
Power Factor	0.6 - 0.7	0.6 - 0.7	0.6 - 0.7
Isolation Yes / No	Typically Isolated	Typically Isolated	Mostly Isolated
Input Voltage Range	0 - 125V_{AC} 0 - 250V_{AC} Output directly proportional to input	105 - 125V_{AC} and/or 210 - 250V_{AC}	90 - 132V_{AC} and/or 180 - 264V_{AC}(without PFC) ---------- 90 - 264V_{AC} (with PFC)

As indicated in the above table, the properties of each topology are quite varied. The choice of power supply type is therefore highly application-specific; for power supplies employed in scientific equipment (neutron monitors), unregulated power supplies are not a viable option due to their intrinsic instabilities and unregulated output.

Since many systems deployed in harsh environments also need to be energy efficient due to their reliance on battery or solar power, linearly regulated power supplies are less than ideal due intrinsic losses. Furthermore, linear regulators don't always provide flexibility in terms of output adjustment or current limiting which reduce the ease of implementation in designs. Conversely, SMPSs are by far the most efficient and compact. Through careful design, SMPSs can be equally reliable. These factors makes these types of supplies well suited for many applications.

The following section will therefore undertake an in-depth study of the different switch-mode topologies in order to establish each topology's suitability for a harsh environment power supply as what is required by neutron monitors.

2.6 Switch-Mode Power Supply Topologies

A large number of switch-mode power supply sub-types exist. As many as eighteen different topologies, or variations are identified by one manufacturer alone **[47]**. Although these all operate via switch-mode principles, the lay-out of each sub-type differ dramatically and have each have different levels of complexity and application. The following section will provide an overview of the most applicable types in the context of general use and possible harsh environmental deployment **[45,47]**.

2.6.1 Buck Regulation

A Buck regulator (Figure 2.8) topology is a type of switch-mode power supply where the output voltage of the regulator is lower than the input voltage **[45]**. Buck Regulators are typically used in applications where a portable device is being powered or charged from the mains supply or in battery powered systems where the supply is higher than the required voltage.

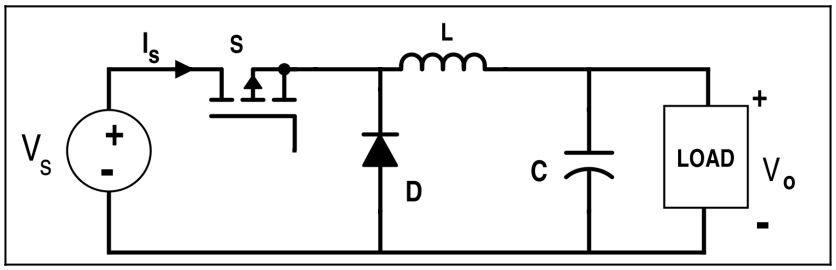


Figure 2.5 Basic Buck Regulator Topology **[45]**

In this topology, the switching element is in series with the power supply of the circuit and is controlled in such a way that the input voltage is proportionally "chopped" or switched off, based on the required output voltage. The output can therefore only be lower than the input. The function of the inductor in this topology is purely to "smooth" the switched voltage. The capacitor aids in this smoothing. Diode D, protects the input against short circuit during the ON time of the switching element S.

2.6.2 Boost Regulation

Boost regulators, as the name implies, boost the input voltage of the regulator to a higher value. These types of regulators are typically found in devices that requires high voltage as is the case with fluorescent tubes in liquid crystal displays' back-lights, high voltage power supplies for scientific equipment and energy harvesting electronics **[33]**. Figure 2.9 indicates the basic lay-out of a Boost regulator:

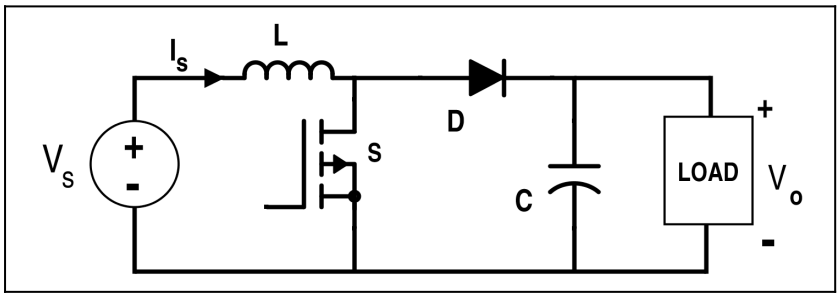


Figure 2.6 Basic Boost Regulator Topology **[45]**

In contrast to the buck regulator, where the inductive element only smooths the switched voltage, the inductor in the Boost topology, plays an active part in the boosting of the supply voltage. During commutation, switch S conducts current and energy is stored in the inductor's magnetic field. When switch S opens, the collapsing magnetic field induces a forward, voltage in the windings of the inductor which is conducted and rectified by diode D.

During the commutation period when the magnetic field in the inductor is built up by current flowing from the input, no high voltage is produced by the inductor. During this time, the output capacitor C smooths the output voltage by supplying the load with stored charge. Due to the collapsing magnetic field, the output voltage of this circuit is higher than the input, hence the term Boost Regulator.

2.6.3 Buck/Boost Regulation

These types of switch-mode regulators can provide voltages from as low as just above 0 Volt to a voltage higher than that of the supply. As the name suggests, they can both operate in the buck configuration as well as in the boost configuration **[45]**. In essence there is little difference between Buck-Boost and Fly-back regulators. In Fly-back regulators, a transformer is employed as an inductive element, whereas in Buck-Boost regulators, a single inductor is used. With the inductor in this design, space, weight and cost is saved, but at the expense of galvanic isolation being sacrificed **[43]**.

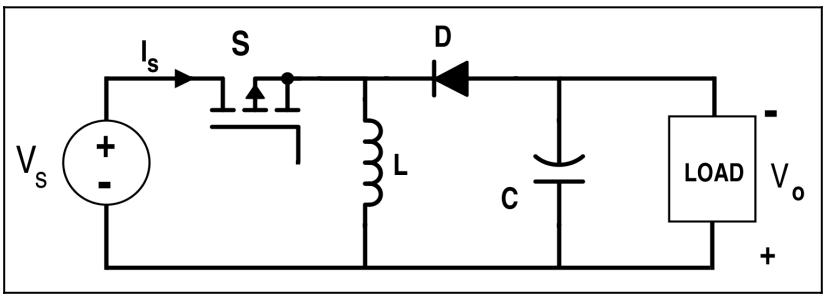


Figure 2.7 Basic Buck/Boost Regulator Topology **[45]**

In the above circuit (Figure 2.10) switch S is controlled based on application-specific requirements. Two types of switching schemes are employed namely continuous conduction mode and discontinuous conduction mode **[33]**.

With continuous conduction, the current in the inductor never goes to zero. Hence the inductor partially discharges earlier than the switching cycle. In discontinuous mode, is the inductor allowed to discharge completely with each switching cycle causing the current through the inductor to be reduced to zero at the end of each cycle. In this way the circuit can operate in both Buck as well as Boost Mode. A disadvantage of this topology, is that the output is negative with reference to the input.

2.6.4 SEPIC Regulators

Another common topology of switch-mode power-control is the Single Ended Primary Inductor Converter (SEPIC). Similar to the Buck-Boost topology, the output of this regulator can be greater, equal or less than at the input. This topology can also accept input voltages higher, equal, or lower than the output, making it ideal for use with batteries as power source **[48,49]**.

Since a battery discharge-curve permits a situation where the terminal voltage of a battery being higher, equal or lower than the output of the power supply, this type of regulator can provide output during any state-of-charge of a battery. In contrast to a buck-boost regulator, the output of the SEPIC topology is of similar polarity than that of the input.

The output of this type of switch-mode regulator can be controlled by varying the duty cycle of the switching element (as explained by Figure 2.6). Figure 2.11 indicates a basic SEPIC switch-mode converter.

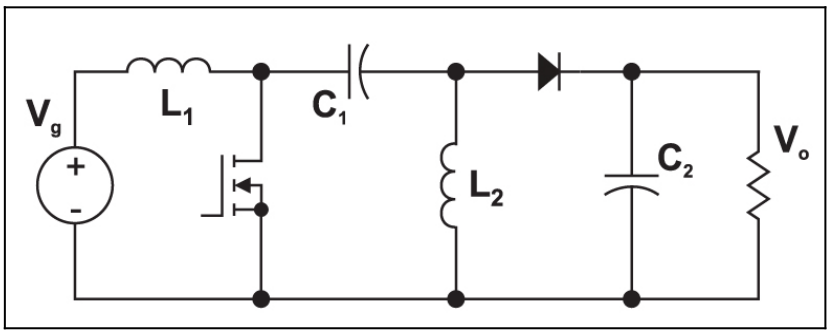


Figure 2.8 Basic SEPIC Regulator Topology **[45]**

In the SEPIC topology (Figure 2.11), L_1's magnetic field is charged during Continuous Conduction Mode (similar to the Buck/Boost Regulator) commutation of the MOSFET switch, with current flowing via L_2 and into the load. When the transistor S, stops conduction, the energy stored in L_1 is transferred via the coupling capacitor C1 to the diode for rectification. During this time the energy in L_2 is also conducted via the diode for rectification. This results in a lower output ripple and better stability in the circuit since the two inductors are generally packaged together and shares a common core (and magnetic field), albeit at the sacrifice of board space for the bigger, coupled inductor and a more complex topology **[33,45,50]**.

2.6.5 Other Switch-Mode Power Supply Topologies

As previously stated, a large variety of switch-mode regulator topologies exist. These are mostly variants of the four types identified in the preceding section except for the use of multiple transistor switches and high frequency ferrite core transformers instead of discrete inductors. Using transformers instead of inductors provide electric isolation between the input and output of the power supply.

2.7 Hybrid Topologies

A fourth major group of power supply topologies exist, although not commonly found in general use due to their complexity as well as increased cost. These are referred to as hybrid power supplies and combines parts of a linear topology with that of switch-mode power supply design.

Since each of these two types of power-control offers advantages, they can be combined to offer a power supply that is very application-specific with very complex specifications but at an increased level of complexity and cost. These types of power supplies are typically found in medical equipment, laboratory equipment as well as high-end audio applications.

In applications such as neutron monitoring, secondary concerns such as complexity and cost is offset by the increased reliability and stable output of a hybrid topology. This makes it a viable option for scientific equipment due to its robustness and combining strengths from both linear and SMPS topologies.

2.8 Power Supply Isolation

All power supplies form a link between the mains supply (power source) and the equipment being powered. In certain applications such as medical equipment, it is required that complete galvanic isolation be obtained to increase the safety of the equipment or to eliminate electrical noise or interference. The following section details the differences and applications of non-isolated and isolated power supplies.

2.8.1 Non-Isolated Power Supplies

For low-complexity designs where cost or physical size is the main consideration, non-isolated power supplies offers a good compromise. These types of supplies however offers no galvanic isolation between the input and output and more readily pass noise from the supply through to the equipment being powered **[99]**. Under fault conditions the full mains potential can also be passed to the equipment which can lead to damage and a potentially dangerous situation.

Non-isolated supplies (Figure 2.12) are generally found in double-insulated devices and powers items where noise or a fault condition will not affect the safety of the device. Power supplies of this type are generally low current devices, only suitable for powering devices such as small circuits and night lights.

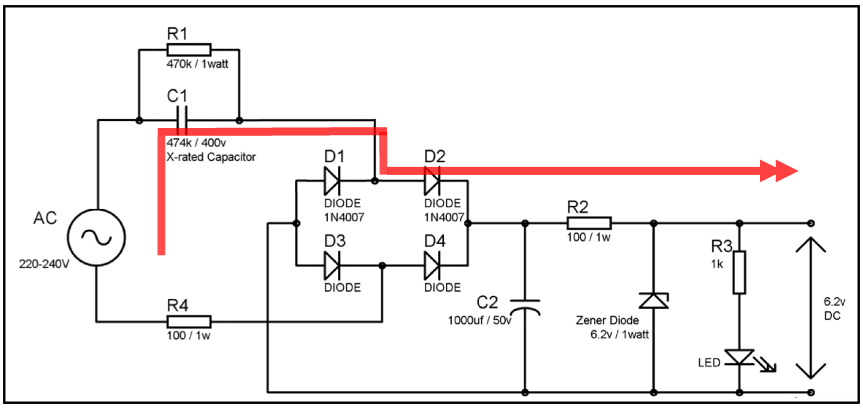


Figure 2.9 Transformer-less Power Supply with Fault-current Path Indicated **[51]**

This supply operates by using the capacitive reactance of a mains rated capacitor. Since the capacitor is not an ideal capacitor as described by capacitor theory, a small quantity of current is passed through the capacitor. This is rectified by the full-wave diode bridge and clamped at the required voltage by typically a

Zener diode (or small linear regulator). R1 ensures that the mains capacitor is safely discharged after power is removed and that harmful spikes on the mains is reduced, thereby extending the life-span of C1. Resistor R1 acts as a current limiter and unofficial fuse, which will overheat during fault conditions. This resistor will fail in an open circuit, thereby interrupting the current flow from the mains supply to the rectifier circuit.

In Figure 2.12, a direct electrical connection exist between the input and the output as indicated by the red arrows. Failure of the mains capacitor in a short circuit mode, can pass the full mains potential to the low voltage output of the supply and cause a dangerous situation such as fire or electrical shock. This type of equipment is only used in double insulated devices and generally contains additional safety devices such as fuses and Positive Temperature Coefficient (PTC) current limiters incorporated into their design for addition safety.

2.8.2 Isolated Power Supplies

An isolated power supply provides galvanic isolation between the input and output terminals. This is done to prevent fault conditions or disturbances on the high voltage input side from being transferred to the low voltage side. The follow reasons exist to isolate the input and output of a power supply:

- Voltage Level Shifting;
- Multiple Outputs;
- Providing Galvanic Isolation;
- Ground Loop Prevention;
- Safety.

These reasons vary in importance and are generally application specific. Galvanic isolation is the practice of isolating functional components or sections of an electronic circuit to prevent the flow of unwanted current. In the context of different types of power supplies, linear power supplies are typically powered by a mains transformer, and are intrinsically isolated due to the isolation between the primary and secondary windings of the transformer used to step down the input voltage. SMPS designs on the other hand require special precautions in order to ensure complete isolation between the input and output.

In power supply design, galvanic isolation is usually attained in a number of ways. Where high power-transfer is required such as the main current path, isolation is achieved by means of transformers using magnetic coupling. To achieve galvanicaly isolated signal coupling on sensitive feedback circuits for example,

optical coupling is implemented through devices such as opto-couplers, opto-isolators and isolation amplifiers **[52,53]**.

Ground loops refer to the effect of various ground currents, finding the path of least resistance to their respective power sources. This is often the case with noise-related currents. Such currents can use components in a system, or whole sub-systems to complete the current loop. A commonly found solution to ground loops is the use of a single earth or ground circuit for each system with a common tie-point. Galvanic isolation prevents ground currents from forming between various parts of a circuit by magnetically isolating sections of a circuit **[54]**.

Safety in electric and electronic devices play an ever-increasing role. The failure of a component or group of components should not pose a risk to humans operating the device. Galvanicaly isolated power supplies increase the safety and reliability of power supplies (especially in harsh environments) where specifically electrical noise is a major concern. Furthermore, the performance of a power supply is greatly enhanced if disturbances are filtered out.

It is important to remember that both non-isolated and isolated power supplies have strengths and weaknesses which requires careful consideration when developing design requirements.

2.9 Power Supply Stress Factors

As all electronic devices require a power supply with certain characteristics, it follows that it is imperative to maintain a stable supply of power to ensure stable operation. Components and circuits are designed and manufactured with defined tolerances and operating parameters. Operation or storage outside of these parameters can cause malfunction or permanent damage to both the power supply and connected equipment. The following section identifies a number of typical stress factors in real-world application.

2.9.1 Electrical Stress

Unfortunately it is not always possible for equipment to operate in perfect conditions. Real-world applications often demand electronics to perform under less-than-ideal circumstances and close to, or even outside the design parameters.

One of the factors contributing to failures of neutron monitors are mains supply instabilities **[22,23]**. If left uncorrected these cause unreliable operation of devices or systems, or damage in worst case scenarios. Since the alternating current used to power equipment is readily available either provided by the supply authority through fixed points, fuel-powered generators or solar-powered inverters, the mains voltage can be easily transformed to the required levels for a specific application. Distribution and transformation networks are typically widespread, and are susceptible to interference, instabilities and interruption.

As an international standard, the mains supply is typically a pure sine wave of 240 V_{AC} at 50 Hz (or 115 V_{AC} at 60 Hz). In practice, however, and due to a number of factors the supply is not ideal and additional precaution should be exercised when designing, building or operating mains powered equipment. Table 2.3 below lists the most common types of disturbances found on mains supply lines as well as the damage caused.

Table 2.3 Characteristics and Causes of Mains Disturbances and their Effects **[55,56]**

Category	Type	Time/Period	Cause	Effect
Transients	Impulsive	< 50 ns	Lightning, Poor grounding, inductive loads switching, power utility switching	Tripping of Residual Current Device, Operation of Magnetic Circuit Breakers
	Oscillatory	< part of mains cycle	PF Correction Capacitors switching by provider	Tripping of variable speed drives
Interruption	Instantaneous	0 to 30 cycles	Lightning, Animals, Destructive weather.	Activation of protection devices after interruption i.e. Fuses/Circuit breakers
	Momentary	20 cycles to 2 seconds	Network switching	Damage to input components of circuit i.e. Input bridge rectifiers/storage capacitors/switching devices
	Short term	2 seconds to 2 minutes	Automatic re-closure switching	Damage to compressors in refrigeration equipment
	Long term	> 2 minutes	Network failure Lightning	Possible permanent damage
	Oscillatory	< part of mains cycle	PF Correction Capacitors switching by provider	Tripping of variable speed drives
Sag/Under-Voltage/ Brown-out	Varying	0.5 Cycle to Minutes	Switching on of loads with high start-up current	Failure of non-linear loads (i.e switching supplies). Cause slow damage over long time period

Category	Type	Time/Period	Cause	Effect
Surge/ Over-Voltage	Varying	0.5 Cycle to Minutes	Lightning, Poor supply network design, Generation problems	Causes high current draw, over stressing of components
Noise/ Wave-form Distortion	DC Offset, Harmonic Distortion, Inter-harmonics, Notching, Noise, Abnormal Frequency	Various	Operation of small appliance motors such as blenders, electric motors, Poor supply network design	Damage to IT Equipment. Interference on RF equipment

As can be seen from Table 2.1, a variety of mains disturbances exist. These disturbances range from fast, transitory effects to major, long term instabilities or even interruptions of the supply. They also have varied orders of effect on equipment and in worst-case scenarios, cause damage to equipment. Mains disturbances can thus be said to include all frequencies, transients and variations not part of the single fundamental sinusoidal wave-form of the mains supply.

Regardless of the origin of these disturbances it is imperative to eliminate as much or all of these to protect the power supply as well as the equipment powered by it against malfunction or damage. International test standards such as MIL-STD-883K **[57,58]** and IEC61000-4-2 **[59]** defines electrical stress testing on micro-electronics and describe a Human Metal Model with standard Human Body Model tested by ANSI/ESDA/JEDEC JS-001-2014 **[60,61]**. These tests (among others) test for a number of electrical and electrostatic stresses on electronic components and systems **[57-61]**.

2.9.2 Mechanical Stress

As much as electronic components have specific tolerances in terms of electrical stresses, so too components and entire systems have a maximum degree of mechanical stress it can withstand before malfunction or damage occurs. Examples of mechanical stresses include acceleration, jolts and vibration. In the context of permanently installed neutron monitors, vibration plays a lesser role since these instruments are typically installed in areas where sudden acceleration and impacts are at a minimum. However, portable neutron monitors are more often than not subjected to different types of vibration profiles. Examples of these are during handling/transport, shipboard installation, on-board aircraft and road vehicles. These vibration profiles can cause malfunction and damage, either instantaneous or through long term exposure.

Environmental testing for vibration hardiness comprises of a vibration controller and makes use of a closed-loop control system with feedback via accelerometers and instrumentation amplifiers **[62]**. The controller controls the power amplifier that drives the electro-mechanical shaker on which the item under test it

placed. Since the vibration profile has been pre-recorded and stored digitally in the controller, exact vibration profiles equal to real-world conditions can be re-created in a laboratory **[63]**.

Additionally, accelerated testing can also be performed. By adjusting parameters such as amplitude and acceleration of the vibration profile accordingly, can real world equivalents conditions be re-created to perform endurance tests. This provides for thorough testing of the design and construction methods of equipment before deployment. Figure 2.1 indicates a typical vibrator system with its various components.

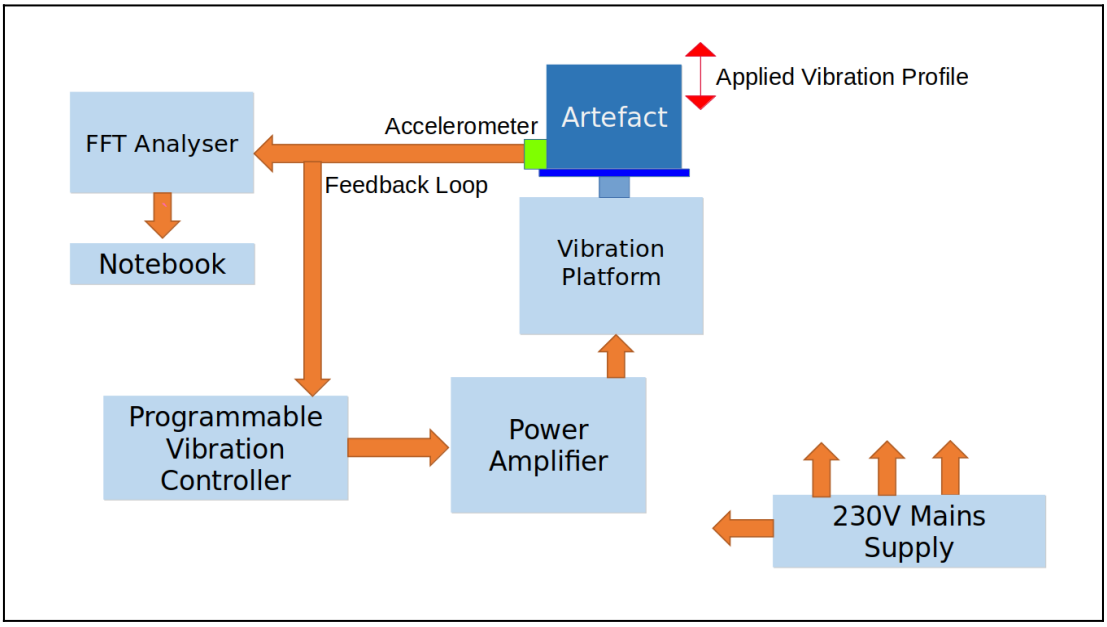


Figure 2.10 Typical Vibration System used for Vibration of Test-Items **[63-65]**

Figure 2.2 indicates a typical vibration profile to which equipment is subjected to during environmental testing **[65]**.

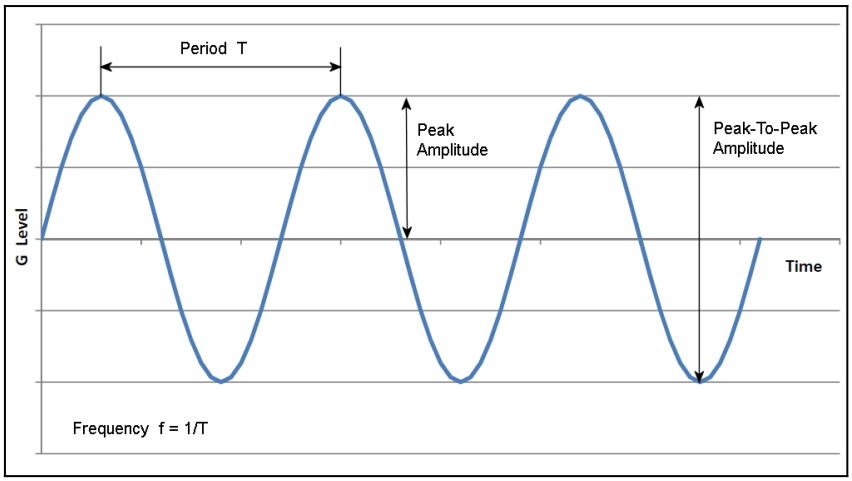


Figure 2.11 Typical Vibration Profile of a Pure Sine Vibration Test **[66]**

Table 2.4 outlines a number of common, real-world problems with electronic equipment, directly observed due to mechanical stresses.

Table 2.4 Mechanical Stress-Induced Problems on Power Supplies **[20,21,23,67]**

Failure	Cause	Mechanical Stress	Severity/Influence
Broken PCB	Incorrect handling, Poor design of mounting, Improper assembly, Old age	Drops, Jolt	Total failure in most instances
Damaged Components	Improper ingress protection	Vibration, Jolt	Malfunction or total failure
Abrasion Marks	Improper securing of wiring/cables and sub-assemblies	Mostly Vibration	Varying from negligible to total failure of system
Loose solder joints / Dry joints in solder work	Poor solder-work during assembly	Vibration, Thermal cycling causing mechanical stress	Malfunction or total failure
Loose or missing nuts/washers/bolts	Insufficient fastening, Lack of thread-locking fluid	Mostly Vibration	Varying from negligible to total failure of system

Road and aircraft transport vibration that simulates mechanical stresses are assessed by means of standards such as ISO 8608 and MIL-STD 810G Test Method 514.7 and 528.1 **[68]**.

2.9.3 Temperature Stress

Temperature also plays a critical role **[69]**, if not the biggest, in the storage and operation of electronic components. Extreme temperatures has a definite, and often negative effect on the performance of components and circuits **[70-73]**.

In essence two basic types of temperature conditions directly affect electronic systems: Steady-state temperatures and thermal shock. An environment where the thermal energy is in equilibrium is prone to problems such as dissipation of generated heat in an already high ambient temperature environment. This is in contrast to a scenario where equipment is subjected to rapid, drastic changes in temperature. Scenarios such as loading equipment on a hot day into an aircraft cargo hold, and rapidly climbing to a high altitude where the temperature is far below ground level temperature, places systems at risk of malfunction. Due to various factors, among which the different coefficients of expansion of the various components and sub-systems, lead to cracking of solder joints and bond wires **[71,72]**.

Test Standards such as MIL-STD 810G, Test Method 501.6, 502.6, 503.6 and 520.4 as well as MIL-STD 883E Test Method 1010.7 and 1011.9 are recommended for tests of temperature related effects on equipment **[57,58,68]**. In these tests, items are typically subjected to a number of temperature cycles between two

predefined extremes. By repeated cycling, the failure-mode of components and systems can be established and corrections to the design be made.

2.9.4 Humidity Stress

Since all electronic devices operate within well defined parameters, it follows that the ingress of moisture due to high ambient humidity or wet conditions affect the flow of current and thus the operating parameters. Moisture present in electronic systems forms erroneous conductive paths and generally always causes malfunction or damage **[24]**.

The ingress of moisture into electrical or electronic equipment (in many instances), can also cause dangerous conditions for operators since high voltages can leak out and deliver lethal quantities of current to operators as well as connected equipment. It is therefore crucial to design equipment enclosures using standards such as the international IP Rating System and test final, ready-for-production systems in accordance to standards such as MIL-STD 810G Test Method 507.6 and 520.4 **[68]**.

2.9.5 Altitude Stress

Neutron monitors and especially portable neutron monitors are often transported to remote locations by aircraft as part of their deployment or high-altitude research **[10,21]**. Since ambient air pressure directly affects components such as aluminium capacitors **[26,27]** it is also imperative to consider the altitude ratings of components during the design phase and ensure suitably rated components that conforms to the design-criteria for a particular application.

Insulating practices used to separate high voltages on printed circuit boards often depend on the physical distance between conductors. One method is the cutting of a slot in the printed circuit board to separate conductors and using ambient air as insulating material. At elevated altitudes, air becomes more conductive as shown in the following table, and designs must cater for this accordingly **[74,75,77,78]**. Table 2.5 indicates altitude versus pressure and air-gap multiplication factor for air-gap insulation on printed circuit boards for power supplies.

Table 2.5 Altitude, Barometric Pressure and Air-gap Multiplication Factor **[76]**

Altitude (m)	Barometric Pressure (kPa)	Multiplication Factor for Clearance between Conductors
2000	80.0	1.00
3000	70.0	1.14
4000	62.0	1.29
5000	54.0	1.48
6000	47.0	1.70

As the table indicates, power supplies intended for operation at 5,000 meters are required to have conductor/components clearances increased by 48% compared to power supplies designed for operation at 2,000 meters. This is due to the difference in air pressure at various altitudes and thus the density and consequently the conductive properties of the air.

For designs relying on air-flow for cooling, it is also imperative to take into account that the density of the atmosphere decreases with altitude. Due to the reduced air density, cooling is also negatively affected and components can overheat due to decreased cooling **[79]**.

In order to fully ensure reliable operation the final, ready-for-production artefact must be verified for its performance at various altitudes according to MIL-STD 810G Test Method 500.6 and 520.4 **[68]**.

2.10 Corrective and Preventative Actions

The following section investigates preventative and corrective actions that can be implemented for each of the previously identified stress factors. A combination of these will then be incorporated into the final design of the artefact to minimise the effect of these stress factors on performance and life-span of the artefact.

2.10.1 Electrical and Electronic Protection Devices

Various forms of protection devices and methods are employed when dealing with mains supply disturbances such as those described in Table 2.1. Undesirable behaviour or damage to equipment is the most common result of these disturbances. The specific requirements in terms of protection devices used in systems varies, but it is generally found that the level of protection utilised in a system is directly dependent on the application. A number of protection devices and their properties are given in Table 2.6.

Table 2.6 Properties of Various Electronic Protection Devices **[80,81]**

Type	Construction	Energy Absorption	Relative Response Time	Operating Voltage	Type of Protection
Fuse	Resistance wire	Device Dependent	Slow to Fast	Whole range	Over-Current
TVS Diode/ Transorb	Semiconductor Material	Low	Ultra Fast	Low Voltage	Over-Voltage
Spark Gap	Electrodes with open air-gap	High to Very High	Slow	High Voltage	Over-Voltage
Gas Discharge Tube (GDT)	Electrodes in Gas-filled enclosure	High	Slow	High Voltage	Over-Voltage
Neon Lamp	Gas-filled	Low to Medium	Slow	High Voltage > 90V	Over-Voltage
Resetable Poly-Fuse	Composite Organic Polymer Matrix	Low	Medium Response	Low to Medium Voltage 6 - 230 V	Over-Current
Varistor (MOV)	Sintered ZnO	Medium to High	Medium	Low to Medium Voltage 5 - 1000 V	Over-Voltage
ESD Protection Diode	Semiconductor Material	Low	Ultra Fast	Low Voltage	Over-Voltage
Thermal Fuse	Spring Loaded Metal Alloy	Low to Medium	Fast	Medium Voltage	Over-Current
Thermal Circuit Breaker	Bi-Metal	Medium to High	Slow	Low to Medium Voltage	Over-Current

As can be seen from Table 2.4, these devices operate in various ways to counter the effect of disturbances as laid out in Table 2.1. The reaction times and energy absorption of these devices are listed relative to each other. Certain disturbances, especially transients, are fast in nature and cannot be absorbed by slow-reacting components. It is therefore critical to incorporate both fast and slower responding protection elements.

Similarly some disturbance events are of higher energy than others and should the protection devices be able to deal with all levels of disturbances. In the event of a mains disturbance the protection device, or devices should operate to their full capacity to completely absorb or at least mitigate unwanted elements. In worst case scenarios these devices will be destroyed in the process rather than the connected equipment.

An important requirement of any protection device is that it should not interfere with the normal operation of the protected system, even in the event that the protection device is destroyed. A good example of this

are the different classes of capacitors used in mains powered equipment. The failure mode of Class Y capacitors is a short circuit, whereas Class X2 capacitors are self-healing and in case of complete breakdown, fails in an open-circuit condition **[82]**. Properties such as this are important in safety and reliability considerations where a short circuited component such as a capacitor connected to mains potential, can lead to an unsafe situation or reduce reliability of equipment.

2.10.2 Mechanical Protection

Common failures of electronic equipment due to mechanical stresses generally consist of physical damage to individual components, or sub-assemblies. In worst-case scenarios the entire system suffers damage due to mechanical stresses in harsh environmental conditions.

The damage generally causes malfunction and in severe cases total failure of the equipment. Table 2.7 lists a number of construction techniques to minimise the effect of mechanical stresses on equipment such as power supplies.

Table 2.7 Various Forms of Protection Against Mechanical Stress **[83-86]**

Typical problem as defined by Table 2.2	Corrective Action	Implementation Phase
Broken PCB	Rubber grommets, Vibration absorbing mountings, Lock nuts, Spring washers, Thread-locking Fluid.	Design phase, Construction/Assembly, Shipping and Handling
Damaged Components	MIL-Specification Components, Thicker/ Larger Solder Pads, Hot-melt glue to secure components. Conformal Coating	Design phase, Construction/Assembly
Abrasion Marks	Cable Ties, Lacing of Wiring with Twine, Thread-locking Fluid. Cable Clamps and Cable Ties. Conformal Coating	Design phase, Construction/Assembly
Loose solder joints / Dry joints in solder work	Thicker/Larger Solder Pads, Correct solder-work/Re-flow Techniques. Conformal Coating	Design phase, Construction/Assembly
Loose or missing nuts/washers/bolts	Lock nuts, Spring washers, Thread-locking Fluid. Conformal Coating, Glue/Binding Agent, Hot-melt glue, epoxy applied to component bodies and vibration-sensitive components. Conformal Coating	Design phase, Construction/Assembly, Shipping and Handling

As can be seen from above table, many problems relating to mechanical stresses can be mitigated by careful design, correct component selection and attention to construction techniques.

2.10.3 Thermal Management

As stated earlier, temperature plays a large, if not one of the biggest roles in the correct functioning of electronic equipment. Harsh environment usage of equipment places the entire system in less than ideal conditions. To add stress to this scenario, individual components are often subjected to larger stresses than others. In a typical application such as a power-supply, components such as power transistors and power-control integrated circuits often operate at much higher temperatures than the rest of the components. This unequal generation and distribution of heat in a system causes various parts of a system to behave differently due the different coefficients of expansion between components and the circuit board, for example. Table 2.8 outlines a number commonly experienced problems due to temperature and highlights solutions that can be implemented to minimise the effect of thermal stress:

Table 2.8 Preventative Actions for Mitigation of Thermal Stresses **[87,88]**

Thermal Stress-related Problems	Possible Causes (Thermally Related)	Corrective Action	Implementation Phase
Dry Solder Joints	Over-Current, Over-temperature, Poor thermal management, Dust Build-up, Lack of regular maintenance to remove dust	Use of heat sinks, Convection cooling, Active cooling such as Forced air and Peltier Modules, Regular maintenance protocols, High melting-point solder	Design phase, Construction/Assembly, Operation and Maintenance
Discolouration of PCB and/or Components due to Excessive Heat	Over-Current, Over-temperature, Poor thermal management, Dust Build-up, Lack of regular maintenance to remove dust	Wider PCB tracks for heat conduction and dissipation, Filtration of cooling air-flow with filter membranes and electro-static precipitators, heat sinks, Convection cooling, Active cooling, High Specifications components	Design phase, Construction/Assembly, Operation and Maintenance
Poor Performance of Components such as LCD and Batteries	Low/High Temperatures, High Altitude (Low Air Pressure)	Higher IP Rating on system enclosure, Built-in temperature control with active cooling/heating	Design phase, Construction/Assembly
Damaged / Failed Components	Insufficient air flow, Dust build-up, Poor thermal management, No or insufficient maintenance.	Higher Design-specifications, Better component selection, Increased maintenance protocols	Design phase, Construction/Assembly, Operation and Maintenance

An often overlooked but highly critical detail in thermal management is software-based thermal control. Not only is the design of hardware important to reduce temperature effects on the performance and life-span of systems, especially in the context of harsh environments, but so too software plays an ever-increasing role in extending the reliability and life-span of equipment.

Through diligent attention to programming techniques, many problems related to thermal management can be avoided. Software thermal management also reduces manufacturing costs since optimisation of software can reduce hardware requirements such as heat-sinking. Table 2.9 summarises a number of software and firmware based thermal management schemes which can be employed to reduce the effects of software on heat generation.

Table 2.9 Software and Firmware based Thermal Management Techniques **[89-92]**

Solution	Implementation
Low-power components with internal safe-area operation and thermal shut-down	Voltage Regulators, Battery Management ICs, Power-path controllers, CMOS manufacture with implemented power control algorithms,
Power supplies with Intelligent control	Switch-mode power control instead of Linear regulation, Intelligent power supplies, light-load optimisation of PWM and PFM characteristics, variable speed cooling
Active power management in high level components	Typically applied in BIOS systems on computers and embedded systems, Peripheral management, Dynamic Voltage and Frequency scaling (typically on processors)
Processor/Micro Controller Sleep Functionality	Software optimisation for the total sleeping of a processor or micro-controller during periods of inactivity

2.10.4 Humidity Stress Management

The highest relative humidity recorded by the North West University's Cosmic Ray Research Group was during neutron monitor operation in Thailand at 90% relative humidity **[20]**. Severe malfunction and eventual failure of the hardware resulted in the experiment failing with insufficient data obtained of the phenomena of interest. Failures such as these could have been prevented if careful design of the system were performed from the onset.

The classification of the means of preventing the ingress of foreign matter into electric and electronic systems, is contained in the Ingress Protection Standard. This standard both deals with moisture related protection as well as ingress protection of physical objects as small as dust particles to items as large as the back of a human hand. This standard is defined by British standard BS EN 60529:1992 and European IEC 60509:1989. This rating standard comprise of the letters “IP” followed by a two digit numeric code indicating the level of protection provided. The first digit provides information regarding the level of protection against the ingress of physical objects while the second digit relates protection against the ingress of liquids. Supplementary letters can be added behind the standard IP rating to indicate additional levels of protection. Figure 2.3 summarises the composition of a typical IP rating.

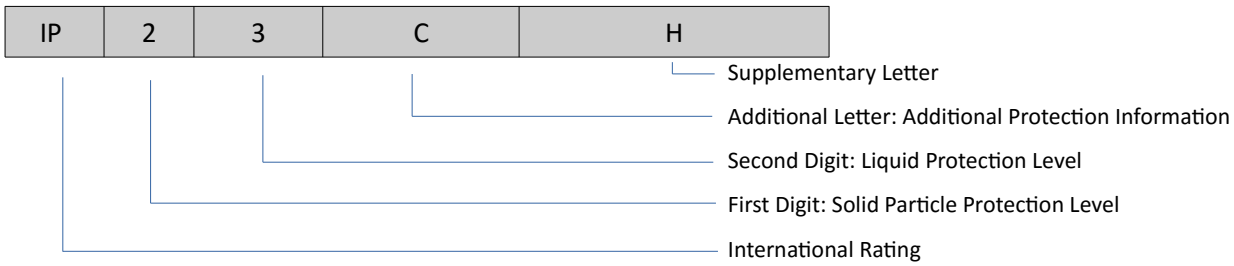


Figure 2.12 Summary of International IP Rating System **[93]**

In the above example the values of Table 2.10 is applicable.

Table 2.10 International Ingress Protection Ratings and Description **[93-96]**

1st Digit	Object Size	Description	2nd Digit	Liquid Ingress	Description
X	-	No data available to specify a protection rating with regard to one of the criteria.	**0**	None	-
0	-	No protection against contact and ingress of objects	**1**	Dripping water	Dripping water (vertically falling drops) shall have no harmful effect on the specimen when mounted in an upright position onto a turntable and rotated at 1 RPM.
1	> 50mm	Any large surface of the body, such as the back of a hand, but no protection against deliberate contact with a body part	**2**	Dripping water when tilted at 15°	Vertically dripping water shall have no harmful effect when the enclosure is tilted at an angle of 15° from its normal position. A total of four positions are tested within two axes.
2	>12.5mm	Fingers or similar objects	**3**	Spraying water	Water falling as a spray up to 60° from the vertical utilizing either a) an oscillating fixture, or b) A spray nozzle (counterbalanced shield). Test a) is for 5 minutes, then repeated with the specimen rotated horizontally by 90°. Test b) is conducted (with shield in place) for 5 minutes minimum
3	> 2.5mm	Tools, thick wires, etc.	**4**	Splashing of water	Water splashing against the enclosure from any direction shall have no harmful effect, utilizing either: a) an oscillating fixture, or b) A spray nozzle with no shield. Test a) is conducted for 10 minutes. Test b) is conducted (without shield) for 5 minutes minimum.
4	> 1mm	Most wires, slender screws, large ants etc.	**5**	Water jets	Water projected by 6.3mm nozzle against enclosure from any direct-ion shall have no harmful effects.

1st Digit	Object Size	Description	2nd Digit	Liquid Ingress	Description
5	Dust Protected	Ingress of dust is not entirely prevented, but it must not enter in sufficient quantity to interfere with the satisfactory operation of the equipment.	**6**	Powerful water jets	Water projected in powerful jets (6.3 mm nozzle) against enclosure from any direction, under elevated pressure, shall have no harmful effects. Found in DIN 40050, and not IEC 60529.projected in powerful jets (12.5mm nozzle) against the enclosure from any direction shall have no harmful effects.
6	Dust Tight	No ingress of dust; complete protection against contact (dust tight). A vacuum must be applied. Test duration of up to 8 hours based on air flow.	**6K**	Powerful water jets with increased pressure	Water projected in powerful jets (6.3 mm nozzle) against the enclosure from any direction, under elevated pressure, shall have no harmful effects. Found in DIN 40050, and not IEC 60529.
			7	Immersion, up to 1m depth	Ingress of water in harmful quantity shall not be possible when the enclosure is immersed in water under defined conditions of pressure and time (up to 1m of submersion).
			8	Immersion, 1m or more depth	The equipment is suitable for continuous immersion in water under conditions which shall be specified by the manufacturer. However, with certain types of equipment, it can mean that water can enter but only in such a manner that it produces no harmful effects. The test depth and duration is expected to be greater than the requirements for IPx7, and other environmental effects may be added, such as temperature cycling before immersion.
			9K	Powerful, high temperature water jets	Protected against close-range high pressure, high temperature spray downs. Smaller specimens rotate slowly on a turntable, from 4 specific angles. Larger specimens are mounted upright, no turntable, tested freehand for at least 3 minutes at distance of 0.15–0.2m. According to specific requirements for the nozzle used for the testing. This test is identified as IPx9 in IEC 60529.

Additional standards such as the “K” rating shown in the above table, were introduced by the Deutsches Institut für Normung (DIN) to extend the ratings for particular applications not described by the standard IP ratings. Parts of the DIN extensions are also introduced into the International Electrotechnical Commission (IEC) rating system IEC 60529 **[67]** as well as the ISO 20653:2013 **[68]** for Road Vehicles: Degrees of Protection standard. Ratings as described in the above table, provide designers of electronic systems with a guideline to quantify the level of environmental protection for a particular application.

2.10.5 Altitude Stress Management

As with the humidity stress management described in the previous section, the effects of altitude on components and systems can also be mitigated by employing a number of strategies. The following table lists a number of issues associated with altitude and the preventative or corrective actions that can be implemented.

Table 2.11 Altitude Related Problems: Preventative and Corrective actions **[74-79]**

Component Failures	Possible Causes of Failure (Altitude Related)	Corrective Action	Implementation Phase
Altitude Sensitive Components: Aluminium Capacitors, EEPROM/ NAND Memories, CPUs	Soft Errors Caused by Cosmic Rays, Aluminium Capacitors Bulging due to low pressure, LCD Seal Failures, LCD Slow Response	Radiation Hardened Components, Improved Screening (e.g. Faraday Cage), Higher IP Rating on Housing	Design phase, Construction and Assembly, Operation
Insulating Air-gaps for High Voltage (Flash-over Prevention)	Reduced Altitude Causes lowering of air-gap dielectric breakdown,	Higher Rated IP	Design phase, Construction and Assembly, Operation
Thermal Problems at High Altitude	Insufficient Air-flow due to Reduced Air Pressure at High Altitude	Higher Fan Speeds, Larger Heat-sinking, Active Cooling Solutions (Heat pipes, Peltier modules), Ambient Cooling Solutions such as Room Air-Conditioner, Software Solutions for reducing Thermal Load on CPUs/Systems	Design phase, Construction and Assembly, Operation

From Table 2.11, a number of problems with electronic systems including power supplies due to altitude are evident. Most of these issues can be reduced at the design stage of equipment since this will directly affect component choices as well as improve the cost-effectiveness of the design during manufacturing.

It is sometimes required to operate systems outside of their original design-criteria or specifications. In such cases additional mitigating solutions should be investigated before deployment to avoid malfunction or damage to these systems.

2.11 Application Specific Power Supplies in Harsh Environments

As neutron monitors are highly specialised devices their components do not offer typical off-the-shelf availability. Early NWU CSR neutron monitors used various voltages to power the detector tubes, signal amplifiers as well as the mechanical counters that operated as recording devices. Modern neutron monitors require less varied voltages with reduced current requirements due to advances in semi-conductors and an increased drive toward miniaturisation **[13,14,20,22]**.

Stable power supply to the electronics hardware in neutron monitors forms an integral part of cosmic ray detection. With the reduction in power consumption, and the increased complexity of modern systems, the importance of a stable power supply hold especially true for scientific instruments deployed in harsh environments.

The following section details a number of real-world neutron monitor power supplies that were used by the NWU CSR. These functioned with varying degrees of success but ultimately proved unsuitable for deployment in harsh environments. The following investigation highlights the fact that a custom-manufactured harsh environment power supply is required for the operating conditions of these instruments.

2.11.1 Previous Neutron Monitor Power Supplies

The fixed neutron monitors presently in use by the NWU's CSR was designed and built in the early 1990s. These operate on a 5 Volt rail for TTL circuits and a split-rail 12 Volt for the high voltage generators and amplifiers. Figure 2.13 shows the power supply of these neutron monitors.

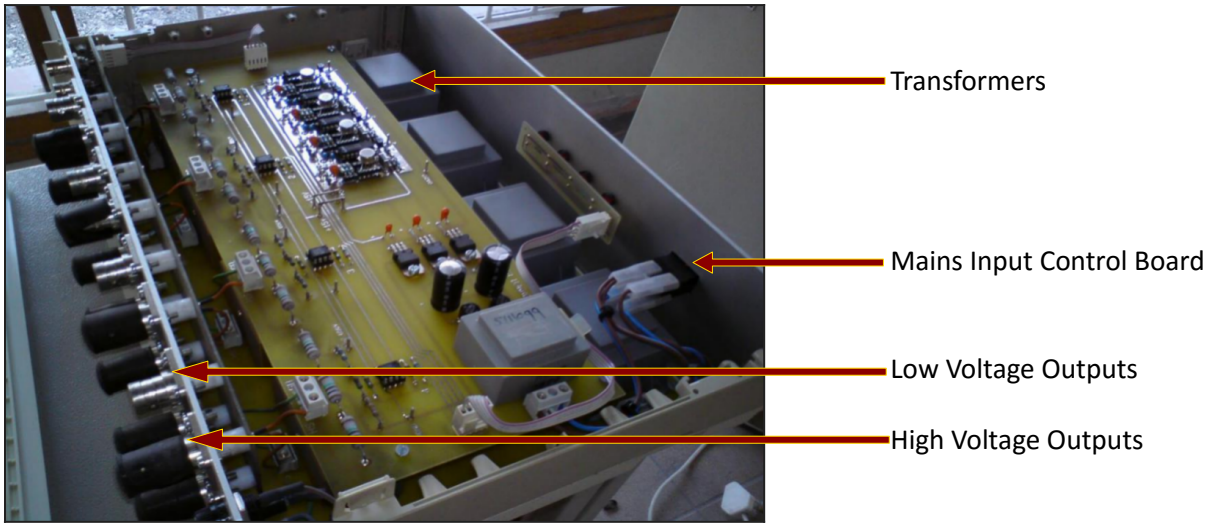


Figure 2.13 Power Supply Module for NWU Fixed Neutron Monitor **[23]**

The high voltage power supply board is shown in Figure 2.14.

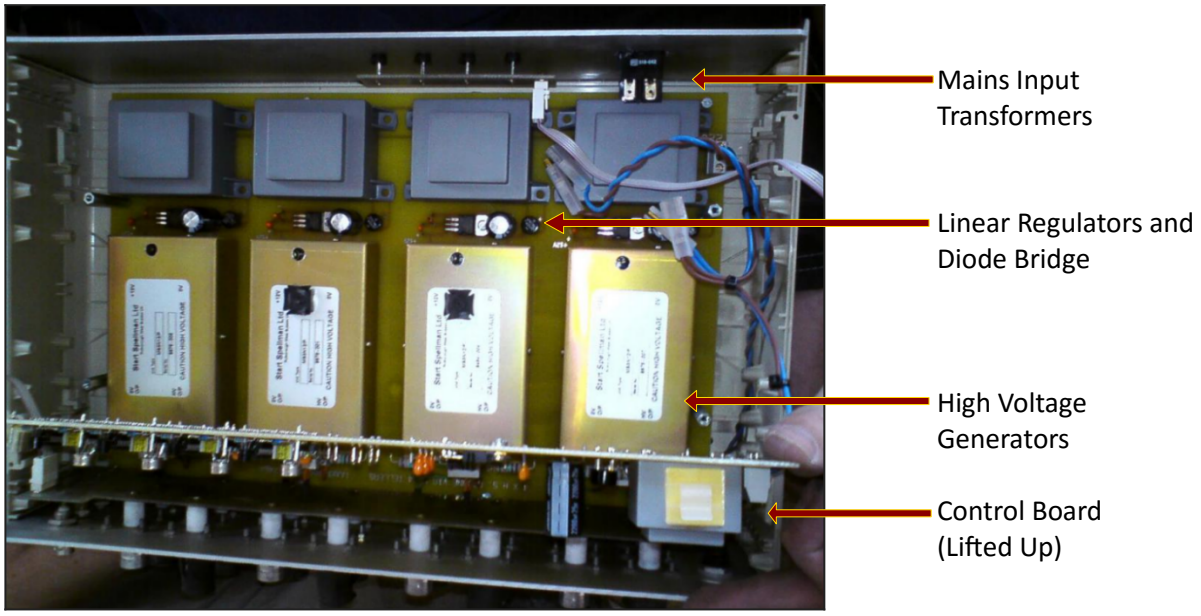


Figure 2.14 High Voltage Generators of the Fixed Neutron Monitor **[23]**

In the above power supply, four individual transformers are connected to the mains input. Linear regulators provides well-regulated power to the four high voltage generators, manufactured by Start Spellman Ltd. Figure 2.15 shows the temperature sensor assembly, with the regulators visible in the middle of the printed circuit board.

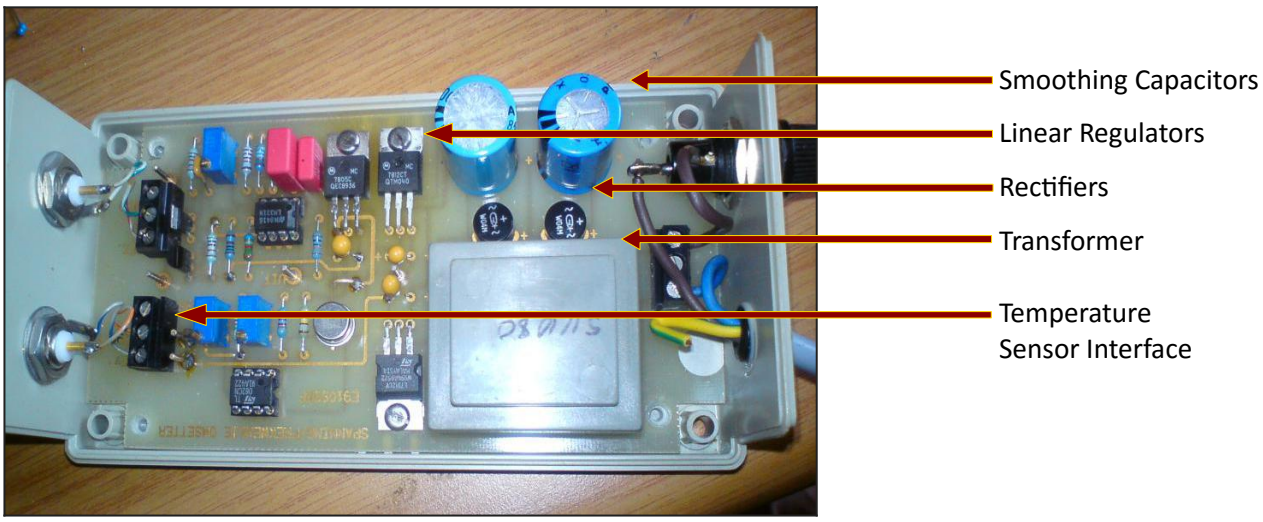


Figure 2.15 Temperature Sensor Power Supply **[23]**

These transformers and regulators provide a well-regulated supply to the various sub-systems and components in the system, but are relatively inefficient in converting the mains supply to the required voltages. As stated earlier, linear regulators dissipate energy in the form of heat and are bulky. These losses and physically large power supplies makes for difficult deployment in a modern neutron monitor context since many of these systems are installed at remote locations with a limited power budget or availability of space.

2.11.2 Calibration Neutron Monitor Power Supply

In ca. 2002 a portable calibration neutron monitor had been developed at the Centre for Space Research at the North West University. Since this instrument was highly portable, its primary function was the inter-calibration of the various fixed neutron monitors around the globe.

This calibration monitor consisted of an embedded computer motherboard with a standard Flex Advanced Technology eXtended (ATX) low form-factor computer power supply as shown in Figure 2.16. A separate circuit board that housed the electronics for the neutron monitor and the required neutron monitor hardware made up the rest of the instrument.

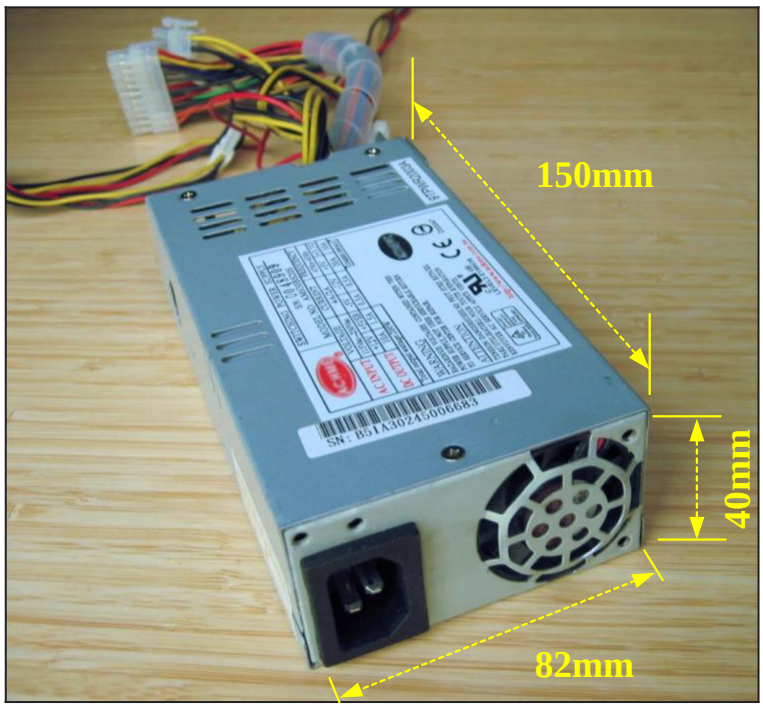


Figure 2.16 Standard Flex ATX Power Supply of the Calibration Monitor **[13]**

This standardised computer power supply has a number of additional outputs and a spare disk-drive connection was used to power neutron monitor electronics. The 5V and 12 Volt rails powering the neutron monitor electronics were taken directly from the power supply and filtered by means of capacitive decoupling.

Numerous problems were experienced with this configuration. Since the filtering of the output power from this power supply was insufficient, noise originating from the mains supply as well as noise originating in the embedded computer was transferred through the power rails to the neutron monitor electronics. This proved no problem in a stable environment such as a laboratory or research facility, but during operation in harsh environments this problem became evident.

Further problems was experienced with the high voltage power supply. This was incorporated onto the custom electronics printed circuit board, and numerous experiments failed due to the following problems that were experienced with this design:

- Ingress of dust into the housing of the neutron monitor;
- Ingress of humidity from humid environments the neutron monitor operated in;
- Ambient- and internally generated heat could not be dissipated

The above factors caused, amongst others, the following problems:

- High-voltage corona discharges on high voltage components;
- Corrosion inside the system power supply due to dust and moisture ingress;
- Malfunction and subsequent system failure during operation.

Coupled with the fact that the neutron monitor operated in what constitutes a harsh environment for which it was not designed, with day temperatures exceeding 50 degrees Celsius at times and ambient humidity of 90% relative, system performance suffered in terms stability and life-span. The Calibration Monitor was retired after expensive attempts to repair the damage was only partially successful.

2.11.3 Mini Monitor Power Supply

Present-day (2010 onward) neutron monitor electronics typically require a 3.3 Volt power supply for the micro-controller and associated components, 5 Volt for USB functions and a 12 Volt rail to supply additional hardware such as the high voltage generator and pressure sensors. Additional filtering around sensitive components such as the pre-amplifier is also employed.

To reduce the development time, a commercial off-the-shelf (COTS) cell-phone charger was bought. These cheap SMPSs are freely available, met some of the electrical requirements and was used to power a mini neutron monitor in the laboratory. A management decision was made that prioritised the development time-line and mandated that a COTS PSU would be deployed since it performed satisfactory under laboratory conditions. Figure 2.17 shows a power supply used in the neutron monitor ca. 2014.



Figure 2.17 Plug-in Power Supply of 2014 Neutron Monitor

Since the mini-neutron monitor requires approximately 3 Watt during operation, these power supplies provide ample current for the neutron monitor. To provide the required voltages for the various circuits, a

small regulator board was also developed which were fed 5V from the plug-in SMPS. Figure 2.18 shows the power conversion board designed to deliver the required voltages to the various components.

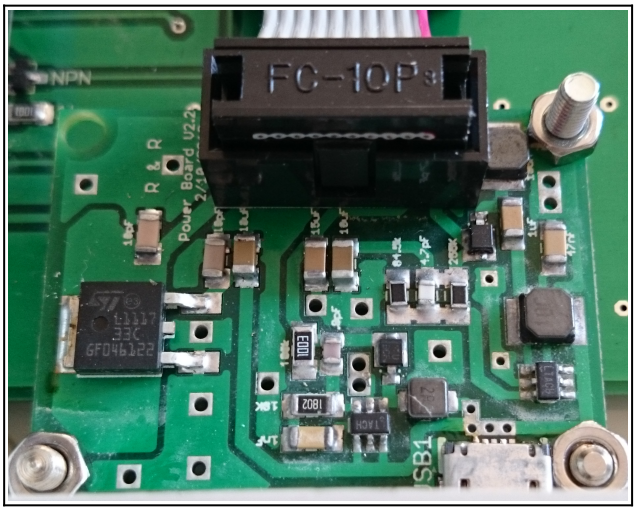


Figure. 2.18 Power Conversion Board of Modern Neutron Monitor

This conversion board accepts 5 V input from the plug-in SMPS and uses on-board switch-mode controllers for producing the required 5 Volt (USB Supply) and an adjustable 7 Volt to 13 Volt switch-mode regulator (High-voltage generator supply). A 3.3 Volt linear regulator is used to regulate the supplied 5 Volt for powering the micro-controller hardware and associated components. The purchased supply has the following specifications:

Table 2.12 Specifications of Cell Phone Charger

Parameter	Value
Input Voltage	$95V_{AC}$ to $240V_{AC}$
Output Voltage	$5V_{DC}$
Current Delivery	1.5A

The custom made, rapidly developed regulator board had the following specifications:

Table 2.13 Specifications of Custom Voltage Regulator Board

Parameter	Value
Input Voltage	$5V_{DC}$ from plug-in switch-mode power supply
Output Voltage	$3.3V_{DC}$, $5V_{DC}$ and $8V_{DC}$ (Adjustable)
Current Delivery	1A Total

2.11.3.1 COTS SMPS Field Performance

Several of these plug-in SMPSs were bought and distributed into the field to power the neutron monitors that were built in 2013 at the NWU CSR. These power supplies were also deployed at the research base, SANAE IV, on Antarctica. The supplies worked well for the first two weeks after which these started failing *en masse*. Urgent arrangements were made to replace the supplies and a better quality off-the-shelf supply was purchased from RS Components and sent to the SANAE IV base. These supplies lasted approximately two years but all have also subsequently failed.

Various factors have been identified as to the cause of the failures of these supplies. The first and foremost problem is the lack of surge suppression on the mains input side which protects the power supply against irregularities on the mains input. This is especially important for generator supplied mains power. These power supplies were never intended for powering scientific equipment, let alone under harsh environmental conditions, and thus has proven lacking in terms of stability and noise-free operation. An oscillograph was taken from one of the off-the-shelf supplies. Figure 2.19 shows excessive instability in the output of this power supply, making it unsuitable for use in scientific research since the equipment requires a stable supply.

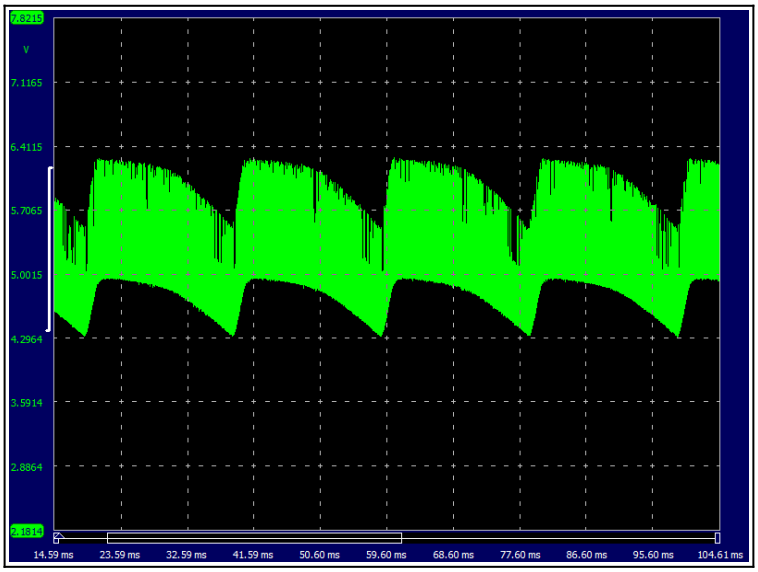


Figure. 2.19 Measured Waveform of COTS SMPS

As can be seen from the Figure 2.19, the output of this power supply vary by as much as 2.2 $V_{P-P,}$ which translates to 22% of the output voltage. The evident noise of this supply did not cause unwanted operation of the equipment under laboratory conditions. However, deployment in the harsh conditions of the Antarctic, and subsequent failures, led to the NWU CSR's conclusion that these supplies were too noisy and insufficiently robust. As conclusion, a different approach was needed in terms of power supplies as used by neutron monitors that are deployed in harsh environments.

2.11.3.2 Status Quo Observations

Further investigation shows that although the power supply is rated to accept input voltages from as low as 90V to as high as 250V, it does not function well in conditions where the voltage is unstable, such as during power surges caused by generator hunting, lightning or high voltage static electric discharges such as what is experienced at SANAE IV base on Antarctica.

With the preceding information, the following properties and short-comings of current neutron monitor power supplies have been identified as problematic during use in harsh environments:

Table 2.14 Current Neutron Monitor Power Supply Shortcomings and Typical Failure-modes **[20-23]**

Initial Observation	Cause	Effect	Possible Corrective Action
No Output	Blown Mains Input Fuse-Insufficient protection against power disturbances on mains input	(Premature) failures of power supplies. Corrupted instrument data due to unstable supply of power. Instrument failures due to undue electrical stress on sensitive components	Replace Fuse. Employ UPS and external isolation transformer
No Output	Damaged Semiconductors (Bridge Rectifier, Switching Element, Switch-mode Regulator) - Insufficient protection against power disturbances on mains input	(Premature) failures of power supplies. Corrupted instrument data due to unstable supply of power. Instrument failures due to undue electrical stress on sensitive components	Replace damaged components. Employ UPS and external isolation transformer.
Incorrect Output / No Output	Lack of Mechanical Robustness	Mechanical damage to off-the-shelf power supplies due to vibration. Failures of power supplies. Instrument down-time. Loss of valuable research data.	Repair / Replace power supplies
No Output / Incorrect Output	Ingress of moisture in high humidity environments	Power supply failure due to moisture damage. Instrument damage due to electric arcing and over-voltage output of power supply. Instrument damage. Loss of valuable research data.	Seal power supply as good as possible. Redesign enclosure with higher IP rating
No Output	No redundancy or secondary power-source input capabilities during power failures	No redundancy provided in current systems. Failure of one component causes instrument down-time. No power path management. Not capable of accepting secondary power input.	Employ UPS and/or generator

Initial Observation	Cause	Effect	Possible Corrective Action
No Output	Lack of battery back-up during power failure	Instrument down-time during power failures. Loss of valuable research data	Employ UPS and/or generator
No / Poor Output.	Corrosion.	Loss of valuable research data	Clean / Repair power supply and restore functionality as far as possible. Replace enclosure with higher IP rated unit.
Physical Damage	Insufficient protection against moisture or dust ingress	Short term malfunction of equipment. Loss of valuable research data. Long term damage and subsequent system failures. Scrapping of equipment due to high expense in repairs	Clean / Repair power supply and restore functionality as far as possible. Replace enclosure with higher IP rated unit. Replace Power Supply
Noise on Output	Poor Design - Not Properly Regulated	Short term malfunction of equipment. Loss of valuable research data	Replace power supply with better type
Output Unstable	Poor Design - Not Properly Regulated	Unstable equipment operation. Loss of valuable research data	Replace power supply with better type

Another factor that should be considered when investigating such power supplies is the question of reliability.

Due to the design-criteria for cellphone chargers whereby a product can easily be replaced should it become faulty during normal use in an office environment or during home use, it must be recognised that this scenario is not always possible in a harsh or environment. Neutron monitors measuring cosmic rays are more often than not located in far-off research stations where little or no support nor supervision is available. Several of these cell-phone power supplies were dis-assembled and inspected for safety and surge protection components if any. It was found that the majority of these supplies lacked any suppression or protection against mains disturbances and suffer from very poor line and load regulation. Typically these power supplies do not contain any grounding pin for connection to the mains supply ground network either.

Furthermore, these off-the-shelf cellphone chargers do not contain any diagnostic reporting facilities or self-monitoring capabilities. This is also a large draw-back in their suitability as power supplies for scientific equipment. Another issue with NM power supplies is that they afford no back-up during power disturbances such as brown-outs and black-outs. As many of the observed events involving cosmic ray studies happens only once, many experiments have not produced data due to power failures or fluctuations.

2.12 Batteries

Single cells, or multiple cells connected together form a battery and are used to supply power through the conversion of chemical energy into electrical energy. This process takes place inside the cells or battery due to the exchange of ions between reactive chemicals **[97,98]**. Two distinct classes of cells or batteries are defined namely Primary batteries and Secondary batteries.

A primary cell, or battery is defined as a non-rechargeable device used to provide power to typical portable systems. Upon full discharge, it is discarded and replaced. Secondary cells, or batteries, however, contain different chemicals which provide electrical power while discharging and which can be re-charged by applying power to the discharged cell or battery, thereby restoring it to a charged state for re-use. Since the proposed artefact will operate unsupervised in many instances, the use of primary batteries is impractical. Secondary batteries of different chemistries be will therefore be investigated.

Another important factor in battery technology is the type of thermal reaction that takes place during charge or discharge. Two types of reactions are defined namely endothermic and exothermic reactions. During an endothermic reaction, heat is absorbed by the chemical compounds during the reaction. In contrast is an exothermic reaction one where heat is produced during the reaction. Care must therefore be exercised when designing systems where batteries are used and to compensate for the type of thermal reaction during use. A summary of the main types of secondary battery chemistries is provided in Table 2.15.

Table 2.15 Secondary Cell/Battery Chemistry Comparison **[97-103]**

Chemistry	Cell Voltage (Open Circuit)	Cell Voltage (Operating)	Charge Cycle Reaction Type	Operating Temperature	Typical Cycle Life	Typical Energy Density (20°C)
Sealed Lead Acid	2.1V	2.00 – 1.80 V	Exothermic	-20°C to 45°C	250 - 500	90 Wh/L
Nickel Cadmium	1.29V	1.25 – 1.00 V	Endothermic	-40°C to 45°C	300 - 700	100 Wh/L
Nickel Metal Hydride	1.4V	1.25 – 1.10 V	Exothermic	-20°C to 50°C	300 - 600	240 Wh/L
Lithium-Ion Polymer	4.2V	4.00 – 3.00 V	Endothermic	0°C to 50°C	1000+	410 Wh/L
Lithium-Ion	4.2V	4.00 – 3.00 V	Endothermic	-20°C to 50°C	1000+	400 Wh/L

From Table 2.15 it is evident that a power supply capable of functioning in conditions as required by typical neutron monitor deployment, the best possible battery solution is the Lithium-Ion chemistry.

Although it has slightly less capacity compared to the Lithium-ion Polymer chemistry, the temperature span is much wider than that of the latter and would be a viable option for deployment in harsh conditions.

2.13 Chapter Summary

This chapter investigated basic neutron monitoring and the typical operating conditions of neutron monitors. It reported on power supply metrics and its importance in comparing different power supplies in terms of performance and reliability. The various metrics are discussed.

It outlines the three basic types of direct current power supplies and makes a comparison between these to establish the suitability of each type for possible deployment in harsh environments. In conclusion to this section ii is found that the only viable option for deployment is a switch-mode power supply.

Chapter 2 investigates various common SMPS topologies as well as hybrid power supplies which combines elements of the linear and switch-mode types. The important factor of power supply isolation is discussed. Power supply stress factors such as electrical, mechanical and temperature stress, amongst others, received attention. Furthermore, corrective and preventative actions that can be implemented to mitigate the effect of the identified stress factors are discussed.

This chapter also details application specific power supplies in harsh environments such as what neutron monitors are exposed to. Previous work on neutron monitor power supplies are presented and conclusions that the off-the-shelf power supplies such as cell-phone chargers are not a viable option as a harsh environment power supply are drawn. Lastly are different types of batteries investigated in order to better understand battery chemistries and a possible solution to the research problem in terms of power back-up during mains disturbances.

CHAPTER THREE

Power Supply Design

This chapter deals with the research process in the development of the power supply. A system analysis which takes cognisance of the outcomes of the literature study is undertaken to determine the system requirements. An operational analysis is performed as basis for the requirements analysis. Finally, a functional design is synthesised from the requirements developed.

3.1 System Analysis

This section details the system analysis of a typical neutron monitor and more specifically its power supply. Various operational parameters will be identified regarding such a system and the most important factors selected for further study in the requirements analysis.

The system life-cycle approach originates from the identification of a need that arises due to a shortcoming of existing solutions, or the development of new concepts such as engineering advancement or environmental changes **[16]**.

The following issues should be addressed when following this process:

- What is the purpose of the system in terms of functional performance?
- What are the time scale requirements of the system?
- What are the operational parameters for the system in terms of duty-cycle of use?
- Where is the system to be deployed?
- What are the effectiveness requirements of the system?
- What are the environmental requirements for the system?

The accepted engineering systems analysis process is given in the flow diagram in Figure 3.1

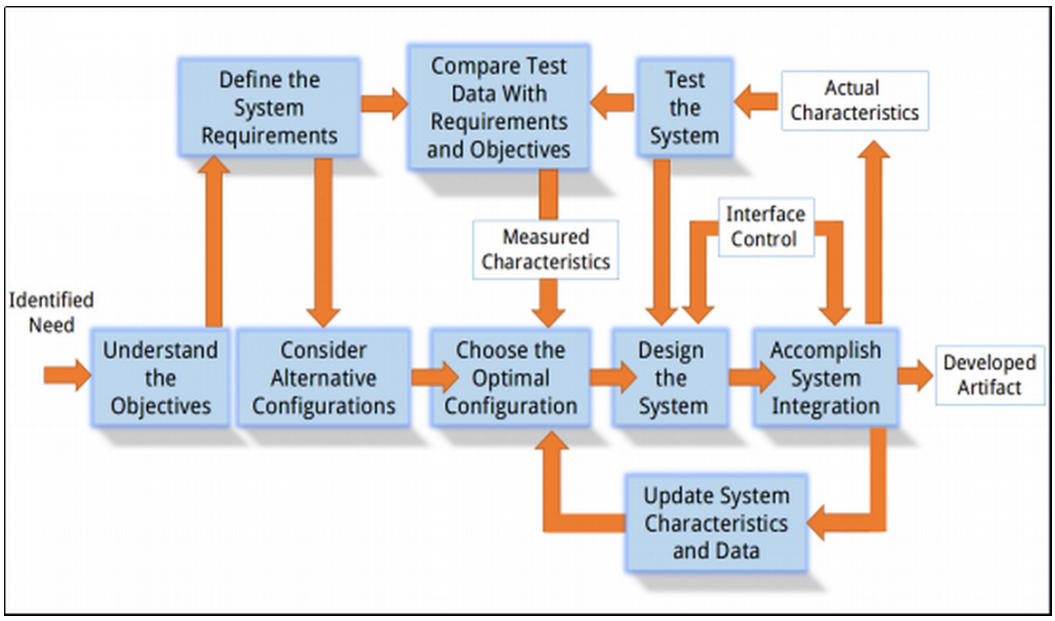


Figure 3.1 Systems Analysis Flow Diagram **[16]**

This process is a closed-loop, in that, where the results from the first steps are put to the test, via feedback, changes are applied and the results are compared against the original requirements.

From the diagram in Figure 3.1, it follows that a need is identified externally to the process. In order to solve engineering problems, a thorough understanding of the objectives should be obtained. Once this is established, the requirements for the new system or process can be defined. Since multiple possible solutions exist for the defined requirements, it follows that alternatives be investigated and weighed against each other. With the optimum configuration established, the detailed development process may be completed.

With the artefact integrated into a working prototype, actual operational characteristics can be determined via testing procedures. Test data is then compared with the system requirements and the measured characteristics used to optimise the integrated system. This iterative design process is repeated until an optimised, fully integrated system that meets all the requirements is produced. Often this artefact will still require further manufacturability optimisation, depending on the degree of the inclusion of these factors in the original requirements.

3.2 Operational Analysis

An operational analysis should be performed on a realistic, real-world scenario. In the context of this dissertation (with the synthesis of a harsh environment power supply in mind), an existing system should be investigated in order to establish a realistic baseline. As identified in the preceding chapter, cosmic ray

research using neutron monitors is a valuable source of tried and tested information for this process. Since these instruments are often deployed in harsh environments, these instruments will be used as a basis for the development of the system requirements.

In essence, a neutron monitor is a micro-processor controlled hardware platform, interfaced to a sensor array and a particle detector housed in in an associated enclosure. The functional operation of a typical neutron monitor is provided by the block diagram in Figure 3.2

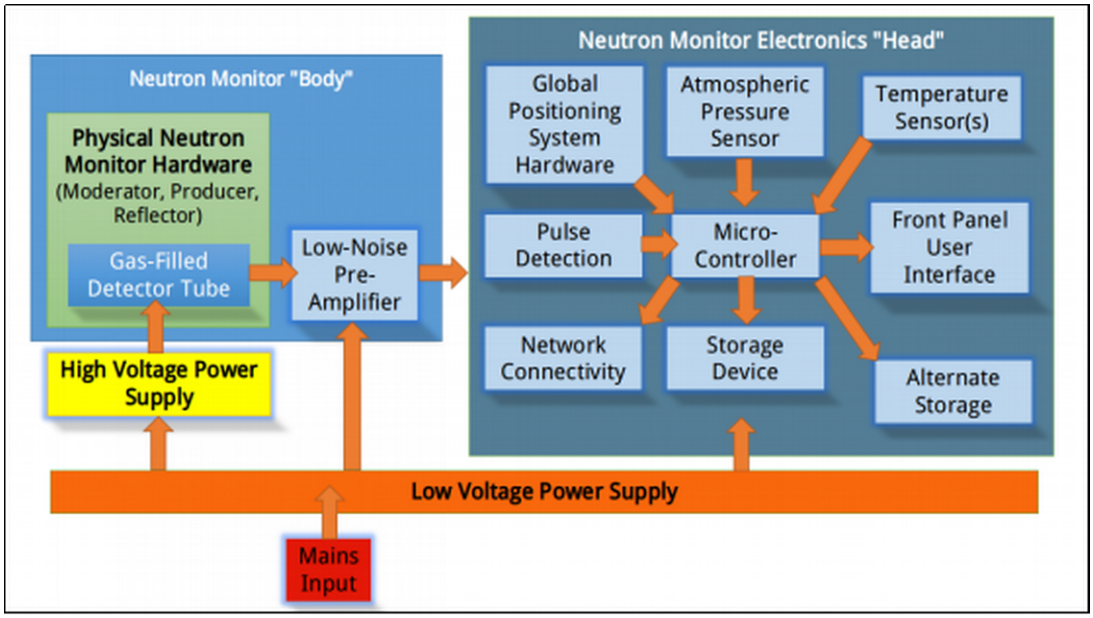


Figure 3.2 Functional Diagram of Basic Neutron Monitor **[13,14]**

In the above diagram, a micro-controller is employed to control system operation via firmware stored in non-volatile memory. A low-voltage power supply provides the correct voltages to the various sub-systems. A low-current, high-voltage power supply (±3600V) maintains the anode of the particle detector tube at the required voltage. This is done in order to accelerate and draw the particles formed in the detector gas toward the anode.

The incident neutron generates a single pulse on the detector tube's anode and is amplified by the low-noise pre-amplifier to a level sufficient for detection. In order to discriminate against noise that might be present on the signal line, a pulse detection circuit is used to register a pulse as a specific event. Average count rates for mini neutron monitors at the NWU CSR in Potchefstroom is 138 counts/minute **[10-12]**.

Once an event is detected, information such as time, atmospheric pressure, ambient temperature and GPS position measurements are taken and added to the data stream. This output is buffered and at predefined intervals written to the storage device(s) and/or network.

The typical operational conditions of neutron monitors of the NWU CSR in the field indicates the following operational parameters:

Table 3.1 Typical Operating Environment of Neutron Monitor **[9,10,20,22,23]**

Factor	Value	Description / Purpose
Optimum Operating Environment for NMs	19 – 25 °C	Ambient room temperature kept constant to minimise effect of temperature on count rate. Extend life-span and reliability through optimum conditions.
Coldest Operating Environment of Mini NM	-15°C Continuous, 3 Months	January 2007 outside the station at the SANAE IV Base, Antarctica absorption of cosmic rays by ice experiment.
Warmest Operating Environment of Portable NM	+50°C Daily Average Temperature	Thailand at the Princess Sirindhorn neutron monitor station on top of Doi Inthanon Mountain at 2565 meters above sea level
Highest Humidity	+90 % Relative Humidity > 4 weeks, Permanent	Princess Sirindhorn neutron monitor station, Doi Inthanon mountain, Thailand, Cosmic Ray Detection at High Altitude Experiment. Fixed NM as permanent installation at various global research stations.
Lowest Humidity	< 5% Relative Humidity 3 Months, Permanent	January 2007 outside the station at the SANAE IV Base, Antarctica absorption of cosmic rays by ice experiment.
Aircraft Transport Vibration	24 Hours (Combined Flight Time)	Such transport is used during shipment of neutron monitors from Cape Town in South Africa to various installation points in Europe, the Americas as well as the Far East.
Road Transport Vibration	Typical 1000 km	NWU in Potchefstroom to the South African Research Vessel in Cape Town Transport by truck to top of Doi Inthanon Mountain in Thailand.
Shipboard Installation	> Months	Low frequency vibration patterns for extended periods of time. Portable neutron monitor on-board the German polar research vessel, the *Polarstern*

Table 3.1 highlights a vast variety of operating conditions. As can be seen, neutron monitors have been operated in the most extreme of environments. These factors, or a combination of factors all contribute in a number of ways to the ageing and ultimate failure of neutron monitoring electronics hardware. The environmental effects on the NM electronics, however are also more pronounced under harsh environmental conditions. Since the gas-filled particle detector consists of a sealed, sturdy metal tube with a single anode wire place co-axially inside, very little problems, if any has ever been experienced with these. Problems experienced with neutron monitors remain largely with the electronic systems connected to the detectors.

The requirements analysis performed in the following section discusses the minute parameters involved in the operation of these instruments.

3.3 Requirements Analysis

As discussed in Chapter 1, Table 1.1, the operating parameters of a neutron monitor are based on physical processes that are minute. The electrical and electronic parameters of the system are therefore critical to the correct operation of the instrument. This holds true even more so under extreme conditions where external factors exacerbate any irregularities in the system design.

The following requirements have been identified as being of critical importance to the neutron monitor operation:

Table 3.2 Operating Requirements of Typical Neutron Monitor **[9,13,14]**

Requirement / Operating Value	**Description**
Infinitesimally minute nuclear reactions in particle detector	Single neutrons enter the particle detector and cause the break-up of detection gas (typically BF_3 or He_3). A small number of single electrons are released and accelerated towards the anode by use of stable high voltage potential. This causes a pulse (pico-ampere range) to form on the anode.
Ultra-Low noise amplification using a charge amplifier	Pico-ampere pulses are amplified and counted through the employment of a discriminator circuit.
Highly sensitive atmospheric pressure measurements;	Cosmic ray counts are directly proportional to atmospheric pressure. Sensitive barometers are used to detect parts-per-million changes in ambient pressure
Accurate temperature measurement	Detector temperature and environment, compensation in calculations
High speed data processing and storage	Pulses are counted, and ambient conditions such as time, atmospheric pressure, ambient temperature and location measurements recorded. This data-stream is stored on non-volatile flash memory or uploaded to a computer network
Reliability under harsh environmental conditions	100% Uptime required to record once-off events such as during solar activity.

From the above table it is clear that a neutron monitor is a sensitive instrument based on complex physics principles. Sensitive electronics are required to obtain accurate research data.

It is therefore imperative to utilise a well stabilised power supply in neutron monitor applications. Furthermore, such a power supply needs to maintain its characteristics under a wide range of operating conditions such as those found in harsh environments. Based on the functional diagram in Figure 3.2 as well

as the real-world operating conditions identified in Table 3.2, the detail requirements analysis can be completed.

3.3.1 Electrical Requirements Analysis

Since the required power supply is inherently an electronic device, its requirements and specifications in this domain must be established. This must be based on the requirements of the neutron monitr system and environment it is intended to operate in.

Referring to the literature study in Chapter 2, the following requirements of a typical, modern neutron monitor power supply, and by extension, a harsh environment power supply of a NM can defined as follows:

Table 3.3 Electrical Requirements Analysis for the Proposed Harsh Environment Power Supply

Parameter	Value	Tolerance
Input Voltage	Nominal AC Mains Supply 220V, 50Hz	Supply Voltage ±20%
Output Voltage	5 Volt	Line regulation: ±5% (Range: 4.75V to 5.25V) [1]
	12 Volt	Line regulation: ±5% (Range: 11.4V to 12.6V) [1]
Output Voltage	5V and 12V	Load Regulation: 5% of nominal mains supply
Output Current	5 Volt Rail: 700mA Maximum	+10% Overload [2]
	12 Volt Rail: 150mA Maximum	+15% Overload [3]
Ripple and Noise	< 100mV$_{P-P}$	Maximum permissible ripple and noise under all test conditions [4]
Output Linearity Over Entire Temperature range of -20°C to +50°C	< 1% of Both Output Voltage Rails	5V Rail – 50mV Non-linearity Over Entire Temperature Range 12V Rail – 120mV Non-linearity Over Entire Temperature Range
Back-up Battery Standby Time	Minimum of 1 hour over entire temperature range of -20°C to 50°C	Typical neutron monitor power consumption of 3 Watt
Back-up Battery Recharge	< 8 hours for full charge absorption	After complete-drain scenario, with deep-discharge compensation
Battery management with Cold-charging compensation	Continuous maintenance charging of back-up battery. Compensation algorithm for low-temperatures.	Maintenance charge at float voltage of 4.1/4.2V or 8.2V/8.4V for single/dual cell application (Coke of Graphite Electrodes) Maximum charge absorption in battery during cold conditions with automatic compensating algorithm.

Parameter	Value	Tolerance
Cold-Boot Feature	Trigger @ 3.3V for >1 second. Initiates ±1 minute power-down of both main output rails to cold-boot entire system.	2 x Independent inputs for watchdog triggered system reset feature to reset high voltage components and locked-up micro-controller/memory. Failure of this reset circuitry must not negatively affect power supply reliability. High noise-immunity input i.e. current driven instead of voltage.
Low-power Memory Back-up Rail	3.3 V, maximum of 20mA	Power supply during extended power outages for Memory, RTC or GPS application. Fully independent from main output rails. Current limited and fused. No low-battery warning. Maximum standby time from on-board backup battery .
Auxiliary Output	Output: ±16V_{DC} Unregulated raw, smoothed and filtered. 3W or 200mA Maximum	Capable of powering additional external equipment while mains supply is present. This includes adjacent NM electronics in case of failures of adjacent modules on multi-detector systems. (This additional load is not included in battery standby times)
Auxiliary Input	8V to 20V Input	Able to accept secondary power input such as external solar panels or power from adjacent NM power supply on multi detector system.
Steady-state on 5V and 12V output rails required	< 64ms	Mini-neutron monitor's micro-controller requirement **[37]**
Additional Criteria: • All inputs and outputs to be protected against over-voltage through the use of transient voltage suppressors • All inputs, outputs and battery lines to be fuse protected • Switch-mode regulators must have notch filtered output at switching frequencies • Power supply must be rated for continuous operation (100% Duty Cycle) under all conditions set out in section 3.4.1. and section 3.4.2.		

[1] Secondary voltage regulation to be provided at various sub-systems of NM

[2] 10% overload on 5V rail due to point [1] and NM micro-controller power requirements and relative stable current draw over full work-load **[14,37]**

[3] 15% overload on 12V rail to ensure system remains stable during start-up of low impedance load such as high voltage power supply and pressure sensors

[2,3] Maximum Combined Load of 5 Watt on both 5V and 12V rails

[4] Full temperature range as set out in Environmental Requirements Analysis

3.3.2 Environmental Requirements Analysis

Because these power supplies are also required to perform under adverse environmental conditions, the following requirements from an environmental perspective will also be mandatory to adhere to in the final design.

Table 3.4 Environmental Requirements Analysis for Proposed Harsh Environment Power Supply

Parameter	Description	Tolerance
Operating Temperature Range	-20°C to +50°C	±5% [1]
Mechanical Robustness	Shocks and Vibration	Artefact must withstand moderate shocks and vibration typical to normal handling and operating conditions to within reasonable limits [2]
Intrinsic Reliability and Safety	Final artefact enclosed to IP rating (as per section 2.4.4) to comply to requirements as laid out in section 3.4.1 and 3.4.2	Power supply must be intrinsically safe when fitted into a suitable enclosure. No part of the unit can be touched while in operation. Limited or no ingress of dust and humidity permissible.
Easy of maintenance	Minimum tool-count required for maintenance. No specialised equipment requirements for repair.	Maintenance personnel should be able to easily replace mains input or battery fuse and perform general maintenance such as inspection or cleaning without excessive dismantling.
Physical Size	Most compact configuration of components and back-up battery to satisfy electrical parameters set out in section 3.4.1 (Electrical Requirements Analysis)	Unit must be compact enough for deployment in typical neutron monitors, including legacy units, current and future neutron monitors.
Flame Retardant Materials	Enclosure, components and fasteners	Artefact to be manufactured from flame retardant materials to limit damage to the surrounding environment in case of malfunction and to increase safety.
Additional Criteria: • Power supply must be rated for continuous operation (100% Duty Cycle) under all conditions set out in section 3.4.1. and section 3.4.2.		

[1] ±5% deviation from specified temperature for a maximum of 5 minutes per deviation. This is to account for typical air-conditioner thermostat hysteresis during normal operation (specifically electro-mechanical thermostats).

[2] Typical NM operating conditions on-board ships, aircraft and permanent installations to within reasonable limits.

[3] Full temperature range as set out in section 3.4.2 (Environmental Requirements Analysis).

As the above table indicates, a final artefact must be constructed in such manner that the reliability is of paramount concern. Since the advent of neutron monitors in the 1950s, the electronics that form part of these instruments have not only decreased in size, but also increased in efficiency and complexity. This statement also holds true for electronic systems in general. Therefore, the establishment of proper design-criteria, before the design-phase of power supplies play an ever increasing important role in the performance of electronic equipment.

Considering that scientific research apparatus (such as neutron monitoring equipment) is used to observe sometimes “once-off” events, the sub-systems that make up these instruments are required to be highly

reliable with factors such as efficiency, compactness and cost considerations of lesser importance. A trade-off is made between these factors with reliability as main criteria.

3.4 Test Methods and Applicable Standards

Power supplies are often required to perform under adverse environmental conditions. Since the artefact designed in this dissertation is a proof-of-concept, the following test methods and international standards will only be used as guideline for performance testing. Table 3.5 summarises the proposed test plan.

Table 3.5 Proposed Test Methods for Harsh Environment Artefact * **[57,68]**

Parameter	Test Standard/Guideline	Test Equipment and Conditions
Output Voltage	As defined in section 3.4.1	Measured by means of Endress & Hauser RSG-30 Recorder at each temperature described in this table. Artefact connected to load resistances on both rails.
Output Current	As defined in section 3.4.1	Continuous measurement using series-connected Fluke 77 DMM and load resistances
Output Ripple	As defined in section 3.4.1	Tiepie HS-3, 2 Channel, 100MHz PC Based Oscilloscope, 10:1 Probes
Standby-Battery Voltage during Maintenance Charge, Discharge and Full Recharge Cycles	Battery Manufacturer Data sheet, Battery Management Device Data-sheet	Measured by means of Endress & Hauser RSG-30 Recorder at each test-temperature described in this table. Connected directly to battery terminals during all tests. Artefact to be subjected to test-temperature for 15 minutes prior to starting discharge of fully charged backup battery. Discharge to be terminated upon battery reaching low voltage. Artefact to remain at test-temperature until battery management declares full charge absorption. Artefact to be moved to following temperature in test sequence as defined in Table 3.5 (Temperature Function)
Vibration Testing	MIL-STD 810G Method 514.6 **[68]** [1, 2]	<u>Sine Vibration Test:</u> Ling Dynamic Systems (LDS) Amplifier, model: DPA.4 and matching electro-dynamic shaker. Ling Dynamic Systems (LDS) Sine Program Controller, model: SPC4 Diagnostic Instruments, Real-Time FFT Analyser/DSO, model: Di-2200 PCB Piezotronics Accelerometer mounted to shaker platform
Shock Testing	MIL-STD 810G Method 516.6 **[68]** Procedure IV - Transit Drop. [1, 4]	Artefact to be dropped once manually in 3 x axis on table-top surface from 300 mm height representative of being dropped while handled by installer or maintenance person during typical use.[4]
Temperature Function	As per sections 3.4.1 and 3.4.2	<u>Multiple steps of 14°C simulating the following conditions:</u> -20°C – Coldest operated portable NM, SANAE IV Base, 2006 -6°C – Average outside summer temperature at SANAE IV Base +8°C – Average room temperature at SANAE IV base during year +22°C – Average maintained fixed NM room temperature, NWU CSR Potchefstroom +36°C – Typical ambient summer temperature, Potchefstroom +50°C – Highest temperature for portable NM, Thailand 2009

Parameter	Test Standard/Guideline	Test Equipment and Conditions
Temperature Shock	MIL-STD 810G Method 503.5 [1] **[68]**	Test is performed by alternating the fully functional and fully electrically loaded artefact between ambient room temperature to -20°C for 5 typical complete cycles. Output voltage, current and ripple comply with specifications outlined in section 3.4.1.
Humidity	MIL-STD 810G Method 507.6 and 520.4 [1, 5] **[68]**	Final design will entail a suitably IP rated enclosure to protect the power supply against any ingress. This proof-of-concept artefact will it not be verified for its performance at various levels of humidity.
Altitude	MIL-STD 810G Method 500.6 and 520.4 [1, 5] **[68]**	The proof-of-concept artefact will it not be verified for its performance at various altitudes. However, altitude rating of components should be considered for this proof-of-concept design to minimise the impact of altitude on the final design.

* THE PROPOSED TESTING OF THE ARTEFACT IS PLANNED IN ACCORDANCE TO THE AVAILABILITY OF TEST EQUIPMENT AND FACILITIES; INTERNATIONAL STANDARDS ARE USED ONLY AS GUIDELINES/REFERENCE AND NOT INTENDED TO BE ABSOLUTE TEST CRITERIA.

[1] As per United States Department of Defence, MIL-STD 810G, tests can be adapted to suit specific needs or environments, please see "Tailoring Guidance" sections in MIL-STD 810G, 31 October 2008.

[2] MIL-STD 810G, Method 514.6A-1: "Levels may be lower than life cycle environments to avoid damage to a prototype"

[3] MIL-STD 810G, Method 516.6-3, TAILORING GUIDANCE, Functional Shock: "materiel [6] is required to function during the shock and to survive without damage to shocks representative of those that may be encountered during operational service."

[4] Test to be repeated after final ready-to-market product is assembled into IP rated Enclosure

[5] Testing of proof-of-concept artefact will not involve these tests but are to be performed on final, ready-to-market product.

[6] Military materials and equipment (Collins Dictionary)

3.5 Preliminary Design

During the period July 2009 to December 2014, the researcher was involved in the design, manufacture and maintenance of neutron monitors for the NWU CSR. A number of power supplies of various topologies were designed and constructed during this period.

Table 3.6 consolidates this background work and the research presented in the preceding chapter. It motivates the various selected sub-systems used to obtain an optimal topology based on the requirements derived.

Table 3.6 Preliminary Design of Artefact

Proposed Topology	Motivation/Description
Mains transformer	• Intrinsic high-frequency attenuation of iron-core transformer acts as passive filter for high-frequency noise that is present on the mains input • A transformer also provides galvanic isolation of several kilovolt between the mains supply and the powered equipment as proven in Chapter Two • Low-loss, high quality toroidal transformers emit very little electro-magnetic interference (EMI) compared to high-voltage, switch-mode power-conversion that directly switches rectified mains
Dual rectifier path	• Separation between main power-path and auxiliary power-path diminish noise cross-talk between main path and auxiliary systems • Redundant components reduces load on each individual rectifier thereby increasing reliability • Wider distribution of heat in 2 rectifiers vs a single rectifier lead to enhanced heat dissipation
Switch-mode	• Intrinsic losses of linear regulators are unsuitable for battery-powered equipment • Linear controllers generates undesirable waste-heat that affects reliability of other components and sensitive electronic equipment such as particle detectors • Switch-mode regulation provide for easier adaptability in terms of input and output voltages • Switch-mode topologies are more accommodating towards battery discharge-curves
High-frequency Switch	• High-frequency operation allow for smaller footprint components • Filtering of switching frequency more easier attainable due to component availability and small size
Battery Chemistry: Li-ion	• Li-ion has highest energy density of all chemistries • Proven track-record in millions of portable devices world-wide • Wide variety of battery management controllers available • Li-ion does not suffer from memory effect • Wide operating temperature span
Solid-State Change-over	• Over-specified solid-state switches such as transistors and diodes have negligible switching-on time compared to mechanical relays • Mechanical relays are prone to failure due to excessive vibration. • Solid-State devices have smaller footprint

From the provided literature, it can be concluded that no one specific topology provides for perfect application in the instance of harsh environment application. All of the discussed topologies falls short on one or more of the critical parameters when investigated for harsh environment application.

Efficiency plays a critical role in any battery powered system due to the limited storage capacity of the cells. A power supply that has to provide power to a system during a mains failure has to maximise standby time by operating at maximum efficiency. As per section 3.4.1 (Electrical Requirements Analysis), a battery back-up will also be provided.

3.6 Proposed Architecture

Based on the results of prior work performed during this researcher's employ at the NWU CSR and this research, a hybrid topology is selected since it provides a "best-of-both" approach, although technically more complex. This hybrid topology provides for a robust input section, capable of resisting sustained mains-borne irregularities, good galvanic isolation and an efficient switch-mode output stage to maximise battery standby time during power outages.

The following functional block diagrams can thus be drawn up, detailing the functional lay-out of the proposed power supply:

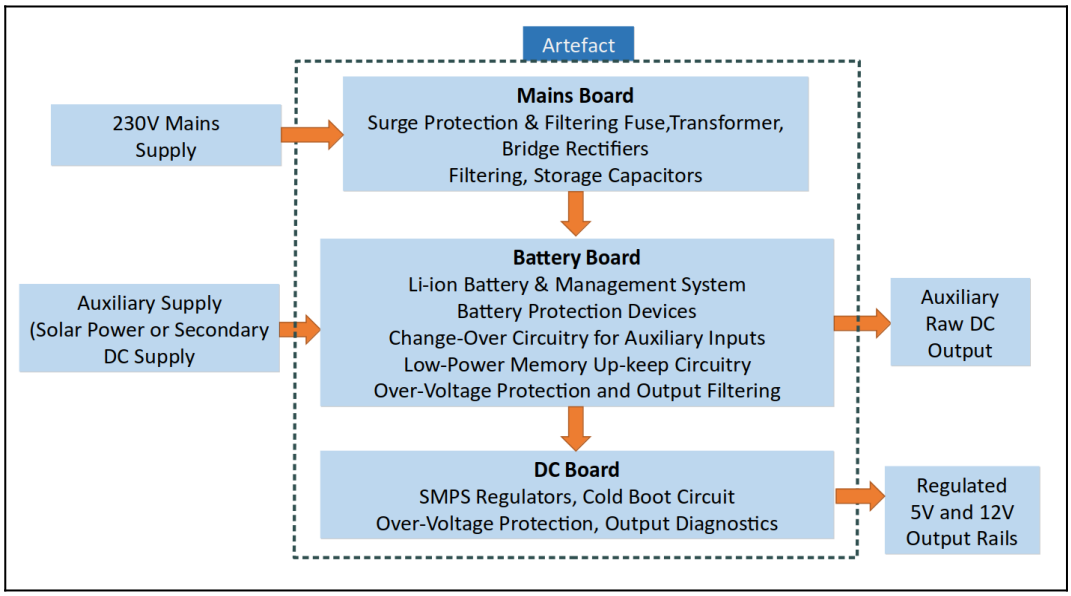


Figure 3.3 Functional Diagram of Artefact

The following sections describes the three sub-assemblies identified in Figure 3.3.

3.6.1 Mains Board

In order to facilitate manufacture, and ease of operation and maintenance a modular construction will be used. As shown in Figure 3.3, the various sub-systems of the power supply will be implemented on separate circuit boards to provide ease of access to components as well as limit the transfer of disturbances from the input through the power supply circuitry to the output.

A further advantage of modular construction, although not initially apparent, is that it aids in fault finding should it be required. Concerning field repair, it is often impossible to undertake fault-finding at the component level. Indeed, the replacement of a whole sub-system often saves down-time during repairs.

The first sub-system is the Mains Input and Filtering section as laid out in Figure 3.4.

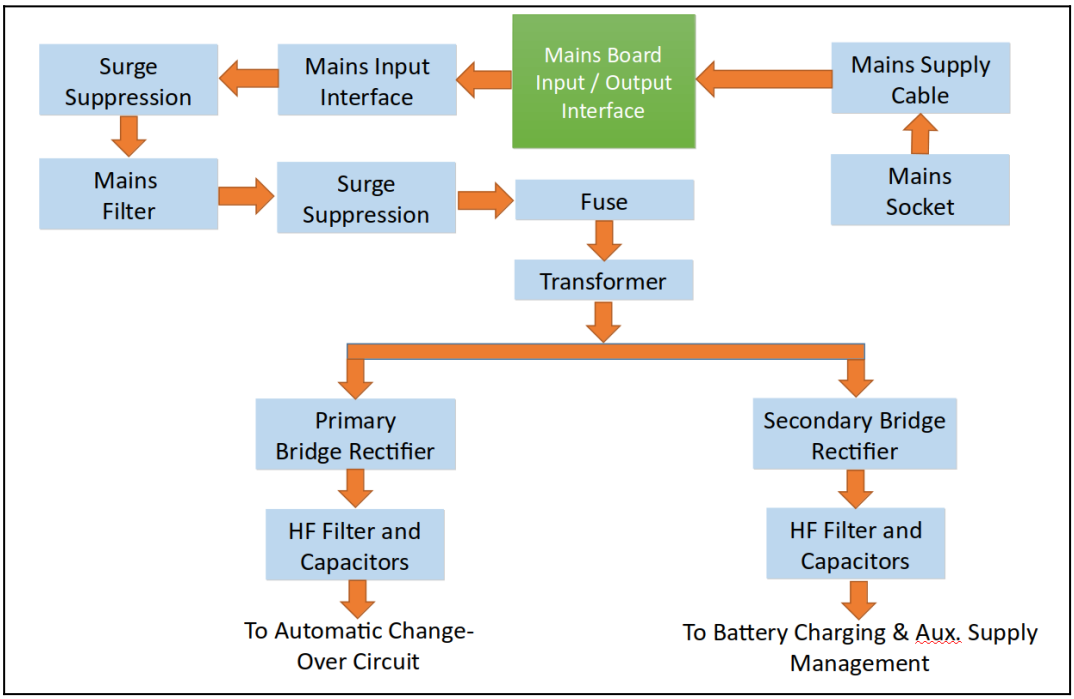


Figure 3.4 Mains Input and Filtering Section Functional Block Diagram

The below table details the motivations for the use of specific components:

Table 3.7 Component Choice Motivations for Mains Board

Components	Motivation/Description
Mains Input Interface	• Voltage rating, Current rating, Mechanical robustness, Safety to both humans and equipment, Physical size, Future expansion capacity • Not required for proof-of-concept artefact but final version to have proper mains input plug/interface not prone to accidental disconnection due vibration or human error • Mains Supply Plug: Sturdy, 3 Pin, Rubber Top Plug • Mains Cable: 3 Core, Double insulated, Hard wearing insulation, Multi-Strand • Input Interface: Mechanically Robust, Voltage/Current rating, Safety, Size, Expansion
Surge Suppression	• Spark Gap: Bulk absorption of power disturbances, Durable and robust under severe overload • Metal Oxide Varistor, Bulk Absorption, Durable, Response time faster than Spark Gap • Neon Lamp, Over-Voltage Protection, Indicates presence of dangerous mains voltages to users (Trouble shooting, diagnostics, safety)
Noise Suppression	• Line Filter, Wide frequency attenuation, Common mode and differential mode noise rejection, Robust specifications, Compact size, Flame-proof construction
Over-current Protection	• Fuse (slow blow), surge handling capability, slightly over specified to prevent false operation and premature aging • Placed after surge suppression and noise filtering components to increase life-span
Transformer	• Relatively high efficiency, Low Volume (compact size), Attenuation of High Frequencies (High Selectivity for 50/60Hz), Low Hum & Noise levels, Low Copper Losses, Flame Proof construction, High Isolation Voltage, Low EM Radiation Toroidal Transformer. • Secondary windings connected in parallel to reduce copper losses

Components	Motivation/Description
Rectifiers	• Full wave diode bridges: Highest rated voltage available in a SMD COTS package
Storage Capacitors	• Storage Capacitors Low ESR, Low Volume, Multiple capacitors to reduce surge current, extend life-span, reduce ripple. • All Aluminium storage capacitors to be de-coupled by small-value ceramic capacitors to reduce high frequency noise and improve filtering • High and Low temperature ratings suitability for temperatures as per section 2.2 and Table 3.1

The mains sub-section of the power supply described above, will be housed on a separate printed circuit board to minimise mains-borne interference from readily passing through to the rest of the low-voltage components.

Because a fuse is a designed weak-spot in any circuit, the fuse is preceded with over-specified surge suppression and filtering to protect the mains fuse. The low-loss toroidal transformer does bulk conversion and provides galvanic isolation between the AC mains input and the low-voltage components of the load. Two robust rectification channels are placed adjacent in order to spread the load on each, thereby increasing the reliability of each diode bridge.

By using two individual rectifier bridges, generated heat is also dissipated over a larger area, aiding in passive cooling of these components. These two channels are responsible for supplying low-voltage unregulated direct current to the main power path as well as auxiliary sub-system s such as battery charging and control functions. This lay-out ensures less electrical stress on any individual component.

3.6.2 Battery and Control Section

The second sub-system detailed in Figure 3.3 is the battery and control board of the power supply. As was the case with the mains board, similar functions are integrated on discrete circuit boards to minimise interference between sub-sections of the power supply and to aid in diagnostic and repair procedures.

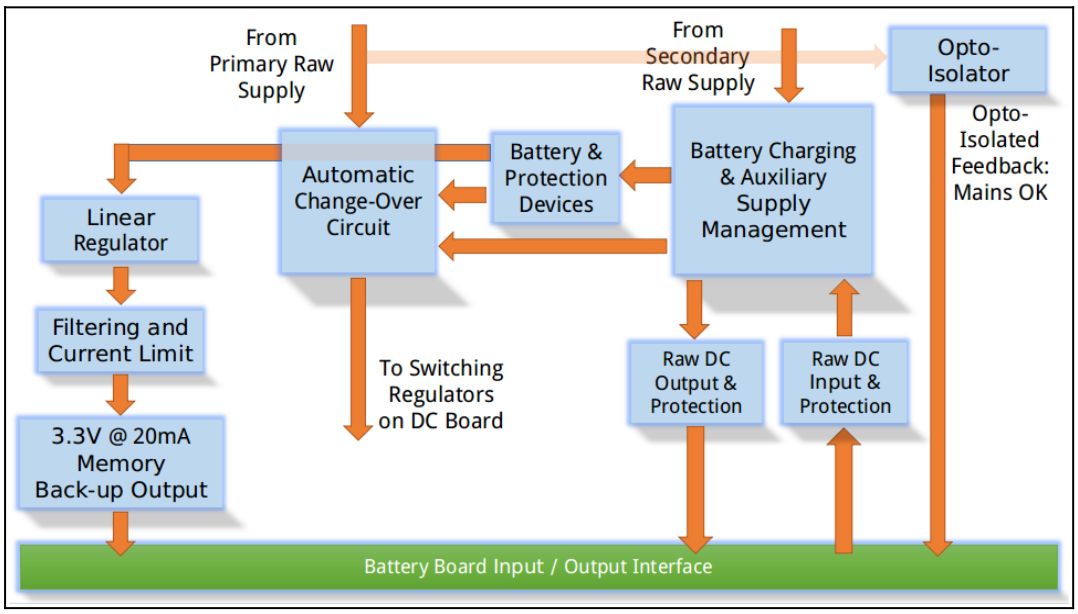


Figure 3.5 Battery and Power Control Section Functional Block Diagram

The following table (Table 3.8) motivates the various sections within this sub-system of the artefact and prescribes the requirements for the various components in order to ensure full functionality and robustness:

Table 3.8 Component Choice Motivations for Battery and Power Control Board

Components	Motivation/Description
Battery Management	• Li-ion Cells for highest energy density, Compact size, Readily available management integrated circuits, Proven track record • Higher voltage / cell than other battery technologies • No memory effect compared to older/other battery chemistries
Battery Protection Devices	• Battery cells / pack must be over-current protected (apart from external battery fuse) • Integrated thermal cut-out in physical contact with battery pack, cut-out at 65°C
External Power Input	• Capable of accepting wide input voltage range • Complete “hit-less” switching from internal to external power input during primary power input failure • Transient Voltage Suppressed
Expansion Options: Auxiliary Output	• Raw unregulated, filtered direct current (DC) available for powering external equipment • Transient Voltage Suppressed
Automatic Change-over Circuit	• Change-over should happen in a “hit-less” manner with no loss of power or induced noise or interruptions during operation i.e. instantaneous transfer of power. • Solid-State device of at least 10x rated current provides reliability and immunity to vibration and effects such as magnetism or induced currents. • Highly robust design to ensure maximum reliability • Low-insertion loss during operation
High Impedance Standby Output	• Voltage regulated and current limited “always-on” output regardless of power supply • High impedance standby output • Transient Voltage Suppressed

Centrally to the battery and power control board is the automatic change-over circuit. This provides a constant flow of current to the switch-mode regulators, regardless of the source of the power. A robust, dual Schottky diode with common cathode is employed in this regard. Figure 3.6 shows the schematic symbol and SMD component lay-out for such a package:

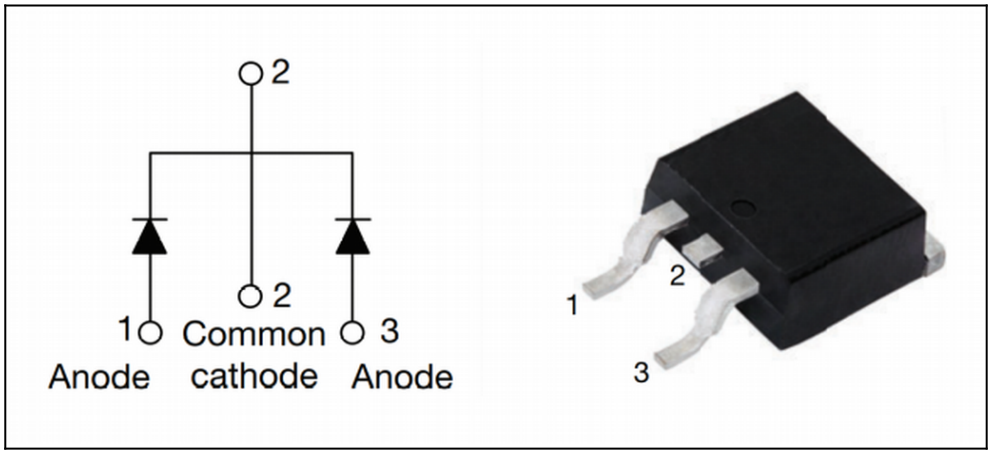


Figure 3.6 Dual Schottky Diode Schematic (left) and Physical SMD Package Indicating the Pin-Out (right) **[104]**

In the event that the input power on the primary power path falls below the voltage of the battery, current is allowed to flow from the battery through the second diode in the package, thereby maintaining continuous input to the down-stream components. Figure 3.7 indicate the circuit diagram with the dual diode package (diode D5) responsible for the change-over. The green arrow indicates the main power-path under normal mains supply conditions. Upon failure of the mains power, either through AC input failure or a component failure, the Schottky diode will conduct via pin3 of D5 (orange arrow) and maintain the current to the switch-mode regulators.

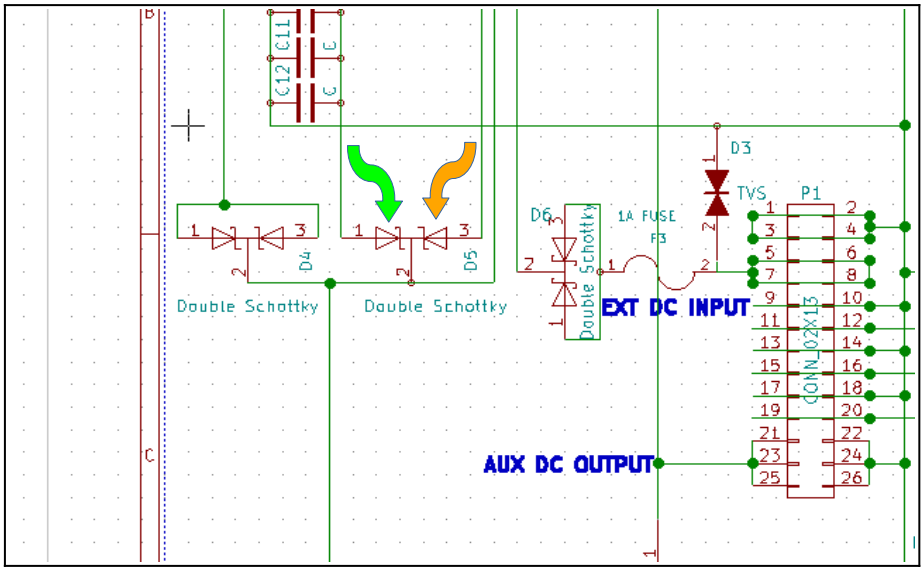


Figure 3.7 Enlarged Schematic: Power-Path Switch (Diode D5)

This circuit board also contains the Li-ion battery management controller. This handles the charging of the Li-ion battery pack and ensure maximum charge absorption in the shortest possible time. Furthermore the management system maintains the battery at the correct float voltage during normal operation.

The unregulated direct current output allows for the powering of external devices such as pressure sensors or even a complete neutron monitor system powered by a similar power supply such as this. This added redundancy shares the load of an adjacent neutron monitor in case of mains input fuse failure of the latter.

The direct current input, allows for an adjacent harsh environment power supply (possibly of similar design) to provide power in the event of a mains input fuse failure on this power supply. Additionally a secondary source of power such as a solar panel and regulator can be connected to this input as backup to the mains power, or as primary source of power to the system altogether. This allows for the artefact to be deployed in locations where no mains power is available. Both these input and outputs are transient voltage protected with MOVs and over-current protected by means of self-resetting poly-fuses.

The linear regulator is protected by a self-resetting fuse and is current limited in order to provide, according to the requirements, a continuous, low-power source for real-time clocks, global positioning hardware or memory backup.

3.6.3 DC Output Board Section

The third and final section of the artefact is yet again implemented on a separate printed circuit board and consists of the switch-mode regulators, cold-boot circuitry, and all diagnostic and fault-reporting components.

In order to further limit the radiated electrical noise from the high frequency switching components, both the 5V and 12V SMPS regulator circuits will be individually shielded. Figure 3.5 shows the functional block diagram of this board.

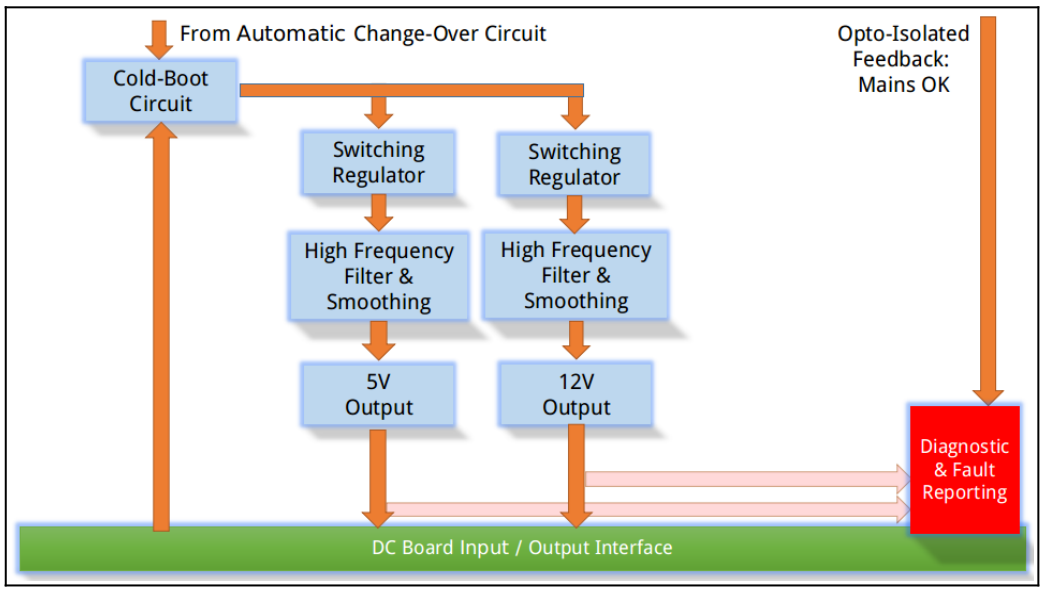


Figure 3.8 Direct Current Output Board Functional Block Diagram

The following table details individual component requirements and motivates the use of specific components in order to finalise the design of the artefact.

Table 3.9 Component Choice Motivations for DC Output Board

Components	Motivation/Description
Switching Regulators	• Switch-mode topology must be capable of accepting input voltages higher, equal and lower than the output voltages • Single Ended Primary Inductor Conversion (SEPIC) regulator satisfies this criteria with low noise output and improved load regulation • High frequency (>1 MHz) operation ensures small footprint components • Monolithic design of controller to increase noise-immunity and limit electro-magnetic interference (EMI) to nearby components • High efficiency, low-loss switch integrated into controller package • High efficiency controlling algorithm to ensure maximum battery standby time during primary power input failure
High-frequency Filter	• Notch filter with maximum attenuation at switching frequency • High current capability • Small footprint, shielded body • Low radiated electro-magnetic interference (EMI)
Smoothing Capacitors on Output Circuit	• Low ESR, Low Volume, Multiple capacitors to reduce surge current, extend life-span, reduce ripple • Aluminium storage capacitors to be bypassed by small-value ceramic capacitors to reduce high frequency noise and improve filtering • High and Low temperature ratings suitability for temperatures as per section 2.2 and Table 3.1 • Transient Voltage Suppressed
Cold-Boot Circuit	• Accept 2 x isolated inputs from watchdog circuitry • Current driven and not voltage driven to improve noise immunity
Output Interface	• Physical robustness against mechanical stresses • Low insertion-loss • Current carrying capacity of total system input/output

The raw, filtered current from the battery and control board are fed, through the cold-boot circuit, to the monolithic, switch-mode regulator of each voltage rail respectively. These regulators will be chosen for factors such as efficiency, reliability, ease of implementation and temperature stability. In order to further reduce volumetric requirements and increase switching efficiency, the frequency of operation will be selected to be as high as practically possible to reduce the size of the inductors and to ease the filtering of unwanted noise from the output.

Since most processor and memory devices operate at a lower voltage level than what is being provided by the output rails, custom voltage requirements can be catered for in this modular approach through point-of-load regulation.

Because switch mode topologies and their associated components have been shown to be noisy in terms of output and radiated electro-magnetic power, special precaution will be needed in the design of the low-voltage filtering circuitry. Integrated switch mode regulator circuits are chosen to be of constant frequency, rather than variable frequency types, even at the expense of lowered efficiency. These regulators operate at a fixed frequency ensuring that the filtering of unwanted switching noise can optimised for the operating frequency and its harmonics. The filter elements will be selected to have maximum attenuation at the switching frequency of the switch mode regulators. Figure 3.9 shows the fundamental switching frequency of 390kHz for a typical SMPS and the harmonics of the fundamental frequency **[105]**.

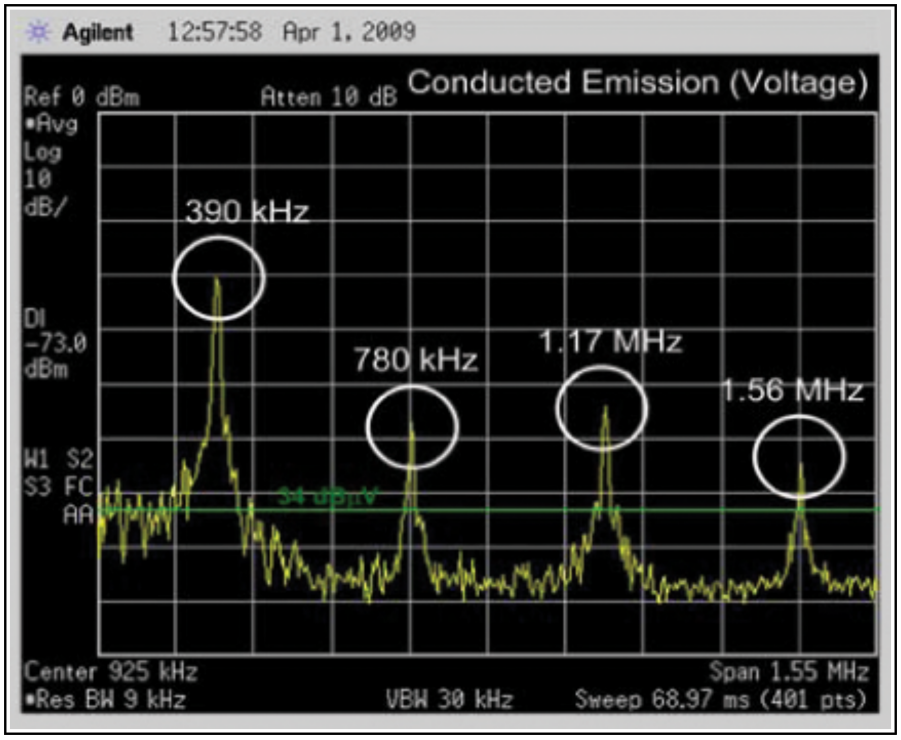


Figure 3.9 Spectrum Analysis of 390kHz SMPS **[105]**

By maintaining the switching frequency constant, the harmonics of the fundamental switching frequency can therefore more readily filtered.

The cold-boot circuitry is chosen for minimum component count with no software that can be corrupted. A single transistor has to be biased with the correct voltage and current for the required time to activate the cold-boot circuit. The main power path is through a vibration immune mechanical relay's normally closed contacts. Under normal conditions, the relay simply allows current to flow to the switch-mode regulators.

When the input to the cold-boot circuit it correctly biased by a command from, for example a watch-dog circuit, the relay coil is energised and the current flow through the primary power path interrupted. After the pre-determined time, the relay contacts is released and power restored. A failure in any of the associated components will not adversely affect the operation of the system since the relay contacts will simply remain in the closed position, allowing uninterrupted current flow.

As a neutron monitor is a sensitive apparatus and contains expensive pressure transducers, high voltage power supplies and memory devices with research data, the output from the power supply must also be protected against abnormal conditions. Over-voltage protection in the form of metal oxide varistors are placed on each of the output rails to protect the powered equipment from catastrophic failure of the power supply or from damage such as a direct lighting strike on the mains input that passes through the power supply.

3.7 Chapter Summary

This chapter dealt with the research of the physical conditions and operating parameters under which neutron monitors operates.

Based on this information, the functional lay-out of the artefact was developed. With this information combined with the literature study performed in chapter 2, the detail design can be completed in the following chapter.

CHAPTER FOUR

Power Supply Synthesis

This chapter provides all relevant information involved in the physical design, lay-out and construction of the power supply. As stated in the Delimitations of Research, it is assumed that the reader is familiar with the standard procedures of printed circuit board design and manufacture. A software simulation on the switch-mode regulators is performed in order to achieve maximum efficiency. Furthermore a brief overview is given of the individual circuit boards, their lay-out and function. The artefact will be synthesised using an iterative process as described Section 3.2 and specifically Figure 3.1

4.1 Simulation

Since the most complex part of the circuit involves the switch-mode regulators for the two output rails, the following section details the simulated design of these. A high frequency SEPIC switch-mode regulator was chosen since these provide for a wide input voltage range, reduced output ripple and a small component footprint. The SEPIC topology also has better immunity against short circuit scenarios **[33,45]**.

Because reliability is of utmost importance in the development of a harsh environment power supply, a low component count directly translate into increased reliability **[45]**. In order to reduce development time and costs, an integrated SEPIC switch-mode controller from Linear Technology is chosen with a minimum external component requirement. Using the parametric search engine on the Linear Technology website, provided a number of options. The LT1377 integrated circuit satisfies all the requirements for such a switch-mode driver and was selected.

Through an in-depth study of the data sheet and application notes the circuit diagram in Figure 4.1 was developed and simulated with the LTSpice software package from Linear Technology.

Figure 4.1 shows a screen-shot of the 5V rail's circuit simulation at a minimum input voltage where the Lithium-ion battery is close to being fully discharged.

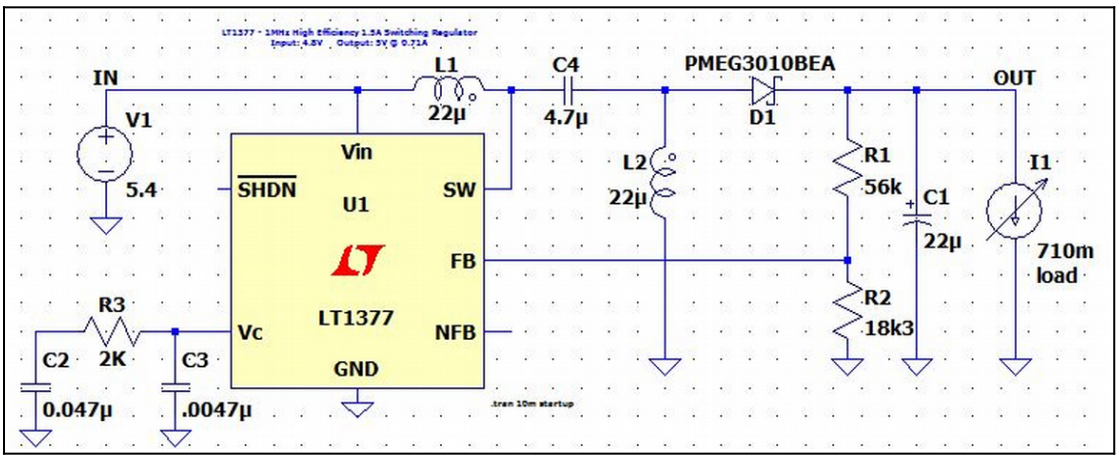


Figure 4.1 Circuit Diagram of Simulated 5 Volt SEPIC Converter

The circuit in Figure 4.1 was designed using the data-sheet for the LT1377 SMPS regulator as basis **[44]**. The following circuit parameters were analysed in the simulation to ensure that none of the power-handling component's operating limits are exceeded and that the optimum design was reached:

Table 4.1 Circuit Analysis Parameters

Parameter	Voltage/Current	Description
Input Voltage	**Voltage**	Typical rectifier output at nominal mains voltage:±16V Li-ion battery voltage at full charge: 8.2V Li-ion battery at nominal voltage: 7.2V Li-ion battery voltage at minimum: 5.6V
Temperature Range	**Load current at Specified Voltage**	All parameters in Table 4.1 analysed over -20°C to +50°C range in 14°C increments
L1	**Voltage**	Ripple Measurement, Steady-state Time duration, Peak voltage over LT1377 switching element and inductor limits
	Current	Peak and continuous current within LT1377 and inductor limits
C4	**Voltage**	Maximum voltage within capacitor limits
	Current	Ripple current through C4 within limits of component
L2	**Voltage**	Ripple Measurement, Steady-state Time duration, Peak voltage within LT1377 and inductor Limits
	Current	Peak and continuous current within LT1377 and inductor limits
D1	**Voltage**	Maximum voltage across junction within limits
	Current	Instantaneous and Average forward current within diode specifications
C1	**Current**	Ripple current on capacitor within limits of component
Output	**Voltage**	Output voltage and ripple within specified limits,
	Current	Ripple currents at minimum, meeting requirements

The micro-controller used in the current mini-neutron monitors specifies a maximum power-up timer period of 64ms **[37]**. This timer keeps the micro-controller in a wait-state after power-up to enable parameters such as the power supply and ADCs to stabilise before the execution of instructions commences.

Along the parameters analysed as per Table 4.1, the circuit diagram in Figure 4.1 was also optimised for reaching a steady-state within this limit of the micro-controller as per the electrical requirements analysis in Table 3.3. With the optimisation complete, the output from the optimised simulation for the 5V rail is shown in Figure 4.2. For clarity, not all simulated parameters are shown simultaneously on the same graph (Figure 4.2).

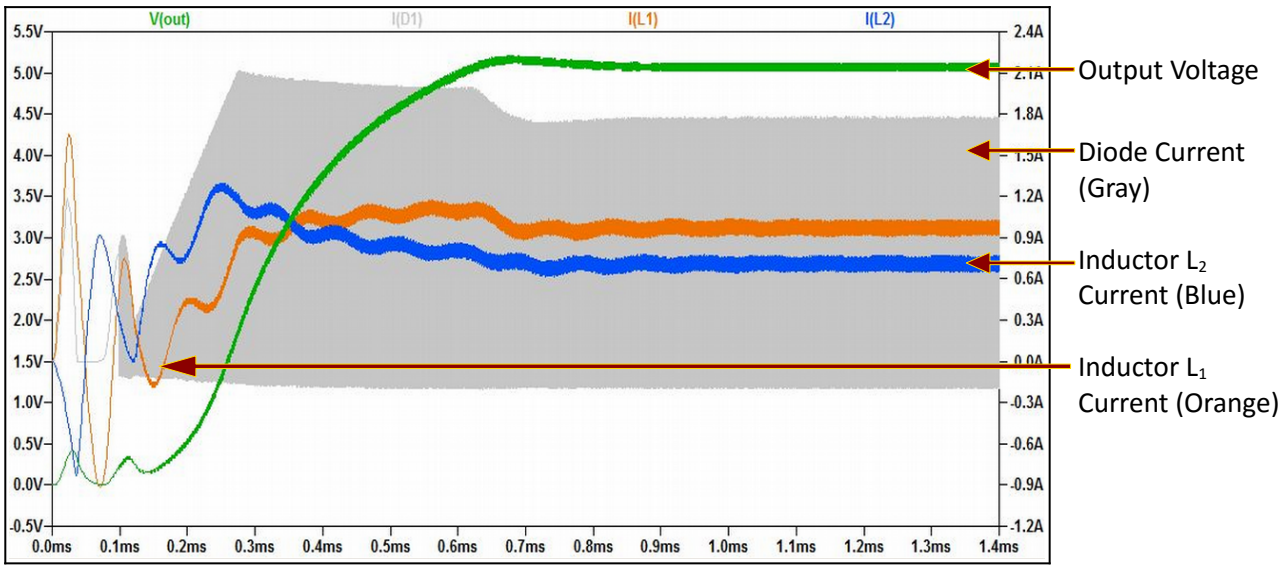


Figure 4.2 Simulated Parameters of the Optimised 5 Volt SEPIC Converter

In the above simulation (Figure 4.1 and Figure 4.2) it was found that the coupling capacitor C_4 plays a critical role in the transfer of energy between the two inductors. If the value of this capacitor is decreased, the coupling between the two inductors is negatively affected causing a high ripple current in both the inductors and the coupling capacitor. By sufficiently increasing the value of this capacitor, the ripple is reduced. This also reduces the stress on the capacitor and, since the capacitor handles lower ripple current, its lifespan is also extended. From Figure 4.2, a steady-state is reached in this circuit after approximately 1.2ms, well within the required limits.

Another critical component in this circuit is the rectifier diode, D_1. Since the circuit switches at 1MHz, standard diodes used in 50Hz rectification which has a very high reverse-recovery time compared to

Schottky Barrier Diodes does not perform well in this application. The high frequency Schottky diode was selected based on factors such as peak current handling capability, total power dissipation and availability.

Although the LT1377 data-sheet indicates sufficiently linear performance over the artefact's required temperature span of -20°C to +50°C, the simulations for the parameters listed in Table 4.1 were each performed at 14°C intervals over this temperature span. This aligns with the test methods proposed in Section 3.5, Table 3.5. The was done to ensure circuit stability across the entire temperature range. Figure 4.3 indicates the current through inductor L_1 simulated at these 6 different temperature steps, with load current at specified levels and at the minimum input voltage of the lithium battery.

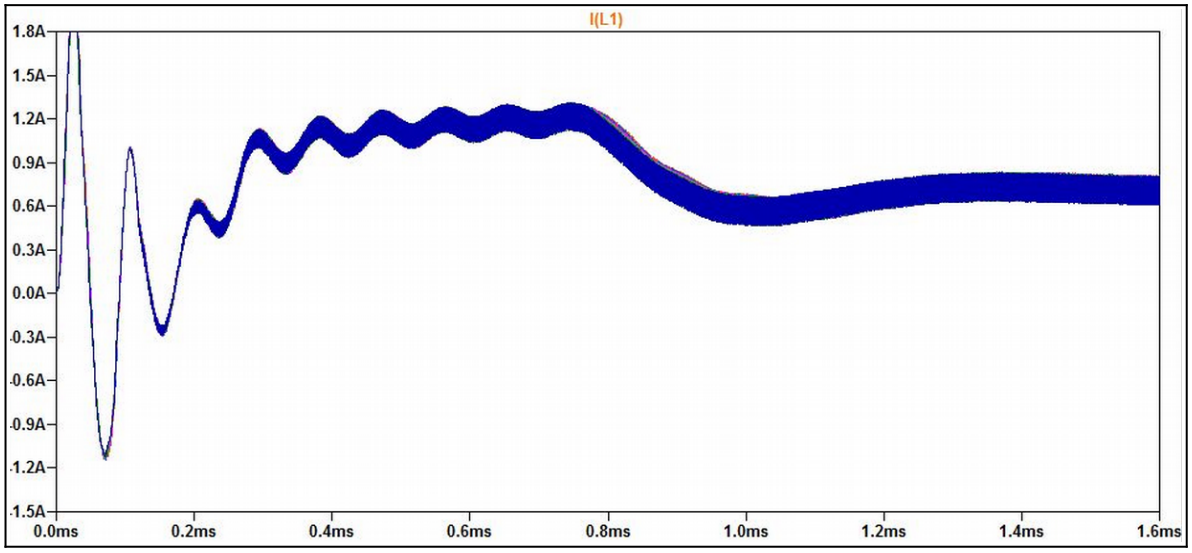


Figure 4.3 Stable Inductor L_1 Current Simulated at 6 Different Temperatures

As can be seen in Figure 4.3, the current measurements through L_1 on the 5V rail remain constant over the entire required temperature range of -20°C to +50°C with barely any discernible difference between the graphs of each temperature except a minor variance between 800µs and 1.2ms which stabilises after 1.2ms.

A similar iterative design process was followed for the 12V rail switch-mode regulator circuit. As example, Figure 4.4 indicates the simulated LTSpice circuit at a temperature of +50°C with the battery at nominal voltage during its discharge cycle.

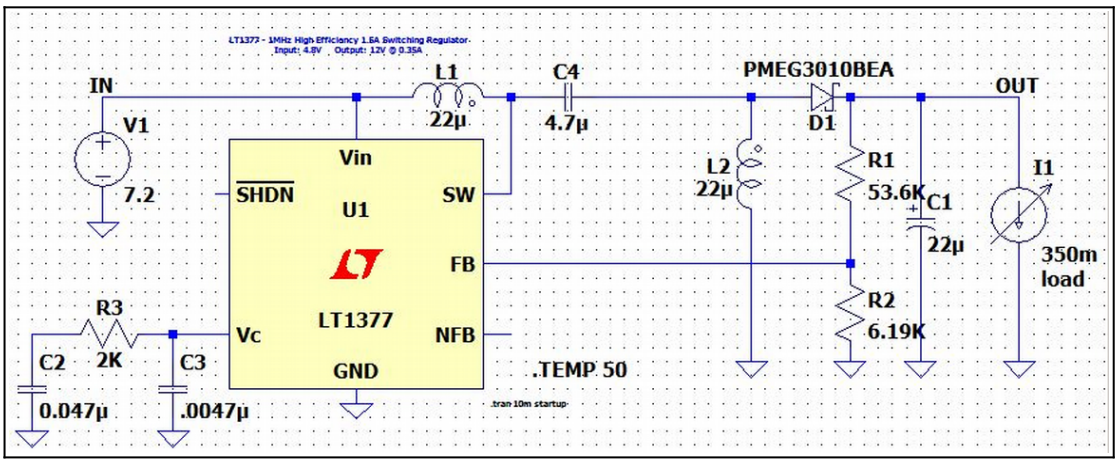


Figure 4.4 Circuit Diagram for 12 Volt Rail as Simulated at 50°C

Figure 4.5 indicates a number of parameters from Table 4.1 simulated on the 12V rail. As can be seen from this simulation the circuit reaches a steady-state after 1.4ms which is well within the required time (as per micro-controller data sheet **[37]**).

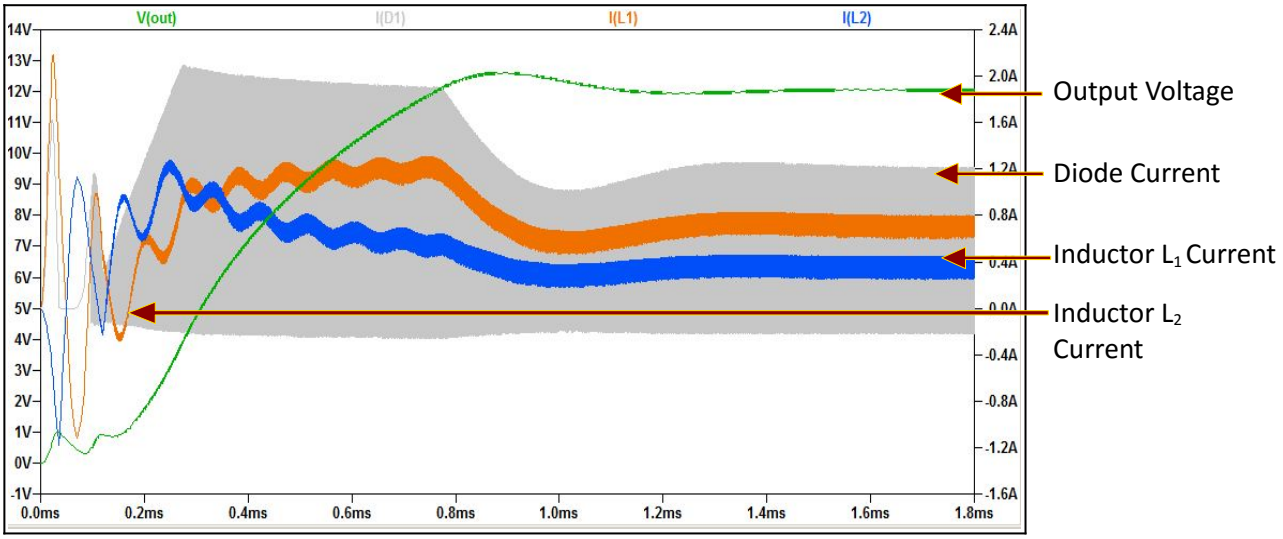


Figure 4.5 Simulated Parameters of the Optimised 12 Volt SEPIC Converter

The two designs were simulated together and further optimised until a fully integrated circuit design was obtained. Figure 4.6 shows both output rails in a combined circuit with the values simulated on the right.

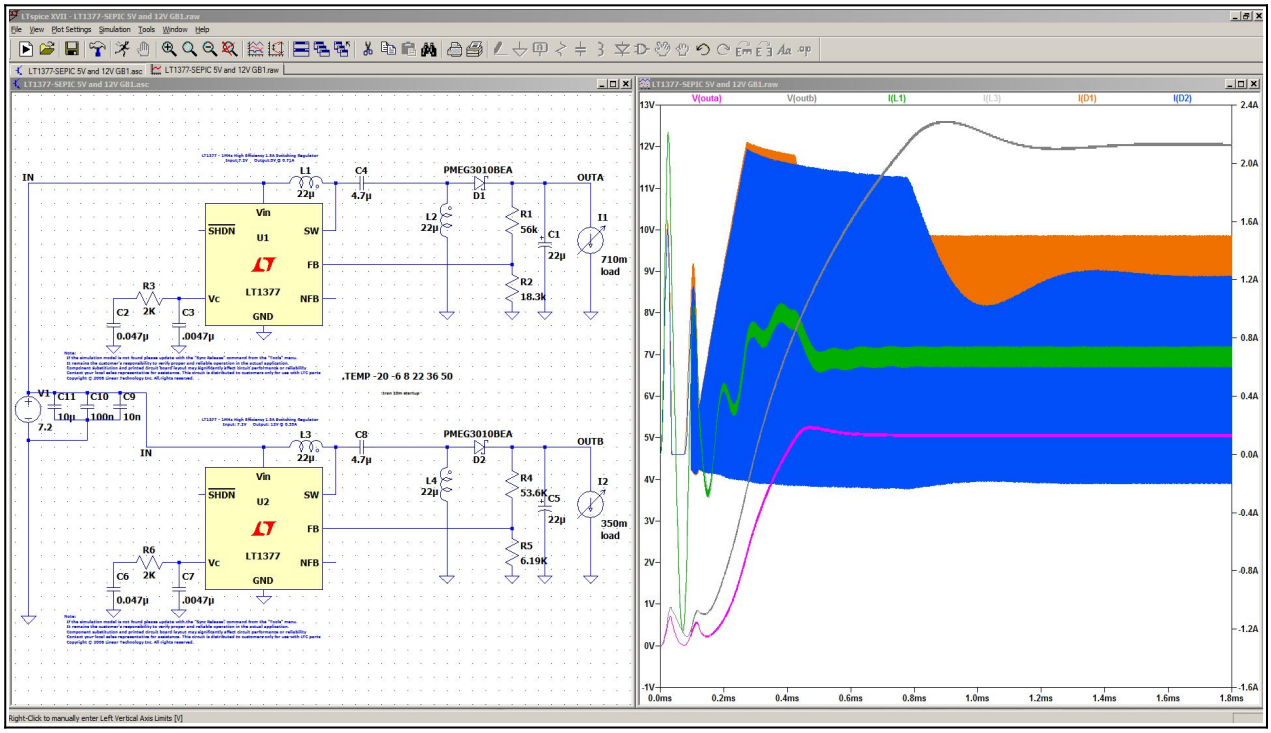


Figure 4.6 Screen Capture of Simulated Parameters of the Optimised Combined SEPIC Converter

The following section details the chosen components as per design-criteria, environmental considerations and simulations performed in the preceding research of this dissertation.

4.2 Component Selection

With component selection it always is a trade-off between the various properties of a number of components. Design decisions has to be taken in favour of one component based on small differentiating factors.

To aid in the selection process and decrease delivery times of components, a list will be drawn up based on one company, RS Components' available stock. By inputting the design-requirements of this dissertation in the cross-reference matrix on the RS Components website, potential candidate components can be short-listed for eventual selection.

Table 4.2 indicates some of the components that were evaluated based on the selection criteria of the electrical requirements analysis (Table 3.3) and environmental requirements analysis (Table 3.4).

Table 4.2 Sample of Evaluated Components based on the Requirements Analysis

Components	RS Components Stock Number	Description	Go or No-Go Decision	Reason
Surge Suppression	• 827-4331	• Littelfuse LSP05 Series Power Varistor, 277V	• No-Go	• Physically Large • Through-hole • High Price
Surge Suppression	• 769-2025	• MOV:275 V_{RMS}, I_{SURGE} > 1000 A, WMAX > 15 Joule, P_{DISS} >200 mW	• Go	• V_{RMS} > 230V Mains Supply • Small Footprint • SMD Technology • Low Capacitance
Mains Filter	• 496-4914	• EPCOS B84110-A Series 1A 250 V ac 60Hz Through Hole RFI Filter, with Pin Terminals, Single Phase	• No-Go	• Low Current Rating • Large PCB Footprint • Low current capacity • Narrow frequency Band and Low Attenuation Factor
Mains Filter	• 782-3982	• Min. 1 A, 250V, >50dB @ 1MHz Attenuation RFI Filter, PCB Mounted	• Go	• High attenuation over wide frequency band • Small Footprint • Low Price • Fully Encapsulated • PCB Mounted
Input over-current Protection	• 284-5388	• T3.15 A Schurter 6.3A Radial T Leaded PCB Mount Fuse, 250V ac	• Go	• Small footprint • Requires no Tools to Replacement • High Surge Rating • Time-Lag Operation
Bulk Conversion Transformer	• 503-990	• RS PRO 6VA 2 Output Chassis Mounting Transformer, 9V ac	• No-Go	• Chassis Mounted • Low Efficiency • Not Encapsulated • Open Terminals • Low Temperature Rating (70°C)
Bulk Conversion Transformer	• 223-9266	• 230V Input 9V, output x2,~7VA	• Go	• Toroidal Construction • Small Footprint • High Efficiency • Fully Encapsulated • Flame Retardant Materials • Test Voltage 4.0kV • High Temperature Operation (105 °C)
Bulk Storage Capacitors	• 520-0918	• Nichicon 1000µF 25V dc Aluminium Electrolytic Capacitor	• No-Go	• Small footprint but very tall • Narrow Temperature Operation (-40°C - 85 °C) • Short Lifespan • Low Ripple Capacity (0.960A)

Components	RS Components Stock Number	Description	Go or No-Go Decision	Reason
Bulk Storage Capacitors	• 795-5673	• > 1500uF, 10000h @ 105 °C, Ripple Current > 2500 mA, < 25 mm dia.	• Go	• Wide Temperature Operation (-55°C - 105 °C) • Long Lifespan • High Ripple Capacity (5.56A) • Small Footprint
Battery Management IC	• BQ24005	• Integrated FET Switch • Coke/Graphite Anode Support • Safety Timers • Cell Conditioning	• Go	• 2 x Lithium-ion Cell Operation • Wide Temperature Span • Interfacing with Host Processor/System
Battery Management IC	• Various Components Evaluated	• Various Components Evaluated	• No-Go	• Single Cell Operation Only • Low Current Capacity
HF Rectifier	• 917-9102	• HY Electronic Corp 40V 3A, Diode, 2-Pin DO-27 1N5822	• No-Go	• Through-hole Technology • Physically Large
HF Rectifier	• 816-6861	• Nexperia 30V 2A, Diode, 2-Pin SOD-128 PMEG3020EP,115	• Go	• SMD Technology • Meets Requirements for High Frequency SMPS Rectifiers • Meets Simulated Requirements

Based on the results from the supplier's search engine matrix, the following tables can be populated. Tables 4.3, 4.4 and 4.5 lists the specific components for the synthesis of the artefact's three sub-systems.

Table 4.3 Mains Board Component Description and Bill of Electronic Components

Components	RS Components Stock Number	Description
Mains Supply Plug	• 481-027	• 15/16 A, Live, Neutral, Earth, Durable Rubber Top, Solid brass conductors
Mains Supply Cable	• 775-6066	• Min. 1000 V rated insulation Minimum 3m Length, White for better visibility
Connector Strips	• 674-2369	• ASSMANN WSW 2.54mm Pitch 40 Way 2 Row Straight PCB Socket, Through Hole, Solder Termination
Neon Indicator Lamp	• 105-017	• T2 Clear Filament Indicator Lamp, Wire Terminal, 110/230 V 500 µA
Surge Suppression	• 878-3630	• Gas Discharge Tube: Littelfuse AC Series 800V 10kA Plug In 2 Electrode

Components	RS Components Stock Number	Description
Surge Suppression	• 769-2025	• MOV:275 VRMS, I_{SURGE} > 1000 A, WMAX > 15 Joule, P_{DISS} >200 mW
Inrush Current Limiter	• 211-8018	• EPCOS B57364S0209M000 Thermistor 2Ω, 21x7mm
Mains Filter	• 782-3982	• Min. 1 A, 250V, >50dB @ 1MHz Attenuation RFI Filter, PCB Mounted
Input over-current Protection	• 284-5388	• T3.15 A Schurter 6.3A Radial T Leaded PCB Mount Fuse, 250V ac
Bulk Conversion Transformer	• 223-9266	• 230V Input 9V, output x2,~7VA
Bridge Rectifier	• 652-6299	• Taiwan Semiconductor DBL209G C1, Bridge Rectifier, 2A 1400V, 4-Pin DB
Bulk Storage Capacitors	• 795-5673	• > 4000uF, 10000h @ 105 °C, Ripple Current > 2500 mA < 25 mm
De-Coupling Capacitors	• 264-4416	• KEMET 100nF Multilayer Ceramic Capacitor MLCC 50V dc ±10% X7R Dielectric 0805 (2012M), Max. Temp. +125°C

The results from the search engine for artefact components used on the Battery and Power Control Board is given in Table 4.3.

Table 4.4 Battery Board Component Description and Bill of Electronic Components

Components	RS Components Stock Number	Description
Change-Over Element	• 486-2559	• STPS20H100CT Dual Schottky Diode, Common Cathode, 100V 20A20A
Li-ion Battery	• 880-1551	• Samsung 3.7V 18650 Lithium-ion Battery, 2600mAh
Battery Management Integrated Circuit	• 817-5815	• Texas Instruments BQ24075RGTT, Lithium-Ion, Li Ion Charger IC, 1.5A 16-Pin, QFN
Battery Thermal Fuse	• 176-9132	• Limitor 2.5 A +70°C Resettable Thermal Fuse, 250V
Battery PCB Mount Fuse	• 284-5423	• Schurter 6.3A Radial T PCB Mount Fuse, 250V ac
Standby Supply Regulator	• 713-9486	• New Japan Radio NJM7810DL1A-TE1 Linear Voltage Regulator, 1.5A, 10 V, 4% 3-Pin DPAK
De-Coupling Capacitors	• 264-4416	• KEMET 100nF Multilayer Ceramic Capacitor MLCC 50V dc ±10% X7R Dielectric 0805 (2012M), Max. Temp. +125°C
Input/ Output Over-Current Protection	• 817-1652	• Bourns 3A Surface Mount Resettable Fuse, 24V
Input/ Output Over-Voltage Protection	• 464-8842	• AVX VC Series 5V 40A 0.1J 12V Clamp 0805 Ceramic Transient Voltage Suppressor

Table 4.5 reflects the cross-referenced results for the DC Output Board's components.

Table 4.5 DC Board Component Description and Bill of Electronic Components

Components	RS Components Stock Number	Description
Switch-Mode Regulators	• 779-9243	• LT1377 IS8#PbFree
High Efficiency Coupled Dual Inductor	• 744-5249	• Wurth WE-DD Series Type 7345 Shielded Wire-wound SMD Inductor with a Ferrite Core, 22 µH ±20% Dual 1.8A Idc
SEPIC Coupled Capacitor	• 515-8508	• Murata 4.7µF Multilayer Ceramic Capacitor MLCC 50V dc ±10% X7R Dielectric 1210 (3225M) SMD, Max. Temp. +125°C
High Frequency Rectifier	• 816-6861	• Nexperia PMEG3020EP,115 SMT Schottky Diode, 30V 2A, 2-Pin SOD-128
Output Filtering	• 839-0843	• Murata BNX02 Series 15A 25 V dc 50 kHz → 1 GHz SMD EMI Filter, with Flat Contact Terminals
De-Coupling Capacitors	• 264-4416	• KEMET 100nF Multilayer Ceramic Capacitor MLCC 50V dc ±10% X7R Dielectric 0805 (2012M), Max. Temp. +125°C
Output Smoothing	• 795-5512	• Storage Capacitors Equal to 1000uF/Ampere, Low ESR, Low Volume
Output Protection	• 747-4928	• ESD Protection diode: Murata LXES Series, Signal Filter, 5.5 V SMD 2.5 x 1 x 0.55mm
Opto-Isolator for Mains Sensing	• 178-3124	• Opto-isolator,HCNW139 5000Vac Isolation DIP8
Cold-Boot Relay	• 775-6066	• Finder SPDT Non-Latching Relay PCB Mount, 12Vdc Coil, 6 A Contacts
Transistor – Cold-Boot Control Circuitry	• 669-7483 • 739-0385	• Diodes Inc ZTX690BSTZ NPN Transistor, 2 A, 45 V, 3-Pin E-Line • ON Semi KSP2222ABU NPN Transistor, 600 mA, 40 V, 3-Pin TO-92
De-Coupling Capacitors	• 264-4416	• KEMET 100nF Multilayer Ceramic Capacitor MLCC 50V dc ±10% X7R Dielectric 0805 (2012M), Max. Temp. +125°C
Output LED Indicators	• 906-3536	• Bivar SM1206GC, 565 nm Green High-Power LED, 3216 (1206) SMD

The artefact is divided into three distinct printed circuit boards, with physical separation and grouping of functional units as main design-criteria. A further advantage of having modular construction is that it eases fault-finding and repair of a power supply such as this. Since repairs will often be affected in the field, limited time and resources can play a big role in the speedy restoration of the correct operation of a power supply for sensitive equipment.

4.3 Physical Design

The physical design and lay-out of the individual sub-systems as previously stated, is done with a modular approach in mind. Fault finding and maintenance can therefore be easily affected, even in the field with minimal tools required, thereby minimising the down-time of the affected neutron monitor.

For Computer Aided Design, an open-source software package called KiCAD was used. This package offers the design of diagrams as well as the rendering of 3D semi-photo realistic images. Utilising software such as this dramatically reduces development time since component placement and track-routing can be easily performed and altered as iterative. Figure 4.6 depicts the schematic diagram of the Mains PCB.

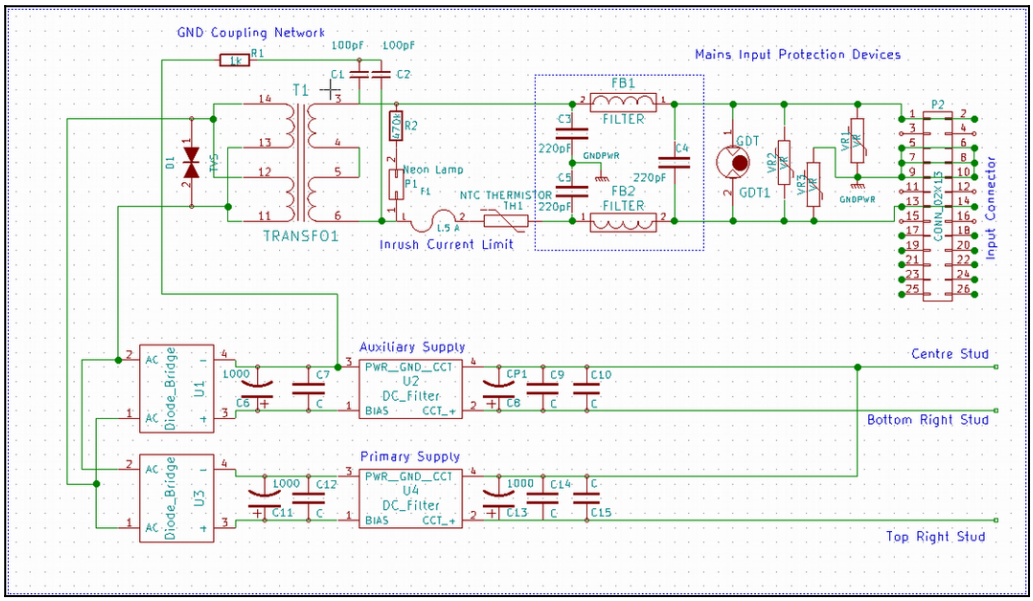


Figure 4.7 Mains Board Schematic Diagram

Figure 4.7 shows the 3D rendered image of the designed board with basic component lay-out indicated.

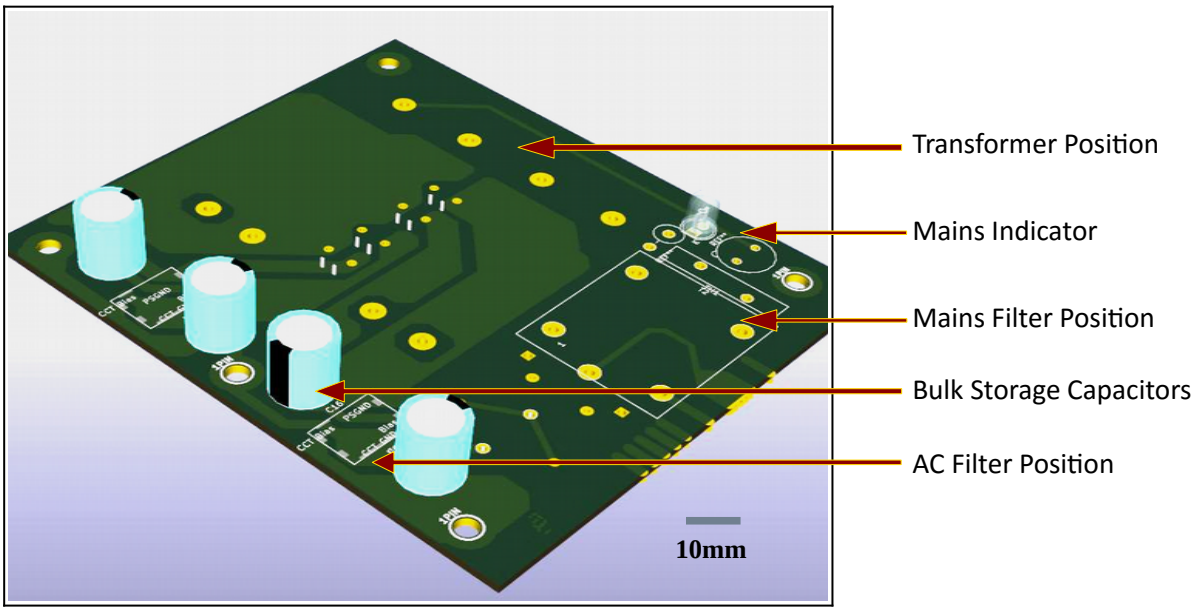


Figure 4.8 Mains Board Rendered 3D Lay-out

Figure 4.8 depict the manufactured Mains board.

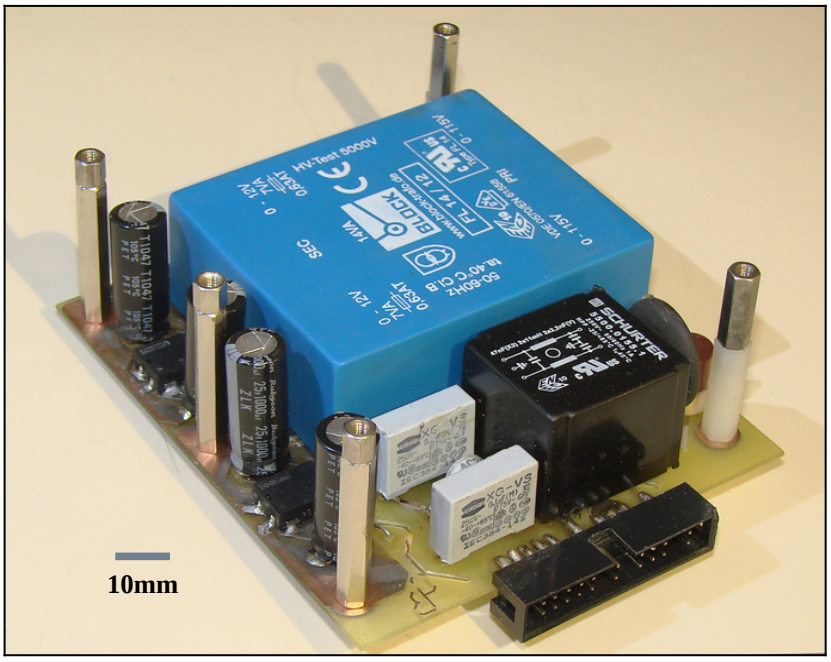


Figure 4.9 Photograph of the Constructed Prototype Mains Board

The schematic in Figure 4.9 shows the Battery Board as designed in KiCAD.

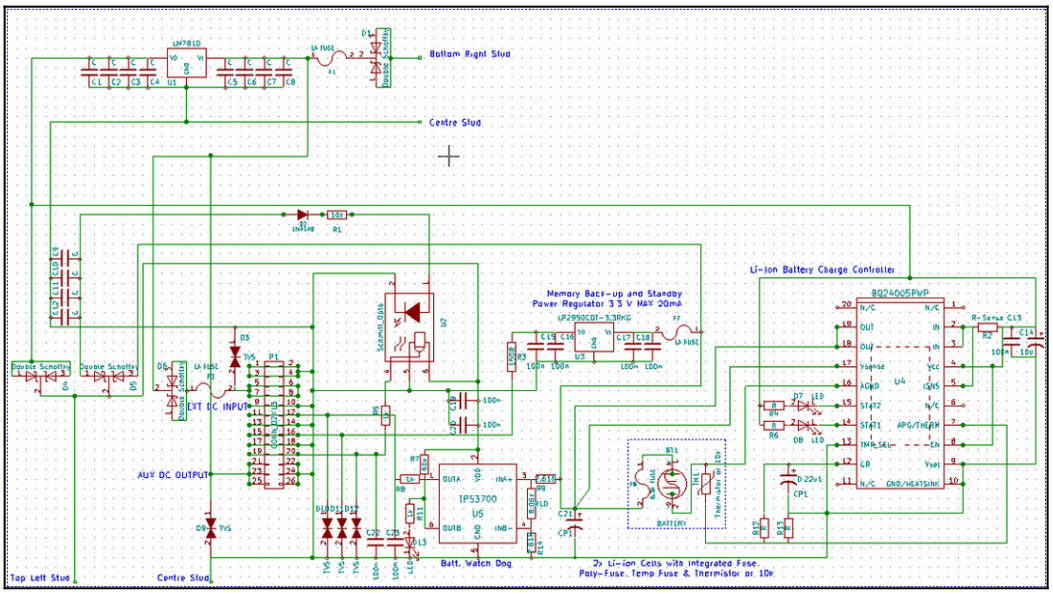


Figure 4.10 Battery and Power Control Board Schematic Diagram

The KiCAD software package was used to render the design in 3D in order to check component placement and physical interfacing between the discreet PCBs. Figure 4.10 Indicates the component side of the Battery Board to show component placement.

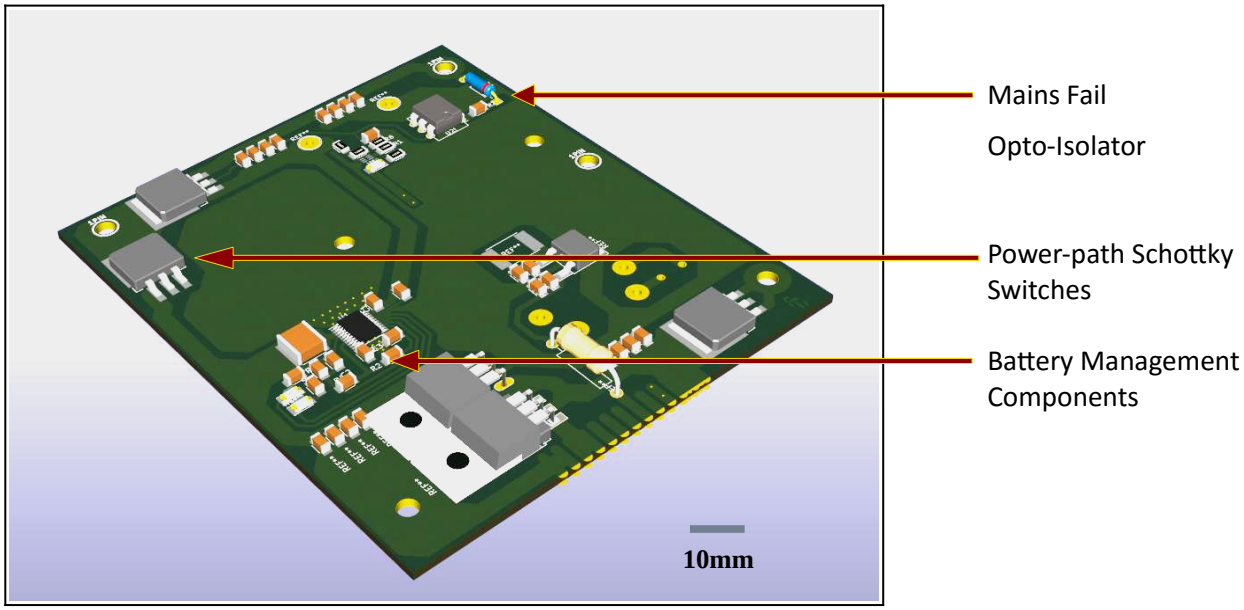


Figure 4.11 Rendered 3D Image of the Battery and Power Control Board

The manufactured circuit board manufactured and is shown in Figure 4.11 and is shown upside down to indicate the Li-ion battery pack with its protective high-temperature wrapping tape as additional insulating material.

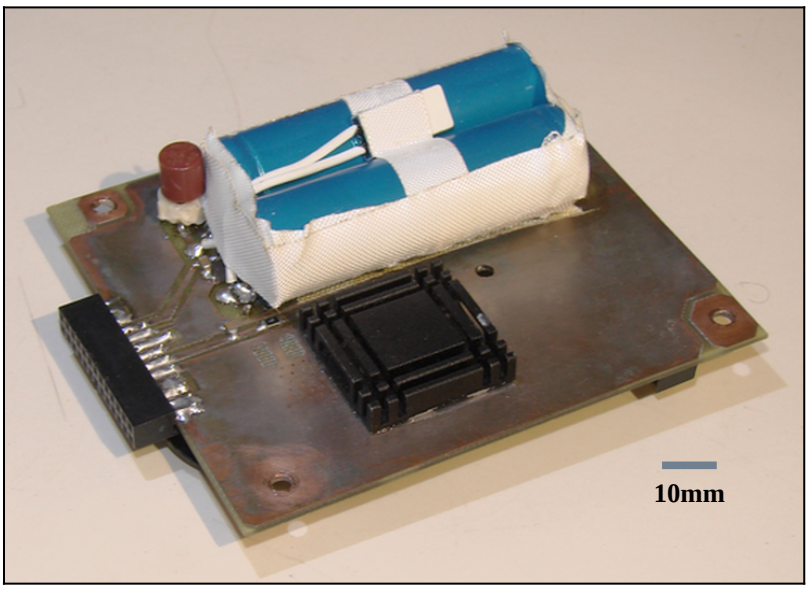


Figure 4.12 Photograph of Prototype Battery Board with Integrated Li-Ion Cells

Figure 4.12 is the schematic diagram of the DC board and contains the switch-mode power-control components as optimised in the LTSpice simulations.

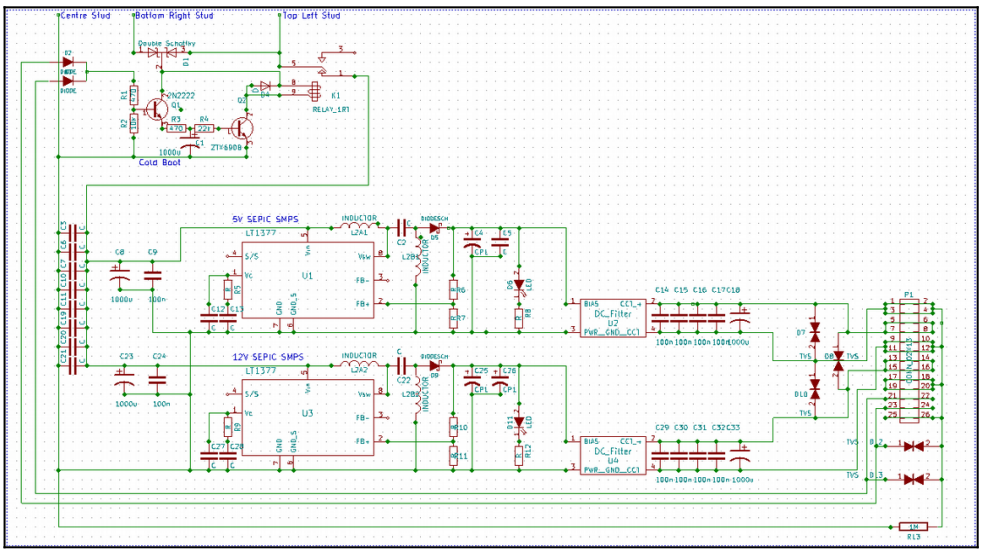


Figure 4.13 Direct Current Output Board Schematic Diagram

Figure 4.13 shows the rendered circuit board. The two groups of components on the left side of the board is the switch-mode regulators for the 5V and 12V output rails. The SMPS regulators will be housed in separate metal screens to limit electro-magnetic noise from being radiated.

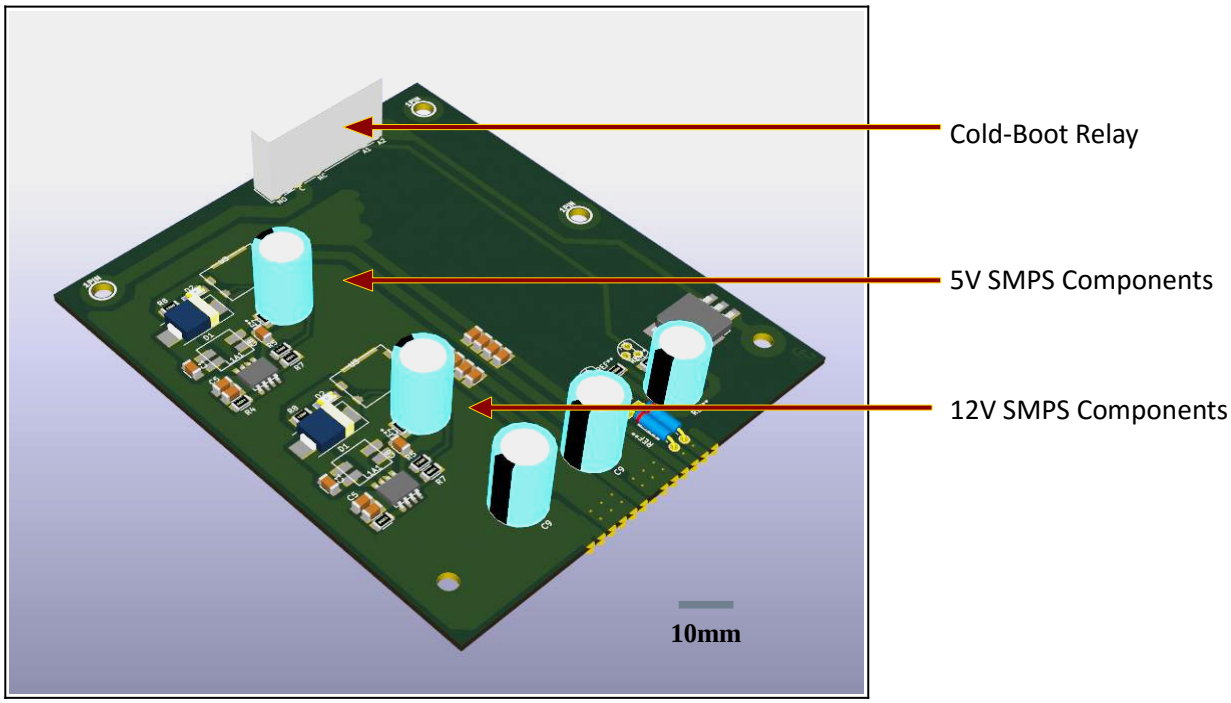


Figure 4.14 Direct Current Output Board Rendered 3D Lay-out

The photograph in Figure 4.14 shows the assembled Direct Current Output Board complete with metal screening over the switch-mode regulators of the two power rails. This is directly in resemblance to the designed CAD model as designed.

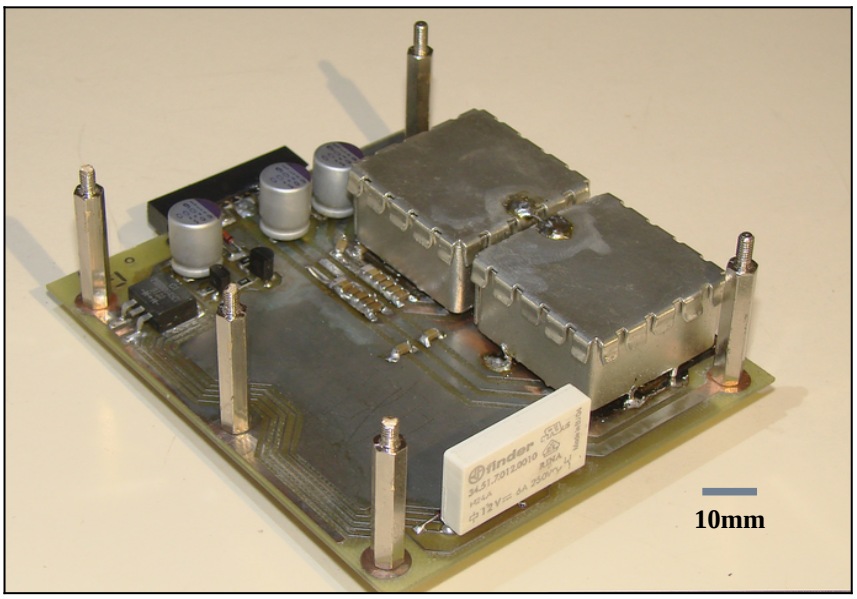


Figure 4.15 Photograph of Prototype Direct Current Output Board

The photograph in Figure 4.15 shows the assembled power supply with output LED indicators showing power on both rails supplied from the internal battery pack.

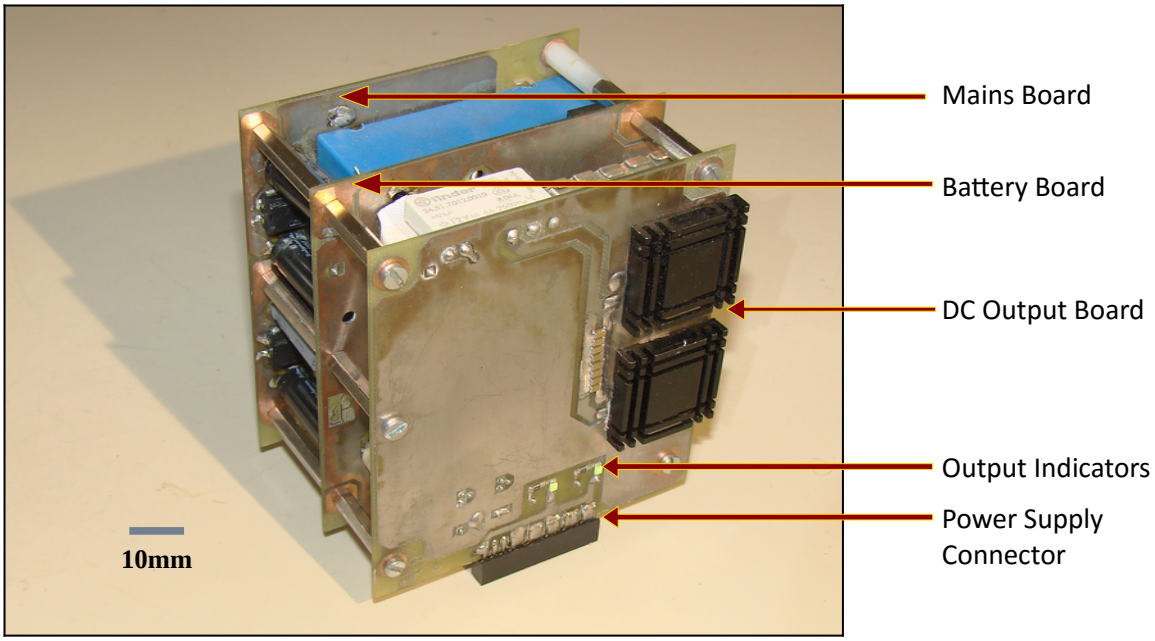


Figure 4.16 Photograph of Fully Assembled Final Artefact

4.4 Conclusion

This chapter dealt with the design and synthesis of the artefact in response to the research question as set out in Chapter 1. Software simulations were performed as part of the iterative design process in order to optimise the switch-mode regulators where efficiency is of critical importance. Since high operating frequencies can cause interference, mitigating measures were put into place in the form of carefully

selected output filters on the output of the SMPS, while all the SMPS components were enclosed in metallic shielding.

The latter part of this chapter provides detailed schematics and 3D rendered images as part of the development process. Photographs of the synthesised PCB and assembled artefact is provided to illustrate the similarity between the CAD models and the final hardware.

CHAPTER FIVE

Validation and Verification

This chapter deals with the validation and verification processes used with regards to the physical artefact that was developed. As outlined in Figure 1.7, the validation and verification processes are just as important as the design and construction of the artefact.

Validation refers to the process that confirms to which degree a system, process or artefact fulfils specific design requirements. It is undertaken in order to confirm that the various research questions have indeed been addressed properly. In conjunction with validation, verification refers to the process whereby the artefact is tested to ensure that its intrinsic quality either meets or exceeds its specified design.

These concepts be summarised as follows:

Validation: *Does the power supply perform the correct functions?*
Verification: *Does the power supply perform its functions correctly?*

5.1 Verification Process

As part of the verification process, the artefact will be subjected to a cross-referenced matrix of tests with reference to the design requirements. The requirements for harsh environment power supplies was set out in Table 3.5 and will be used to test the artefact against.

Table 5.1 outlines the requirements of the neutron monitor power supply as previously set out. Each criteria is measured and evaluated thoroughly during a test in order to perform the verification procedure.

5.2 Verification Summary

The verification process outcomes are summarised in Table 5.1 with detailed descriptions given in the subsequent sections.

Table 5.1 Summarised Verification Parameters

Requirement as set out in Chapter 3	Requirements Fulfilled Yes / No?	Verification Section
Electrical Requirements		
< 5 % Line Regulation	Y	5.3.1
Output Rail: **5V Supply Rail @ 700 mA**	Y	5.3.2
Output Rail: **12 V Supply rail @ 150 mA**	Y	5.3.2
Ripple and Noise on output rails < 100 mV_{RIPPLE} **Over temperature range of -20°C to +50°C**	Y	5.3.3
> 1 Hour back-up time on battery under typical load (3W) over entire temperature range of -20°C to 50°C	N	5.3.4
Fully depleted battery recharged within 8 hours	Y	5.3.5
Low Temperature Battery Charging	Y	5.3.6
Battery Management & Protection over entire temperature range as set out in requirements analysis	Y	5.3.7
Cold Boot Feature – Suitable reset pulse applied over entire temperature range of **-20°C to +50°C must reset power supply for** **1 minute**	Y	5.3.8
Low Power, 'Always-on' memory back-up output of 3.3V at maximum 20mA	Y	5.3.9
Mains Disturbance Protection: **Human Body Model and IEC61000-4-2** **150pF & 330 ohm @ 4kV** **10 Repeated Discharges**	Y	5.3.10
Environmental Requirements		
Temperature Shock: -20°C to 20°C	Y	5.3.11
Temperature Function over -20°C to +50°C range and at specified load	Y	5.3.12
- Cold Test Cycle	5.3.12.1	
- Hot Test Cycle	5.3.12.2	
Vibration Robustness	Y	5.3.13
Shock Robustness	Y	5.3.14
Long Term Endurance Test	N/A	5.3.15

5.3 Verification Process

The verification procedure comprises a number of tests to determine that the operational characteristics of the artefact satisfy the requirements set out in Section 3.3. The artefact was designed to operate in harsh environments and will, through its life-cycle, be exposed to electrical disturbances, vibration patterns, and a

relatively large range of temperatures. It is expected to perform without fail under all these conditions. In order to verify that the synthesised power supply unit (PSU) answers the research question, it will be subjected to a number of physical non-destructive tests. As stated in Section 3.4.3 the tests will be performed based on the availability of equipment and testing facilities. Although international standards will be used as testing guidelines, will this proof-of-concept artefact only be shown to conform to the minimum standards. It will therefore not be tested to the full extent of said international standards. Table 5.2 outlines the testing action plan use to perform the environmental tests.

Table 5.2 Verification Testing Parameters/Actions Plan

Testing Procedure:	International Standard as Guideline:	Description / Action:
Environmental Testing **Test 1 – Temperature Shock** **Test 2 – Discharge/Re-charge Cycling at Temperature Intervals**	MIL-STD-810F • Test Method 503.5 - Temperature Shock • Test Method 501.5 - High Temperature • Test Method 502.5 - Low Temperature	• Temperature Shock – artefact repeatedly moved between ambient and -20°C. Noise measurements taken after 5th cycle at ambient. • Artefact to be moved from ambient into -20°C. Then increments of 14°C to +50°C • Oscillographs taken of output rails at each test temperature to measure noise levels • Full discharge/recharge cycle of Li-ion battery at each temperature. • Artefact loaded to full output current +10% on both output rails
Vibration Testing	• ISO 10055:1996 MIL-STD-810F • Test Method 514.6 (Vibration)	• Vibration testing performed on calibrated equipment with accelerometer feedback • Testing for 15 minutes at each frequency to establish signs of damage • Additional vibration tests on random pattern to attempt to identify weak spots, poor design or construction
Human Body Model Electrostatic Discharge	• MIL-STD-883K and • ANSI / ESDA / JEDEC JS-001-2014 • IEC61000-4-2	• 4 kV discharge from 150pF capacitor through a 330Ω resistor • 3 Positive pulse and 3 Negative Pulses minimum

The above table provides guidelines as to international test specifications and all tests performed will be based on these within the availability of specific test equipment.

The remainder of Section 5.3 details the various tests that were performed in order to verify that the power supply conforms to the requirements. For electrical testing, an oscilloscope and digital multi-meters were used. For all other tests, measurement equipment is suitably indicated where applicable.

5.3.1 Line Regulation

Line regulation as per Table 5.1 was verified by means of applying mains voltage to the power supply via a variable autotransformer (Variac). Since the power supply is designed to seamlessly maintain its output in the event of low or absent mains input voltage as is the case in this test, the internal Lithium-ion battery was disconnected, thereby disabling the secondary power-path. This was done in order to reflect true line regulation without aid from the back-up power-path. The experimental setup is depicted in Figure 5.1

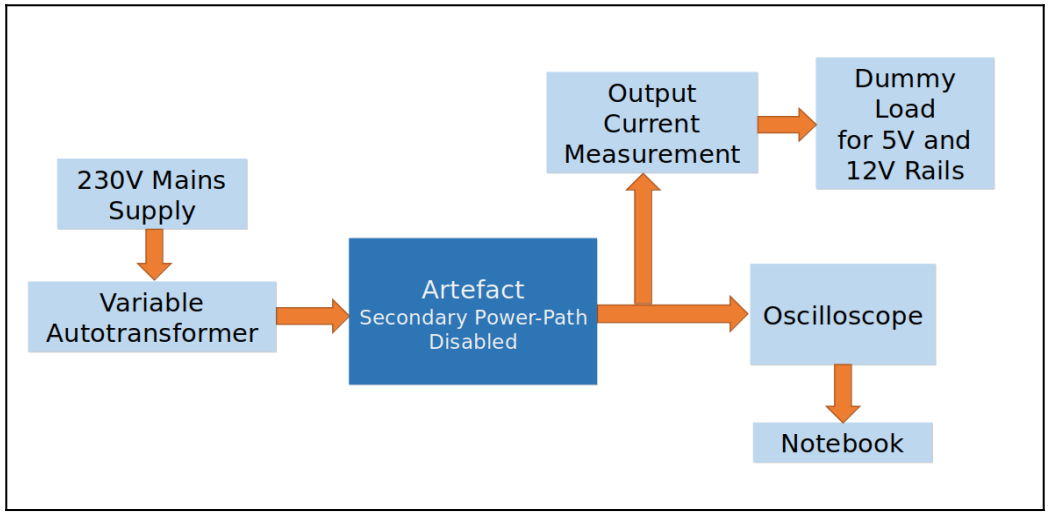


Figure 5.1 Line Regulation Experimental Setup

The input and output voltages of the power supply was measured with an oscilloscope and recorded in Table 5.3 and plotted as a graph in Figure 5.2

Table 5.3 Line Regulation Test Values

Mains Input Voltage As per Table 3.3 (220V,50Hz,±20%)	**Measurements Results on 5V Output Rail**	**Measurements Results on 12V Output Rail**
176V_{AC}	5.182	12.108
180V_{AC}	5.181	12.110
190V_{AC}	5.181	12.109
200V_{AC}	5.182	12.110
210V_{AC}	5.182	12.108
220V_{AC}	5.181	12.110
230V_{AC}	5.181	12.109
240V_{AC}	5.182	12.107
250V_{AC}	5.181	12.107
260V_{AC}	5.182	12.110
264V_{AC}	5.182	12.109

The data in Table 5.3 is plotted in the graph in Figure 5.2.

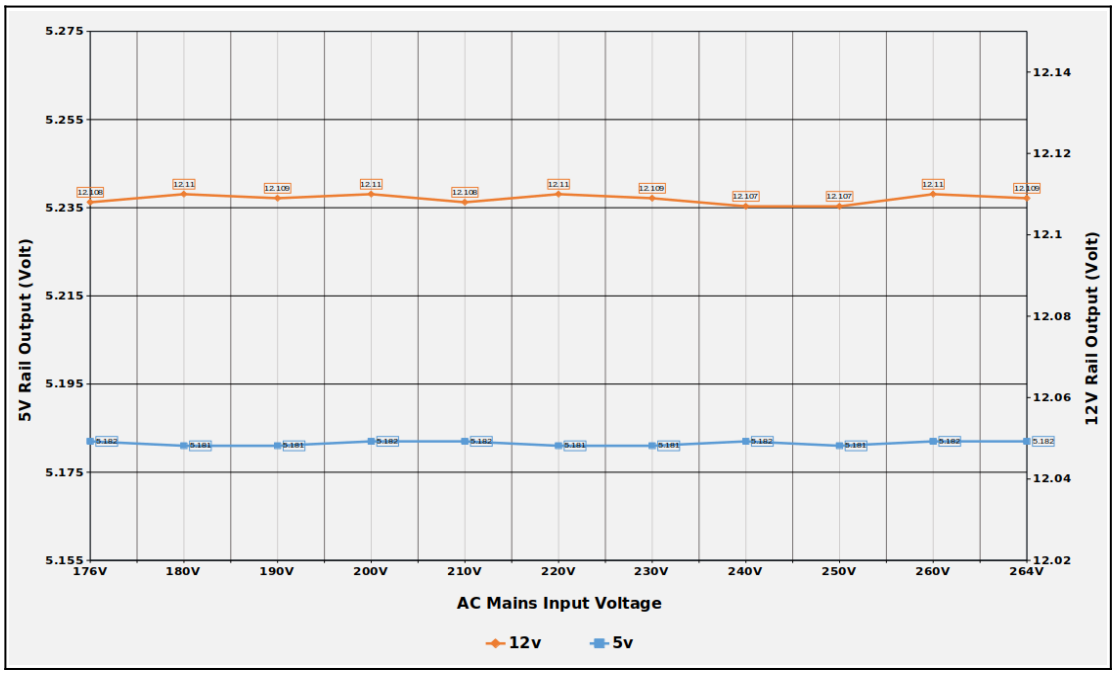


Figure 5.2 Line Regulation Test Values

From the values in Table 5.3 and the graph in Figure 5.2 the output of the power supply remains within the required tolerances. The maximum difference in the 5V rail's output is 1mV or 0.019% over the entire range of input voltages. The 12V rail's output changed 3mV which translate to 0.024% line regulation.

5.3.2 Output Voltage

As part of the verification procedure for the output rails, the output of both the 5V and 12V rails were measured with an oscilloscope. The 5V rail was measured at 5.178V while supplying a 710mA load. The 12V rail was supplying a load of 180mA with an output of 12.121V and was measured by means of two Fluke 77 digital multi-meters. These values are within the requirements as set out in Table 3.3.

5.3.3 Output Ripple and Noise

For verifying the power supply's performance in terms of the ripple voltage that is present on the output, an oscilloscope was used while subjecting the power supply to temperatures over the entire range of -20°C to +50°C. The measured ripple was 80mV$_{P-P}$ for the 5V output rail and 75mV$_{P-P}$ for the 12V rail. This is less than the 100mV$_{P-P}$ as per requirement (Table 3.3). Figure 5.3 indicates the screen-shot of the measurements with the oscilloscope AC coupled and the power supply at full load at 22°C ambient temperature.

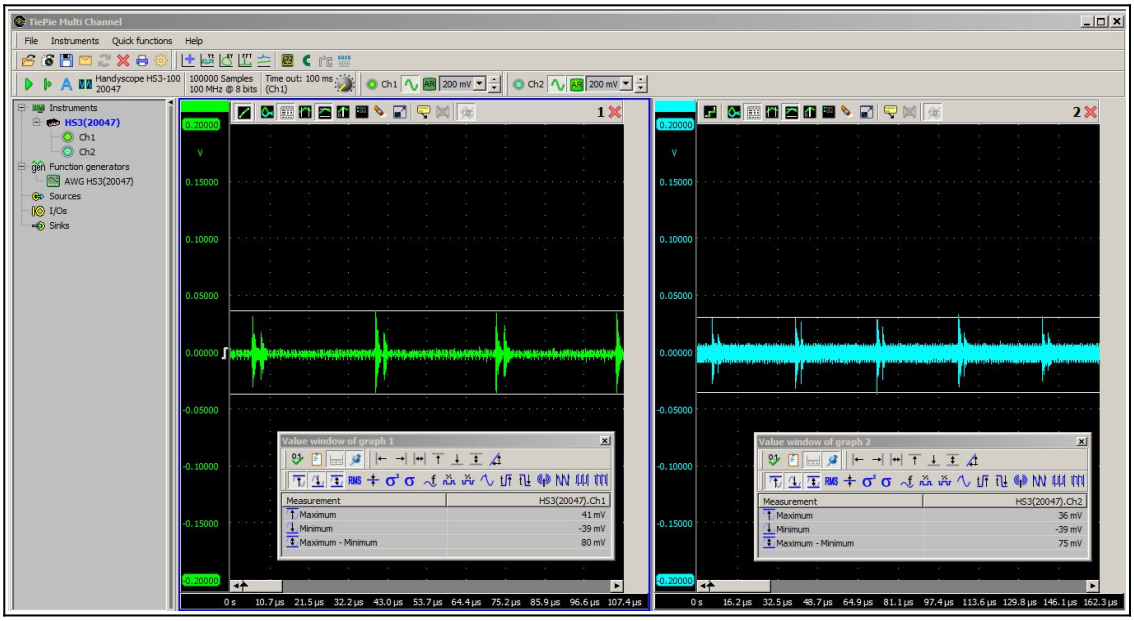


Figure 5.3 Screen Capture of Ripple and Noise Measurements on 5V and 12V Rails

Figure 5.3 measures the ripple and noise on both the output rails. The “spikes” in the above measurement is the switching frequency that is present on the output.

5.3.4 Battery Back-up Time

In order to establish the power supply’s conformance to the required 1 hour standby time during a power failure, and over the entire temperature range (-20°C to +50°C), the following tests were performed. During each of the temperatures of the Temperature Function Test (see Section 5.3.12), the power supply was discharged from a fully charged state. The test temperature as well as the discharge and recharge curve was recorded by means of an Endress & Hauser RSG30 recorder.

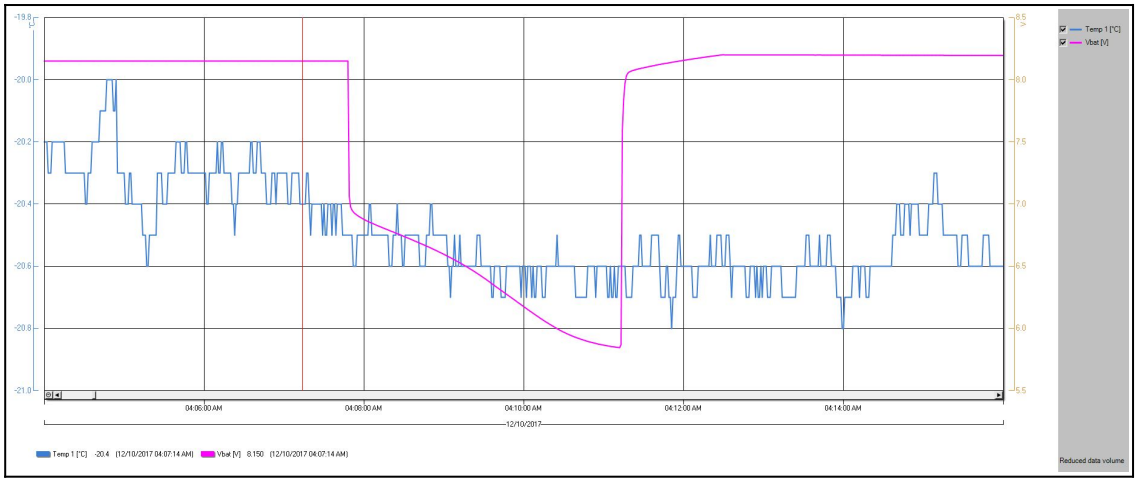


Figure 5.4 Battery Discharge and Recharge Cycle at -20°C

Figure 5.4 indicates the discharge-time (pink curve) of the lithium-ion battery to be approximately 3 minutes in this test. As per requirements from Table 3.3, the power supply does not conform to this requirement.

Figure 5.5 shows the battery stand-by time as a function of temperature over the entire require temperature range.

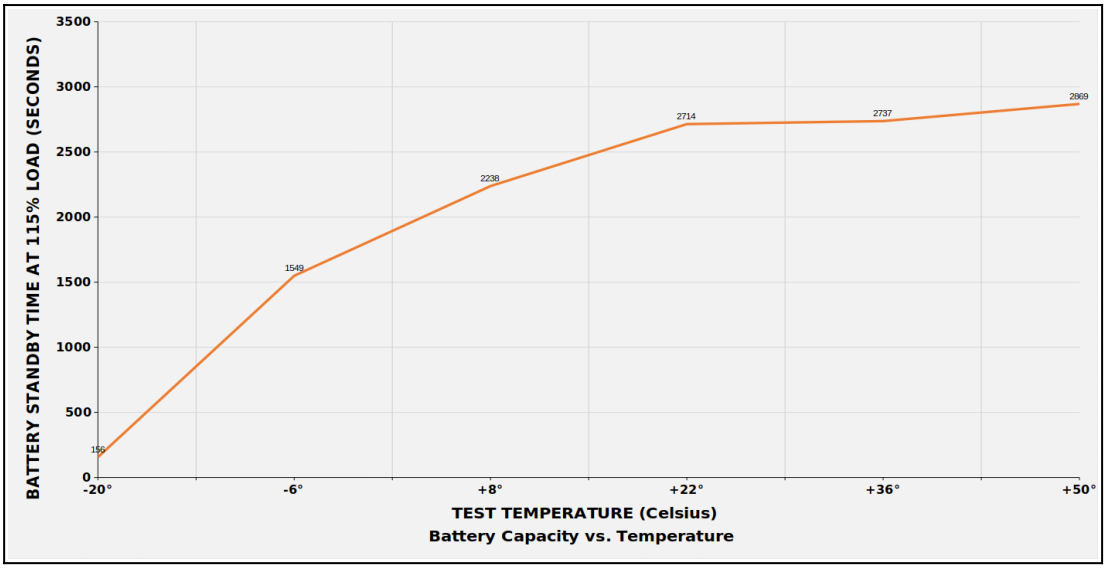


Figure 5.5 Battery Stand-by Time vs. Temperature (-20°C to 50°C)

From the graph in Figure 5.5 it can be ascertained that the Li-ion battery capacity suffers severely at low temperatures. As the artefact temperature increases, the battery capacity also increases.

5.3.5 Battery Recharge Time

During the test performed in section 5.3.4, it was found that the lithium-ion battery does not perform well in cold temperatures and suffers from a severe loss in capacity at low temperatures. It was also found (see Figure 5.4; -20°C) that the recharge time was also drastically shortened at lower temperatures.

In order to test the power supply's performance against the 8 hour recharge time requirement, the worst-case recharge scenario was selected (50°C charge-discharge test). Figure 5.6 shows the graph obtained during this test.

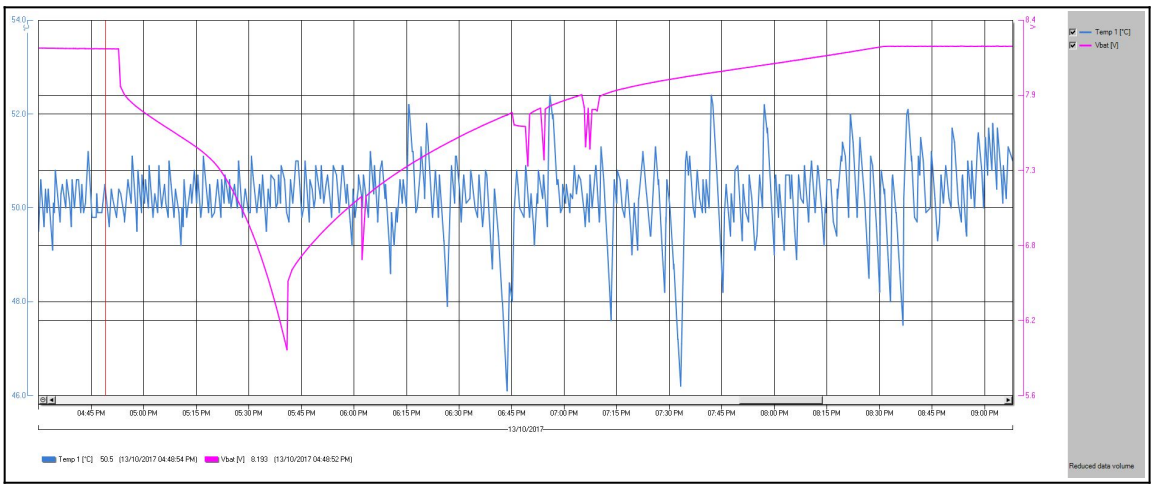


Figure 5.6 Battery Discharge and Recharge Cycle at 50°C

The interruptions in the recharge cycle between 6:45 and 7:15 is the result of the measurement probe that did not make proper contact on the measuring point on the battery terminal during this time. This however did not interrupt the recharge cycle of the battery.

The result of this test indicate a worst case recharge time of approximately 2 hours and 30 minutes which satisfies the requirement of a less-than 8 hour recharge time after full battery depletion.

5.3.6 Low Temperature Charging

From Figure 5.4 and Figure 5.6 can it be seen that, although the recharge times vary considerably because of temperature, the Li-ion battery does recharge to its full state (8.2V) over the entire temperature range of -20°C to 50°C.

5.3.7 Battery Management

From Figure 5.4, Figure 5.5 and Figure 5.6, it can be concluded that the Li-Ion battery management controller performs its function over the entire temperature range with a pre-charge algorithm controlling a deeply discharged battery successfully over the temperature range of -20°C to 50°C.

5.3.8 Cold-Boot Feature

The functioning of the cold boot circuit is to enable a micro-controller or watch-dog circuit to shut-down an entire system based on certain criteria such as excessive noise or communication errors that are detected.

For this test, the power supply's cold boot circuit was provided with a suitable pulse at each of the test-temperatures in Section 5.3.12. On each of the various temperatures during this test, the power supply switched the output rails off for the approximately 1 minute as per requirement in Table 3.3.

5.3.9 Low-power Output

As per requirement (Table 3.3), the power supply must also provide a low-power, "always-on" output under all conditions. This output can be used to power a GPS receiver's memory, or supply current to a micro-controller's real-time clock.

The output from this circuit was measured with a Fluke 77 DMM and a short circuit placed over the output during each of the temperature test levels as performed in Section 5.3.12. The measured current remained constant over the entire temperature range. The current was measured at a constant 20mA as per requirement.

5.3.10 Electrostatic Discharge Test

In order to simulate a high voltage discharge on the input of the power supply (thus a typical mains disturbance such as lightning strikes or static discharge) two different international standards were used as guidelines. The first standard is the Human Body Model (JS-001-2012 and MIL-STD-883H) and dictates conditions where a statically charged human touches an electronic device. This is typically found in dry ambient conditions, with a person walking across a carpet and becoming statically charged. Upon toughing the device, the built-up charge is discharged into the equipment.

The second international standard which was used as a guideline is the IEC61000-4-2 specification. Although these standards appear similar at first glance, is the testing required for conformance to the IEC standard is much more stringent **[106]**.

It was therefore decided, based on the availability of test equipment, to use both standards as guideline in order to simulate real-world high voltage mains disturbances. A test setup was configured according to the block diagram in Figure 5.7.

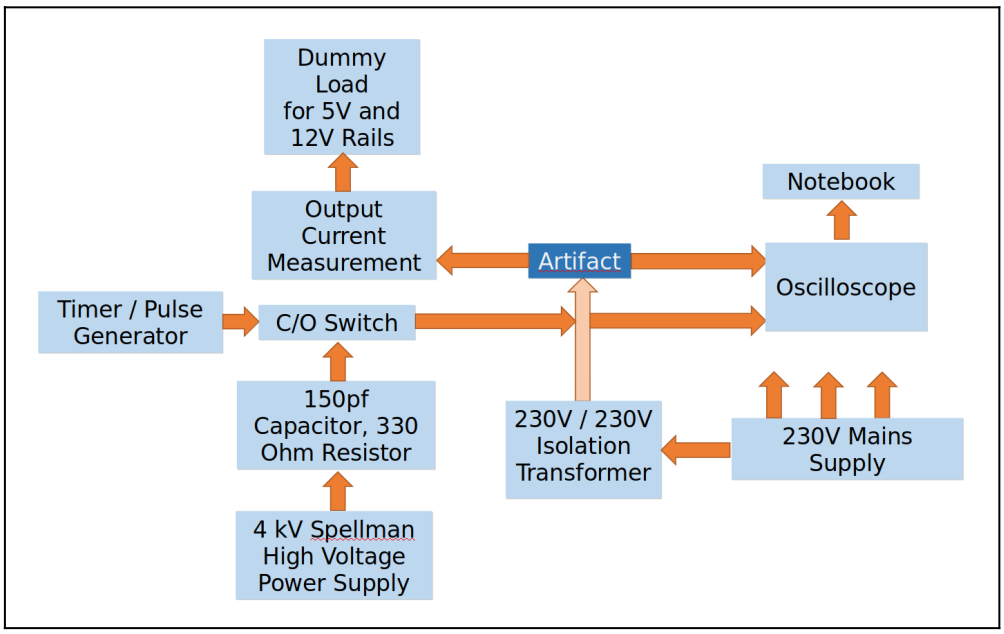


Figure 5.7 Block Diagram of High Voltage Disturbance Test Setup

The photograph in the following figures shows the test setup that was constructed according to the block diagram in Figure 5.7.

The high voltage capacitor is charged up, and through the pulse generator, the change-over switch is connected at regular intervals to the mains input of the artefact. The oscilloscope measured the mains voltage as well as the one output rail of the power supply.

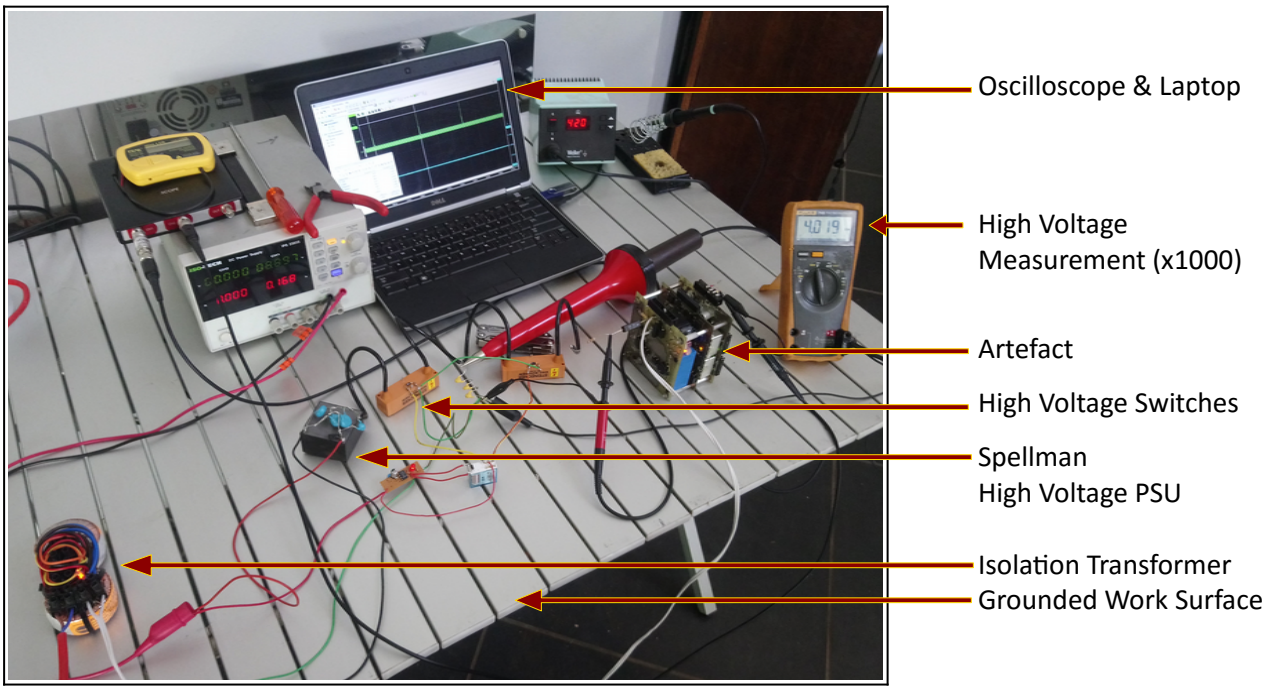


Figure 5.8 Photograph of Physical ESD Test Setup

Figure 5.9 shows a close-up of the power supply during the ESD test with the high voltage blocking diode in the foreground. The function of this diode is to prevent the mains supply voltage from charging the test capacitor before the test is performed.

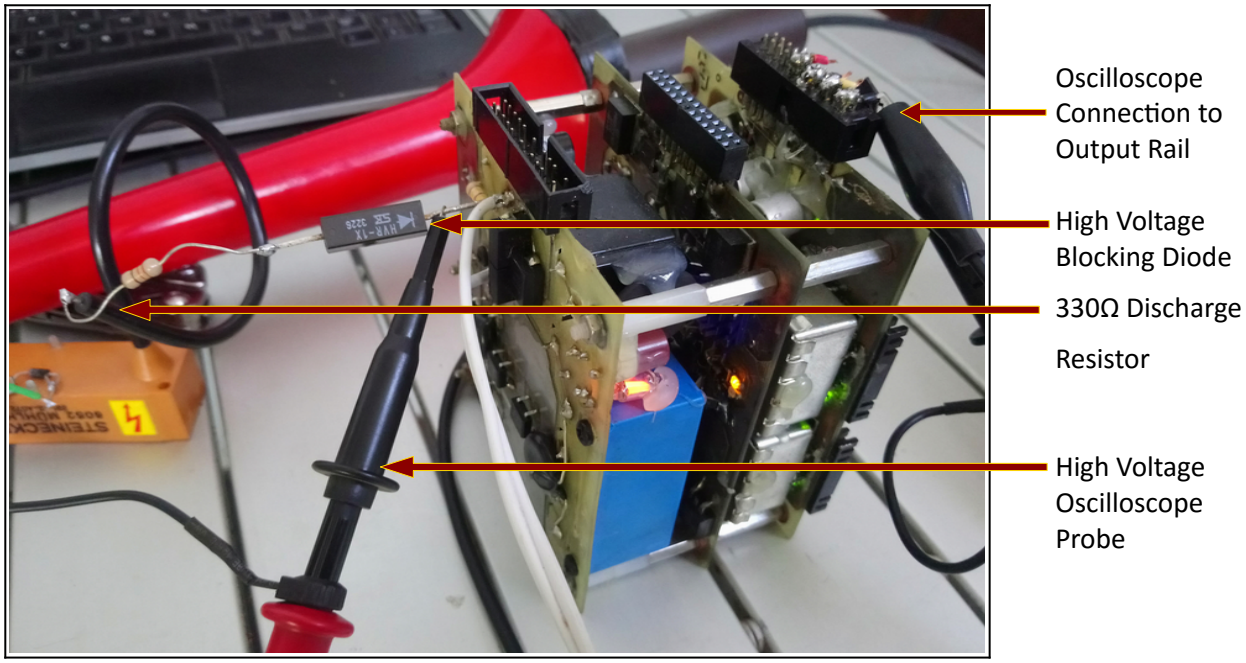


Figure 5.9 Close-up Photograph of PSU and Test Connections

The discharge capacitor was measured with an Atlas LCR meter to be 146.9pF. The high voltage output of the Spellman power supply was measured with a Keithley high voltage probe and a Fluke 79 DMM. The high voltage output was adjusted to measure 4.020kV. The additional 20V above the test specification is added to overcome the losses in the high voltage switch and reverse voltage blocking diode. The IEC61000-4-2 standard requires a minimum of 3 positive pulses and 3 negative pulses applied to the EUT **[59]**. This standard has different test levels and is given in Table 5.4.

Table 5.4 IEC61000-4-2 Test Levels **[59]**

Level	Contact Discharge (kV)	Air Discharge (kV)
1	2	2
2	4	4
3	6	8
4	8	15
X [1]	Special	Special

[1] X is an open specification. The level has to be specified in the dedicated equipment specification. May also require specialised test equipment.

From the above specification (and table), two test scenarios are possible. The air discharge simulates non-contact high voltage application. Because the power supply is only proof-of-concept and will ultimately be housed in a suitable enclosure, this test is not directly applicable. The second IEC test described in the IEC61000-4-2 standard is a contact discharge and bears direct relevance to the EUT. The high voltage generator will thus be directly connected to the mains input of the power supply. This test will be performed to a level 2 of the IEC61000-4-2 since the available high voltage generator can only supply up to 5kV.

Furhtermore, the available Spellman high voltage power supply can only generate positive high voltage. It was decided that three pulses would be applied to the Live conductor of the mains supply and 3 pulses to the Neutral conductor. The oscilloscope was connected to the test point on the mains supply via a 100:1 probe in order to prevent the high voltage from damaging the input.

The oscillograph in Figure 5.9 indicate the measured mains-borne high voltage spikes applied to the Live conductor by means of the high voltage power supply and the change-over switch. The measured peak value was 4.208kV. The additional 208V can be ascribed to the adding of the 4kV pulse to the mains sine-wave at the exact moment when the pulse was applied.

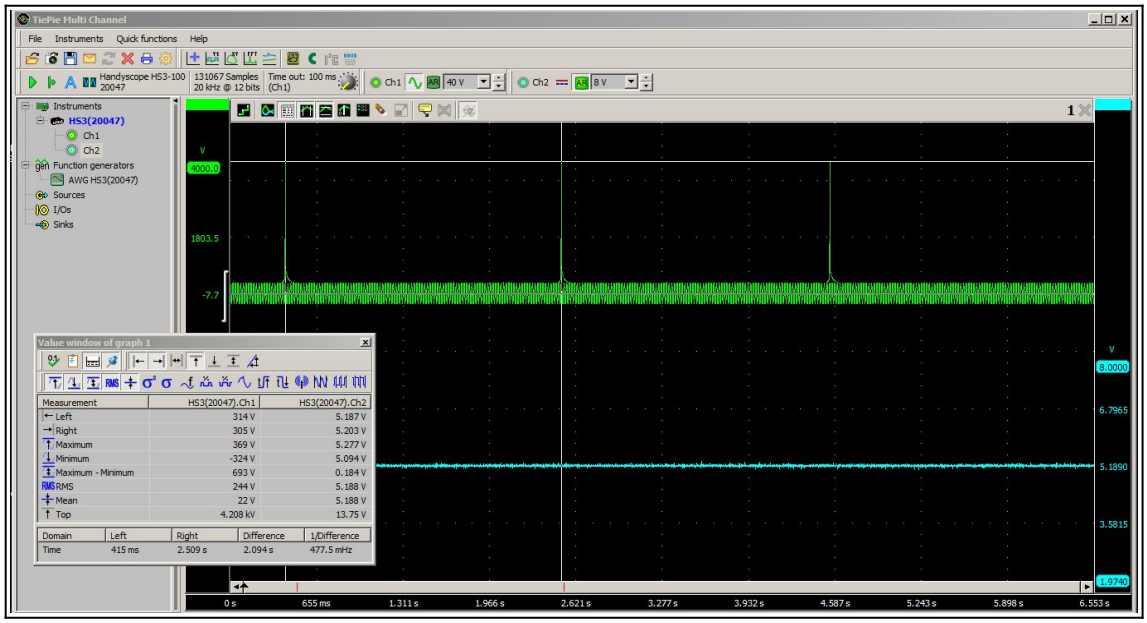


Figure 5.10 Oscillograph of High Voltage Pulses Applied to the Power Supply Mains Input

The output of the artefact remained stable as can be seen in Figure 5.10 (Bottom cyan trace indicating 5 V rail with no visible peaks during applied high voltage pulses on top, green oscilloscope trace). The same test was repeated with the second oscilloscope channel connected to the 12V rail. No transfer of the high

voltage pulse was observed on the output in this instance either. No visible damage to the artefact was also observed upon applying the charged capacitor to the input of the artefact.

Environmental Testing

5.3.11 Temperature Shock

The first part of the environmental test sequence in Table 5.2 is the cycling of the artefact between ambient and a much lower temperature. Although the applicable MIL-STD prescribes temperature shock as a rapid change in temperature of at least 10°C, the artefact will be tested from between ambient room temperature and -20°C to simulate a real-world harsh environment. During typical use a real-world artefact would be subjected one full cycle between ambient and cold temperature and back, with a second cycle in worst case scenarios.

In order to test the endurance of this PSU, the artefact will endure 2½ times that of a real-world operational scenario with 5 complete cycles between ambient and -20°C. Upon completion the performance will be tested and the power supply inspected for physical damage. Figure 5.11 depicts the planned test cycle for the temperature shock test and details a full 5 cycles of temperature shock.

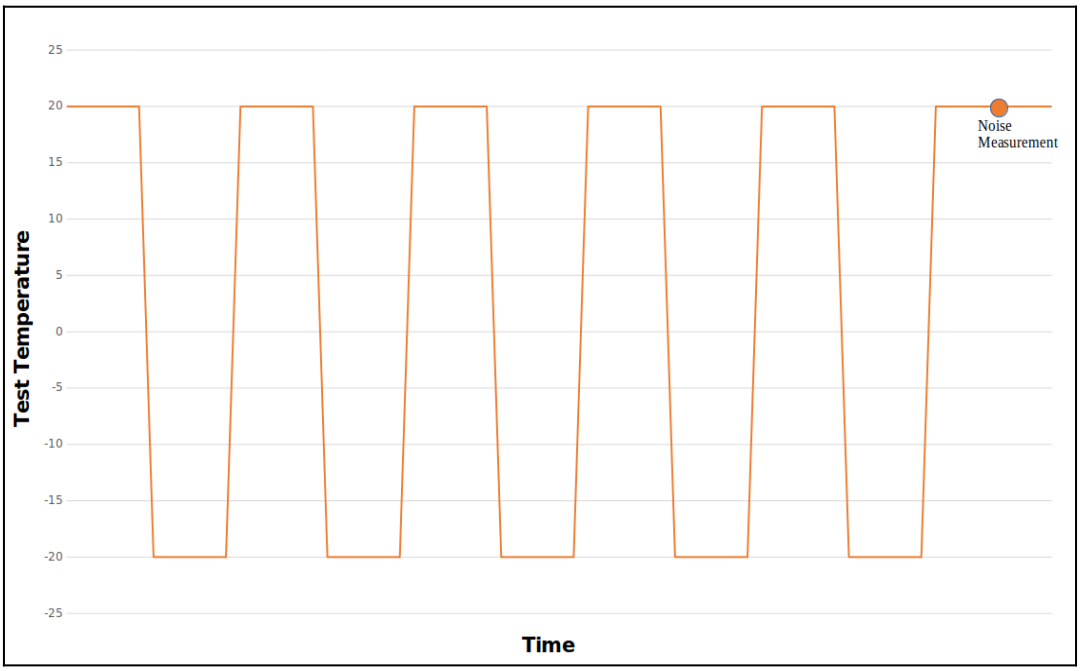


Figure 5.11 Proposed Temperature Shock Test Plan

Noise measurements was taken after the 5th complete cycle. The PSU was allowed to naturally return to ambient temperature of ± 20°C. The output from the oscilloscope is shown in Figure 5.12.

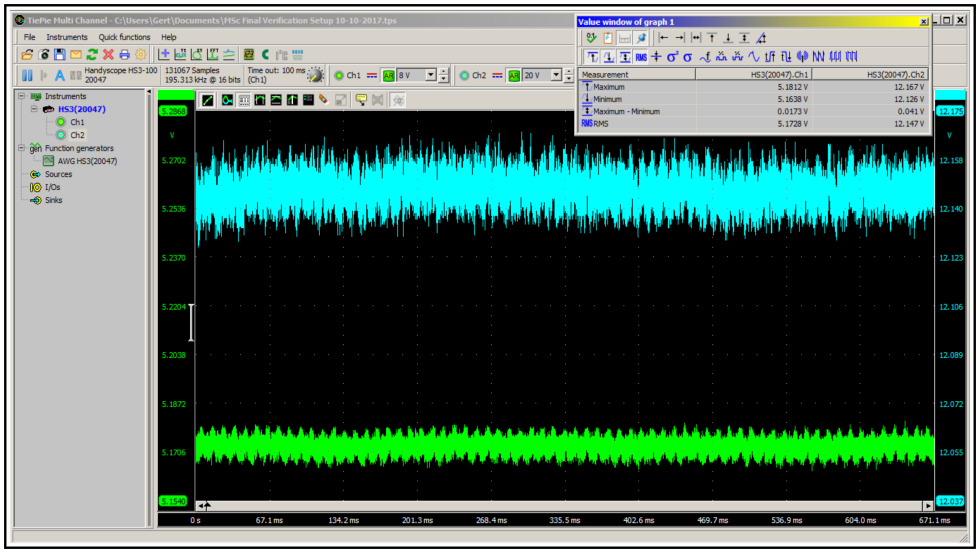


Figure 5.12 Screen Capture of the Noise Measurements after 5 Temperature Cycles

From the above figure and related measured values, it can be seen that under full load, noise on both the output rails is 17.3mV and 41mV respectively, both still within the limits of the design requirements and similar to the measurements taken before the test.

The artefact's three discrete circuit boards were also visually inspected with a stereo microscope at X45 magnification for signs of damage to solder joints and components. No visible evidence of any damage could be observed.

5.3.12 Temperature Function

The test will verify the power supply's performance, battery discharge and recharge cycles and output rail noise levels at intervals across the entire temperature range as per Figure 5.13.

In order to determine the linearity and stability of the PSU, the discharge and recharge cycle will be repeated at increments of 14°C from -20°C to 50°C as per the design requirements section.

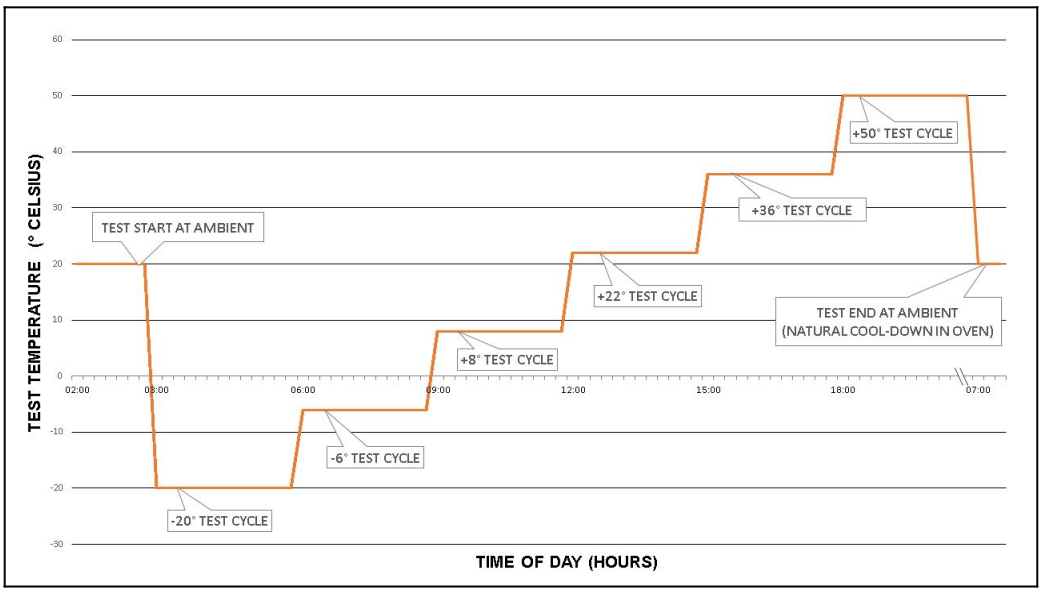


Figure 5.13 Proposed Temperature Test Plan

Figure 5.14 details the test steps to be performed during each of the test temperatures depicted in Figure 5.13.

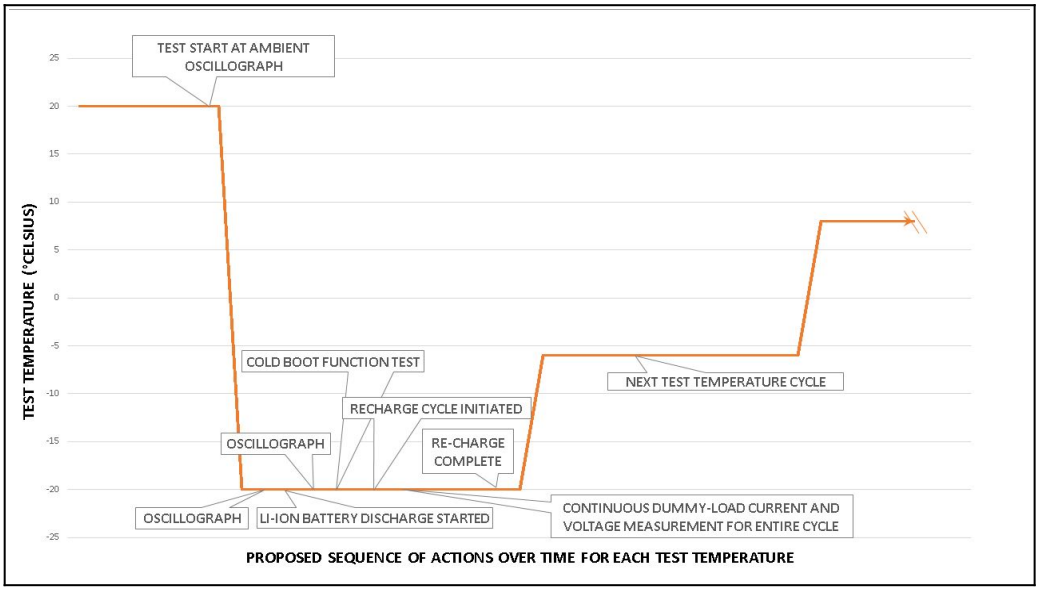


Figure 5.14 Proposed Temperature Test Plan Detailed Information

As can be seen from Figure 5.14 a multitude of actions must be performed for each of the temperature intervals.

5.3.12.1 Cold Test Cycle

In order to simulate the cold environment for which the power supply has been designed, it was placed inside a thermostat-controlled refrigerator, whilst operating at 115% load. The artefact, which until this

point had been operating at an ambient temperature (i.e. 20°C) was placed into the pre-cooled refrigerator. This was undertaken in order to simulate a further temperature shock cycle from +20°C to -20°C as was previously done.

As soon as the refrigerator temperature had stabilised (at -20°C), the battery discharge and recharge sequence was performed at 115% load. Once the Li-ion battery was fully recharged, the test temperature was increased to the next test point (i.e. -6°C) and the discharge / recharge sequence repeated upon reaching temperature stability. This operation was again repeated at the subsequent test temperature interval (i.e. +8°C).

In order to minimise the thermal load on the refrigerator, the dummy loads were placed outside the cold compartment to radiate the generated heat into the ambient air. Temperature, voltage and current measurements were continuously taken for the entire duration of the tests.

The refrigerator is thermostat-controlled and has a circulating fan placed inside to ensure even temperature distribution. Figure 5.15 shows the test setup with the oscilloscope and 2x Fluke 77 DMMs connected to the EUT. The latter placed inside the cold compartment.

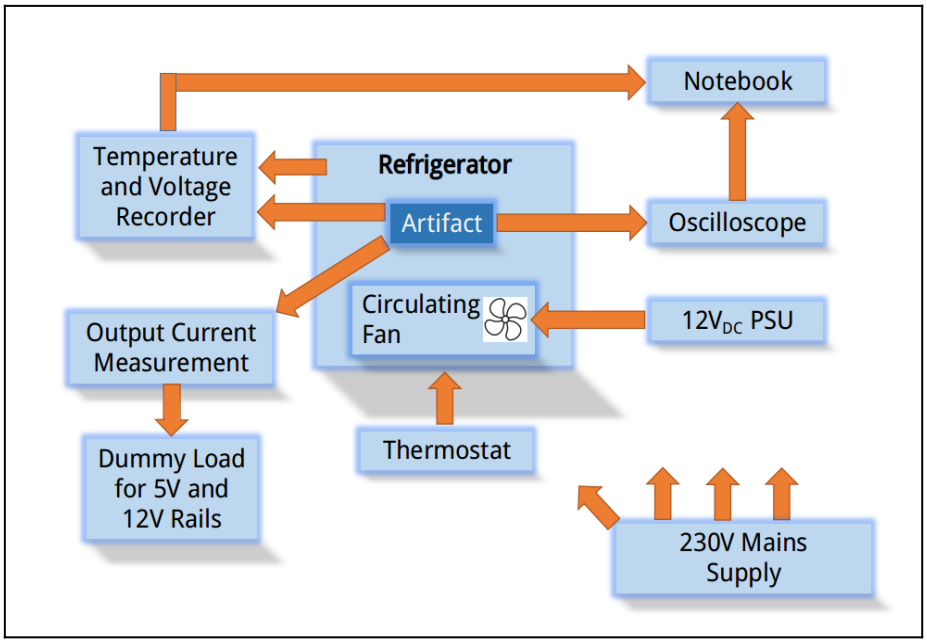


Figure 5.15 Block Diagram of Cold Cycle Test Set-up

As can be seen in Figure 5.16, a circulating fan is placed inside the cold compartment to ensure even temperature distribution.

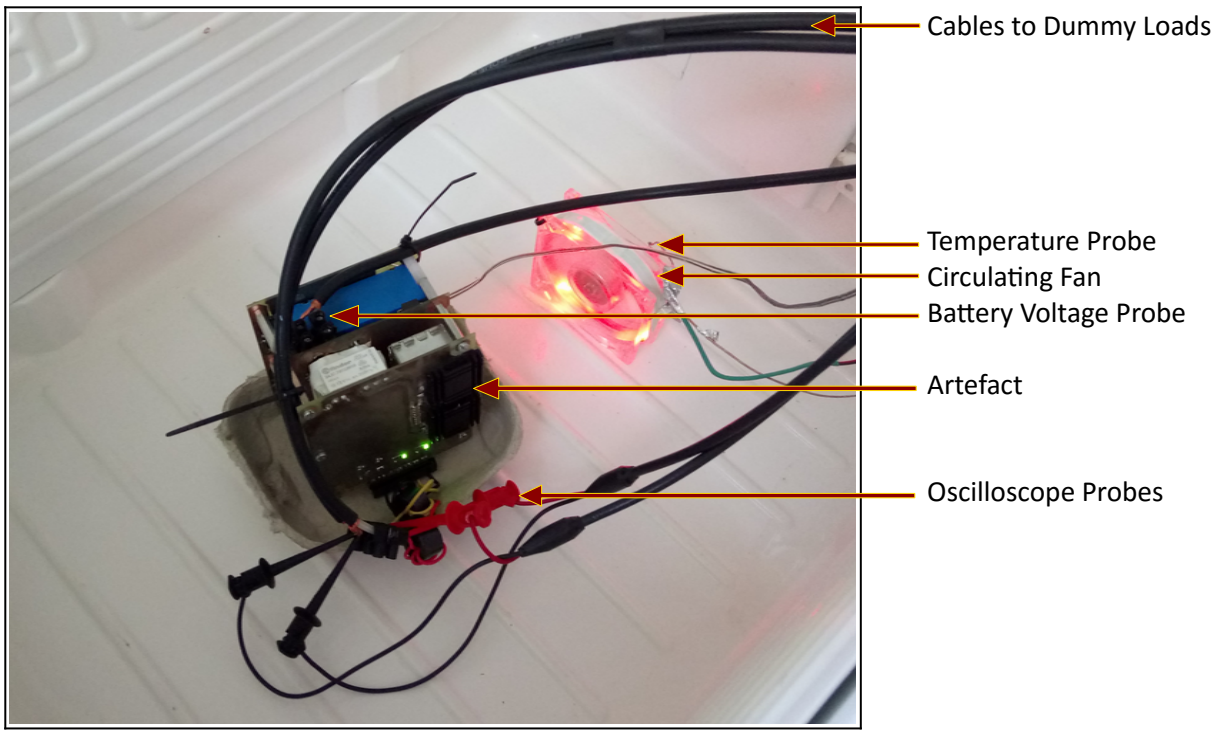


Figure 5.16 Cold Cycle Test Set-up in Refrigerator

Temperature measurements was performed with a K-Type thermocouple and recorded along with battery voltage by an Endress & Hauser RSG-30 Data recorder at a sample rate of 1 Sample per second. The below graph indicates the cold compartment temperature of -6°C (Blue Line) and the battery voltage (Purple Line) before and during the discharge cycle. The recharge cycle was initiated as soon as the battery reached a fully discharged state, as can be seen in Figure 5.17 below. The spike in the temperature graph was recorded when the refrigerator compartment was opened to visually inspect the power supply. The discharge and recharge curve (Figure 5.17) of the 2 x 18650 Lithium-ion cells of which the battery comprises of is a typical discharge curve of this type of cell **[100,101]** at this temperature. Due to the extreme cold the capacity of the cells are severely reduced.

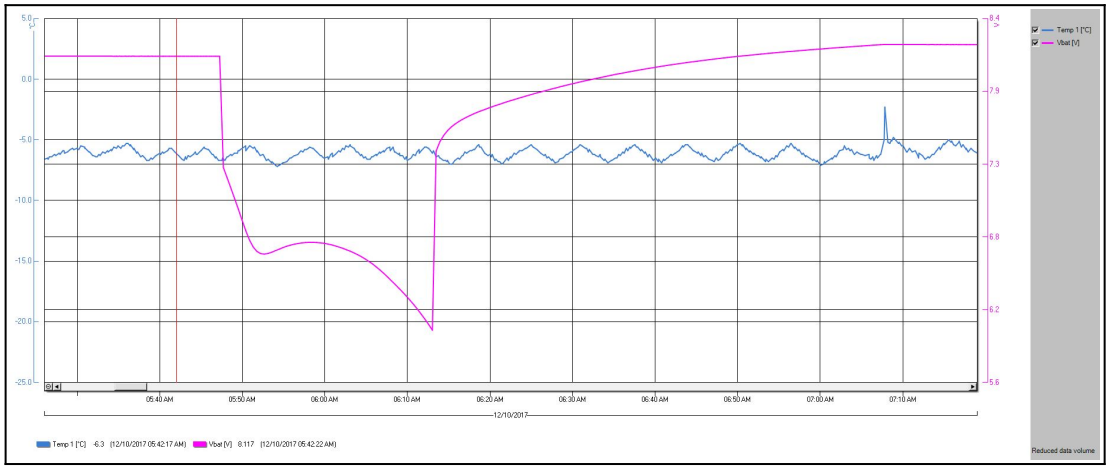


Figure 5.17 Graph of Battery Discharge/Recharge Profile at -6°C Test Temperature

Noise measurements on the output rails were also taken during each of the cold cycles. A representative measurement at +8°C is shown in Figure 5.18.

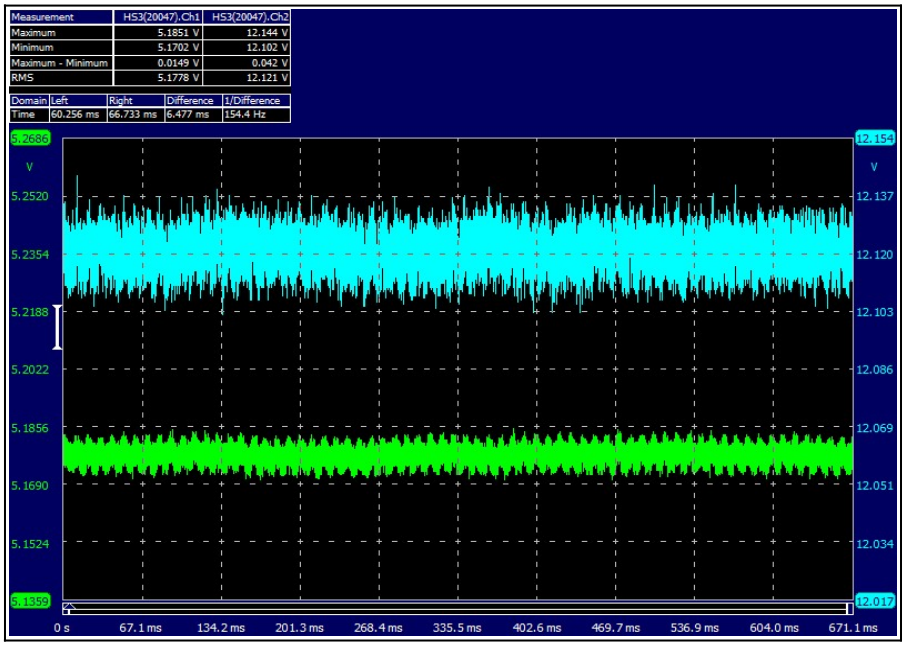


Figure 5.18 Oscillograph of Output at +8°C During Discharge

As can be seen in the above figure, the voltage and noise measurements are within specification.

5.3.12.2 Hot Test Cycle

For temperature test intervals from +22°C to +50°C, the artefact was placed in a thermostat-controlled oven. Figure 5.19 indicates the functional block diagram of the test set-up.

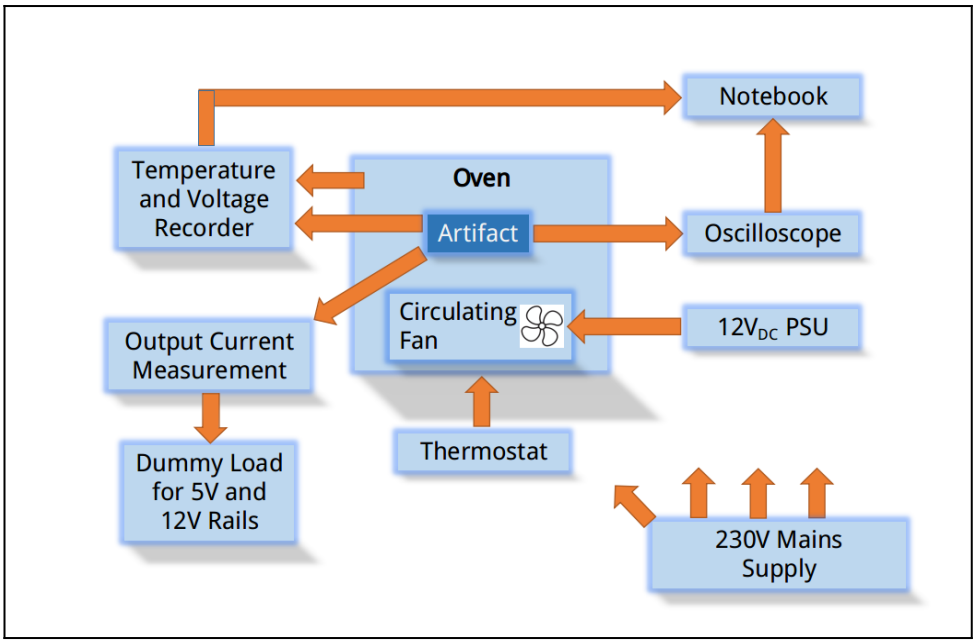


Figure 5.19 Block Diagram of Hot Cycle Test Setup

A small COTS, home-use oven was utilised with essentially the same procedure followed as was the case with the cold test cycle. The oven was consecutively set at each of the three temperatures (i.e. +22°C, +36°C and +50°C) for each of the three tests as laid out in Table 5.2 (Verification Testing Parameters/Actions Plan) and Figure 5.13.

Figure 5.19 shows the test set-up for the hot test cycle with the artefact, various probes and cables leading to the externally located dummy loads for the 5V and 12V rails. These load resistances were placed outside the oven compartment in order to reduce the effect of the generated heat on the test set-up.

A circulating fan was also placed inside the oven as was the case with the cold compartment tests previously performed. The purpose of this fan is to ensure even temperature distribution throughout the oven compartment.

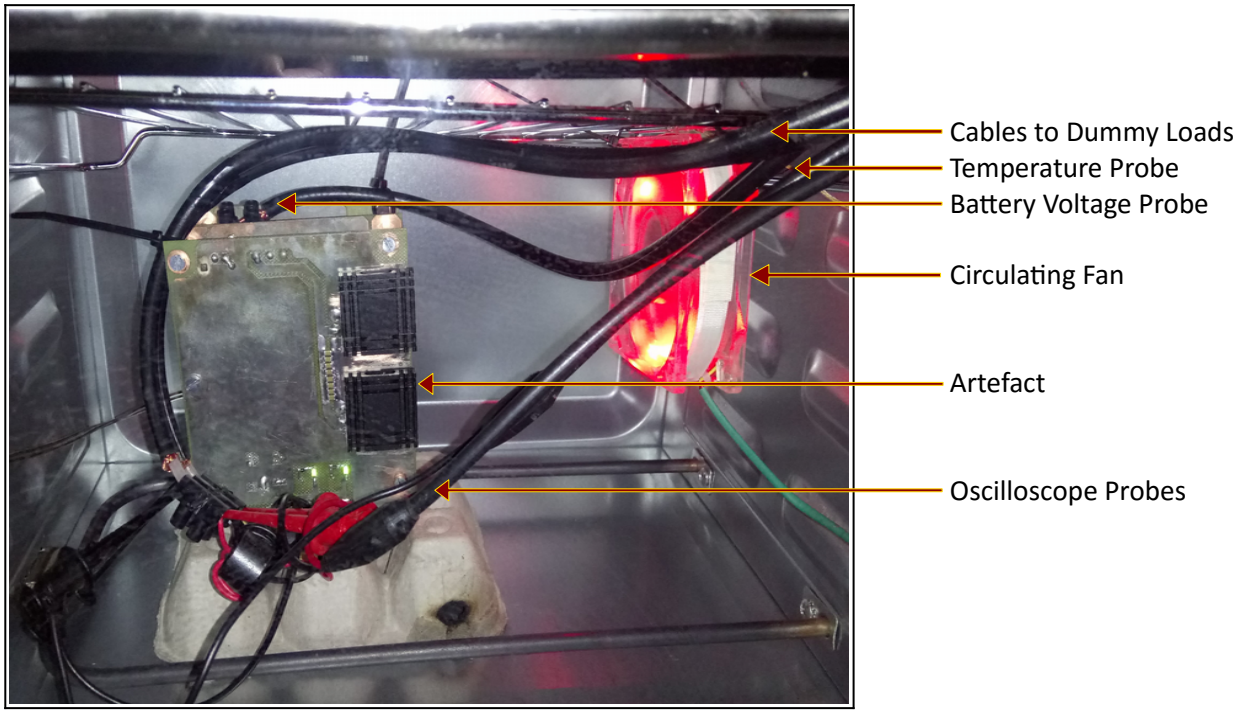


Figure 5.20 Hot Cycle Test Set-up in Oven Compartment

The graph in Figure 5.21 denotes the recorded temperature (+36°C) and the battery voltage before and during the discharge cycle as well as the immediate recharge cycle of the lithium-ion battery at the test temperature.

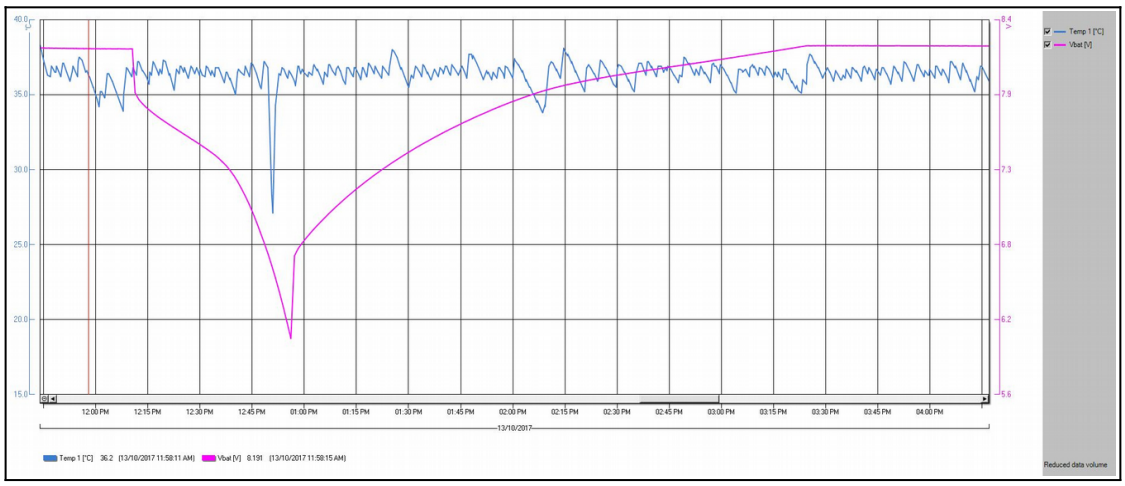


Figure 5.21 Graph of Battery Discharge/Recharge Profile at +36°C Test Temperature

In the above graph can it be seen that the battery voltage was stable at the float-voltage of 8.2V during which time the temperature inside the oven compartment was allowed to attain equilibrium. The discharge test was started as soon as the temperature inside the compartment stabilised. The recharge cycle was immediately initiated after the full battery drain and is depicted by the rising edge of the purple line in Figure 5.21.

The photograph in Figure 5.22 shows the screen of the Endress & Hauser RSG30 temperature recorder (as reference) before the discharge test at +50°C was started.



Figure 5.22 Temperature Recorder Display Before Start of Discharge/Recharge Profile at +50°C

Figure 5.23 shows the output of both the voltage rails during the discharge test of the Li-ion back-up battery at +50°C with the mains primary input switched off.

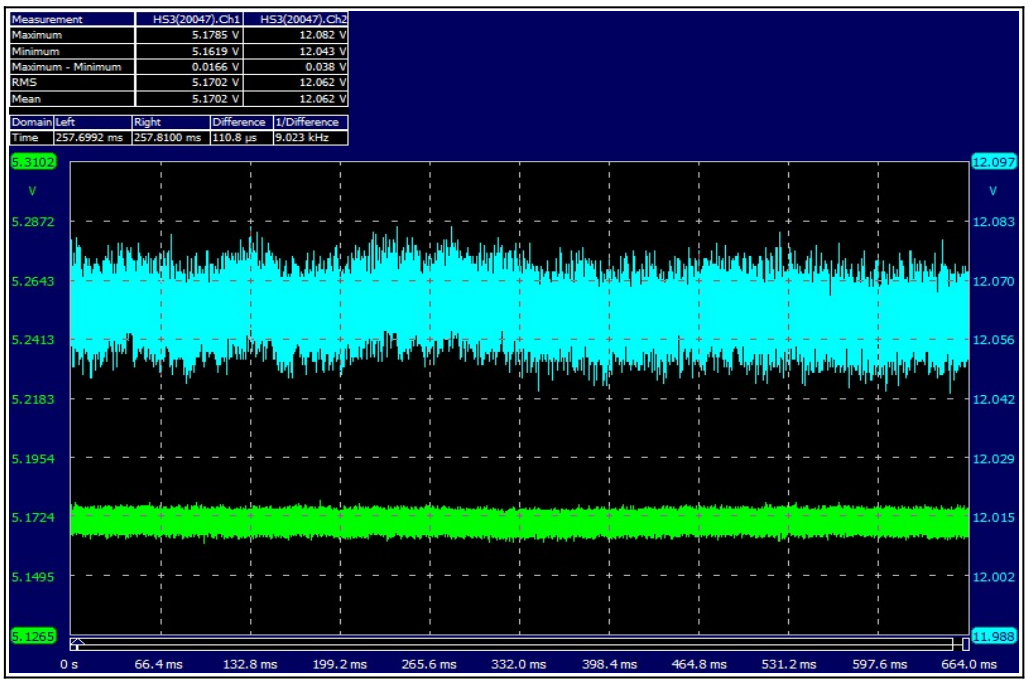


Figure 5.23 Output Rail Voltages and Noise Measurements during Discharge at +50°C

As can be seen from the oscillograph, both the output rails' voltage are within the 5% tolerance and measured noise is less than 50mV.

Data obtained during the six tests performed at each of the temperatures was plotted and the linearity of the artefact was determined. This data is summarised in the following graph in Figure 5.24.

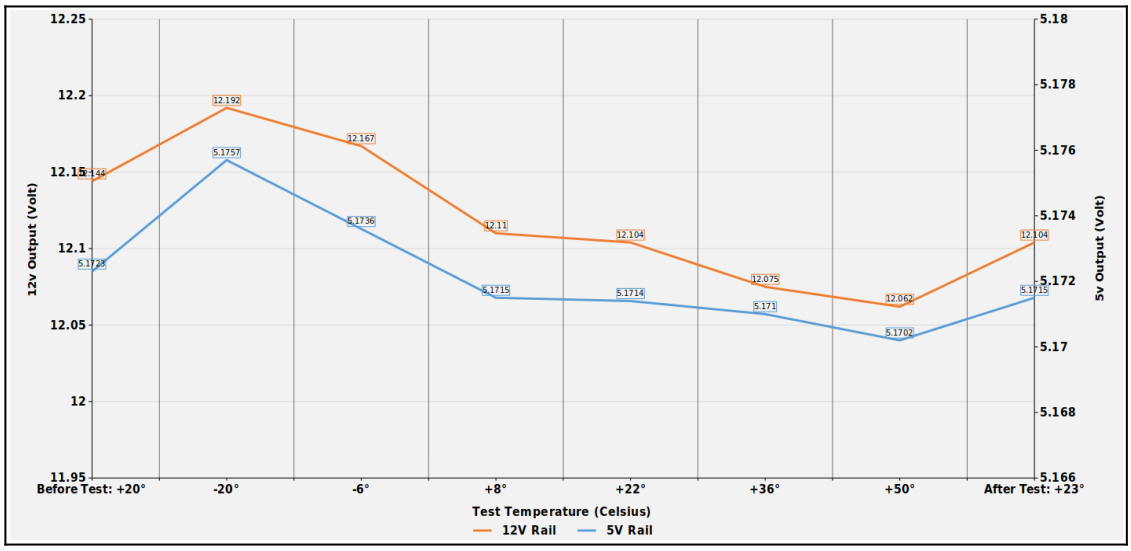


Figure 5.24 Output Voltage Linearity vs. Temperature

The above graph shows the relative linearity of the output of the artefact over the entire temperature range. The maximum difference between the voltage amount to 5.5mV on the 5V rail and 130mV on the 12V rail. This translate to 0.11% for the 5V rail and 1.08% for the 12V rail.

From the graph it is also evident that the switch-mode regulators are more efficient at lower temperatures and with a fall in the output voltages becoming evident at elevated temperatures. Although this is expected (since electronic circuits generally perform better at lower temperatures), these values are well within the stipulated tolerances as per Table 3.3 (Electrical Requirements Analysis)

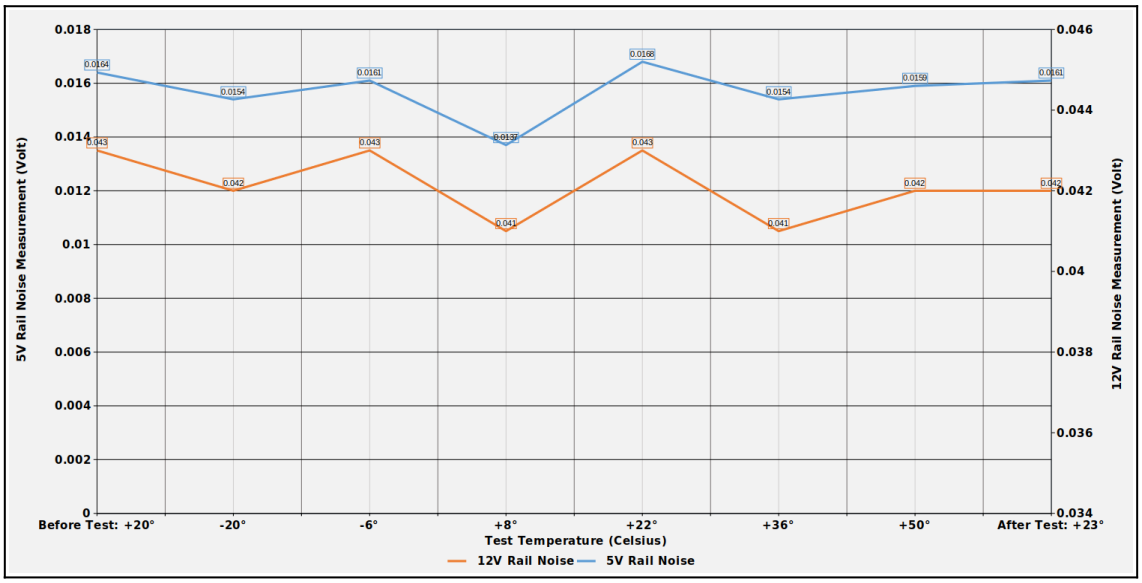


Figure 5.25 Output Noise Linearity vs. Temperature

The graph in Figure 5.25 shows the noise-performance of the artefact to be somewhat linear over the entire temperature range. The maximum difference is 2mV (5V Rail) and 3.1mV (12V Rail). These figures al below the limits as outlined in the design-requirements.

The output of both rails fall within the parameters as specified in Section 3.2.4 over the entire temperature range at which the artefact was tested. However, based on the observations during the preceding test it is recommended that further research is done in order to extend battery capacity at low temperatures.

5.3.13 Vibration Test

As per MIL-STD 810G Test Method 514.7 and 528.1 **[68]** and MIL-STD 883E **[57,58]** the initial vibration tests are performed on an artefact to establish which vibration levels it can be exposed to before malfunction or damage occurs. As per Table 3.5 limited vibration tests will be performed since complex vibration patterns such as aircraft or road-transport simulating equipment is not readily available. Furthermore, the artefact as synthesised in this dissertation is not enclosed in a final enclosure and not all real-world equivalent tests can thus be accurately performed.

5.3.13.1 Vibration Test

With the aforementioned limitations in mind, a rudimentary vibration test was performed on the power supply using an electro-dynamic shaker system. The system controller generates sine-wave patterns which is amplified by a high-power amplifier which in turn drives a vibrator platform **[107,108]**.

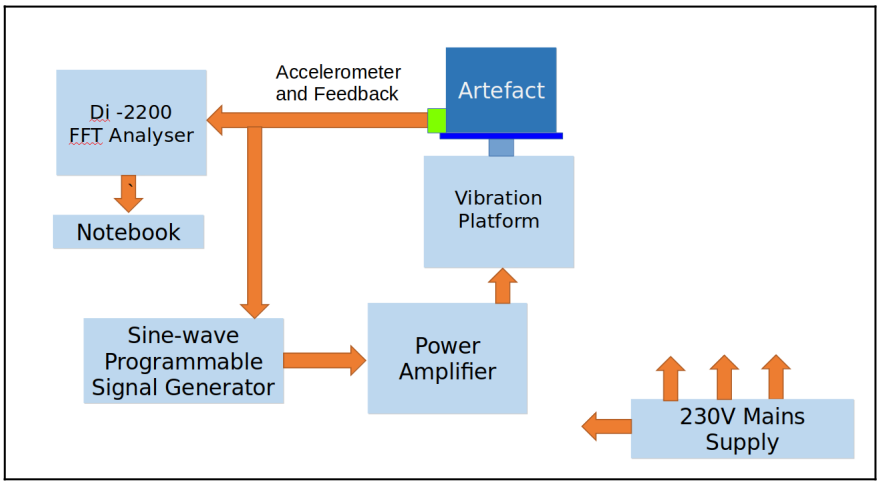


Figure 5.26 Block Diagram of Vibration Test Set-up

The artefact is securely mounted on the platform and is subjected to various frequencies and pre-set displacement values. After vibration, the artefact is evaluated for any signs of performance degradation as a direct result of the vibration tests.

The operation of the vibration system as outlined in Figure 5.26 is a closed-loop. The sine-wave programmable signal generator is programmed to produce a sine-wave of specific amplitude and frequency. This signal is amplified by the power amplifier which in turn, drives the vibrator with high current to facilitate movement. The vibrator is in essence a big loudspeaker with the armature resembling the voice coil. This armature is connected to the platform onto which a test item is secured.

An accelerometer is placed on the artefact or platform in order to measure the vibration. The signal from the accelerometer is fed back into the signal generator which controls the level of its output accordingly. Thus a constant amplitude and frequency vibration is maintained on the device under test.

The Fast-Fourier Transform analyser uses the signal from the accelerometer in order to provide visual output of the applied vibration pattern. It also calculates the magnitude of the applied G-Force to the artefact. Figure 5.27 shows a photograph of the artefact and test setup.



Figure 5.27 Vibration Platform with Artefact Mounted in Position on Top of the Platform During the Test

Table 5.5 indicates the various frequencies and g-forces to which the artefact was subjected to during the 15 minutes of each test frequency.

Table 5.5 Test Frequencies and Applied g-Forces

Test Frequency	Applied g-Force
13Hz	3.559g
50Hz	3.677g
1kHz	8.325g

The frequencies in the above table were arbitrarily chosen based on typical operating conditions of harsh environments in real-world scenarios. Shipboard vibration is typically around 13Hz, mains frequency at 50Hz (cause of long-term damage due to transformer vibration at mains supply frequency) and at 1kHz high frequency vibration simulating road transport and aircraft vibration environments. These frequencies were also readily available on the frequency generator used during this test.

The photograph in Figure 5.19 shows the screen output of the Di-2200 FFT Analyser during the 50Hz test.

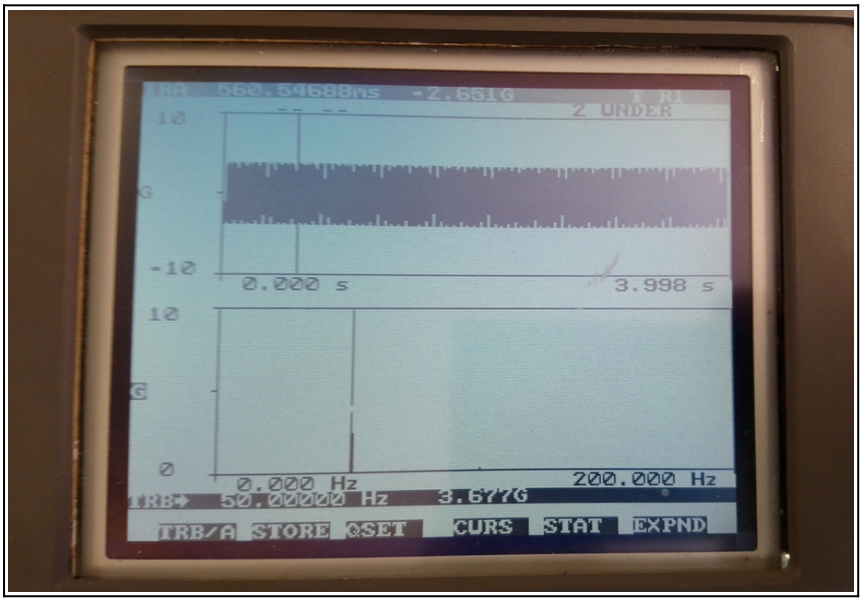


Figure 5.28 Analyser Screen During 50Hz Test

Figure 5.29 shows the measured vibration from the accelerometer as analysed by the Di-2200 FFT Analyser.

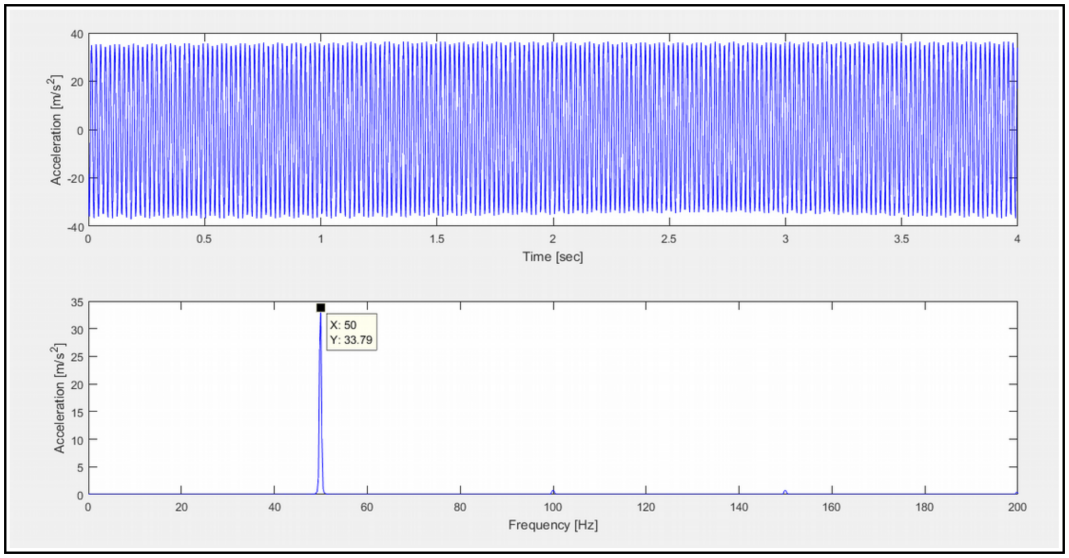


Figure 5.30 Analyser Measurements for Time and Frequency Domains

Figure 5.31 shows the artefact *in situ* on the shaker platform during the 13Hz test with the feedback accelerometer attached in the foreground (blue cable).

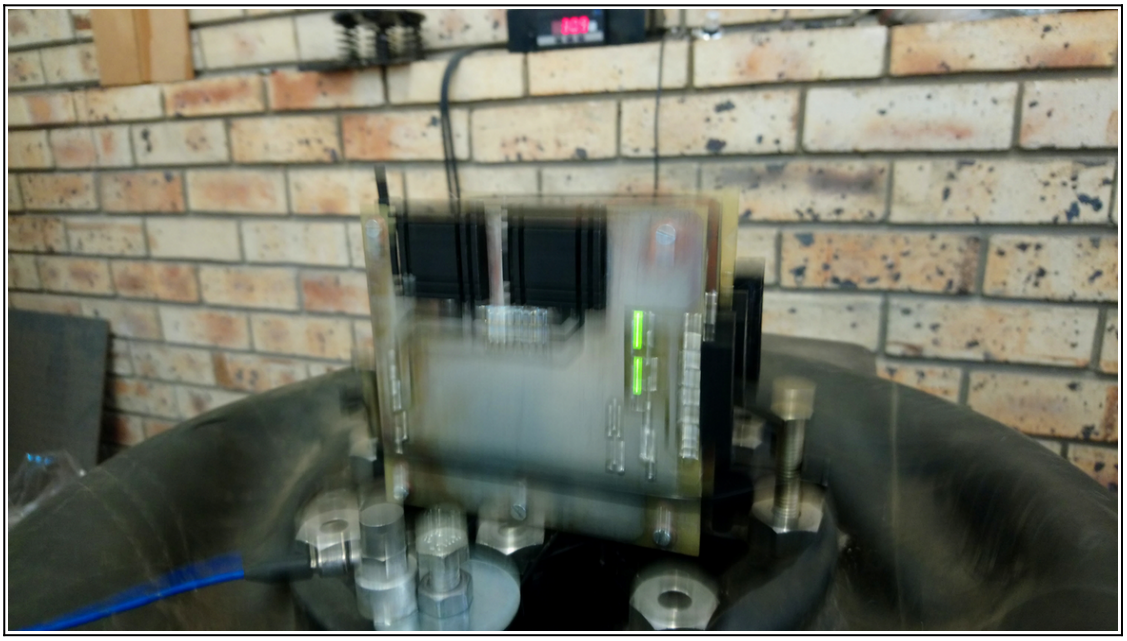


Figure 5.31 Artefact During 13Hz, 10.3mm Displacement Vibration Sequence

Upon completion of the sine-wave vibration, the PSU was again evaluated for poor performance or signs of physical damage. As previously tested, was output voltage and noise measurements taken and were the recorded values within limits as specified. The artefact was again dis-assembled and scrutinised under a 45x stereoscopic microscope for signs of visible damage. No signs of physical damage was observed.

5.3.13.2 Further Vibration Testing

Since only sine-wave vibration patterns could be generated during the previous test, a second vibration endurance test was performed in order to evaluate the artefact for vibration hardiness.

An elementary vibration platform was employed to test the artefact's degree of tolerance to vibration. To this end, a rudimentary vibration platform was constructed with an aluminium sheet (400×400×3 mm) and mounted on four steel coil springs.

A small 12V direct current electric motor was mounted on the bottom of the plate and a solid brass eccentric fly-weight was lathed and fitted onto the shaft of the motor. A variable bench power supply was used to power the motor at different voltages, thus resulting in different frequencies. Figure 5.32 outlines the test set-up.

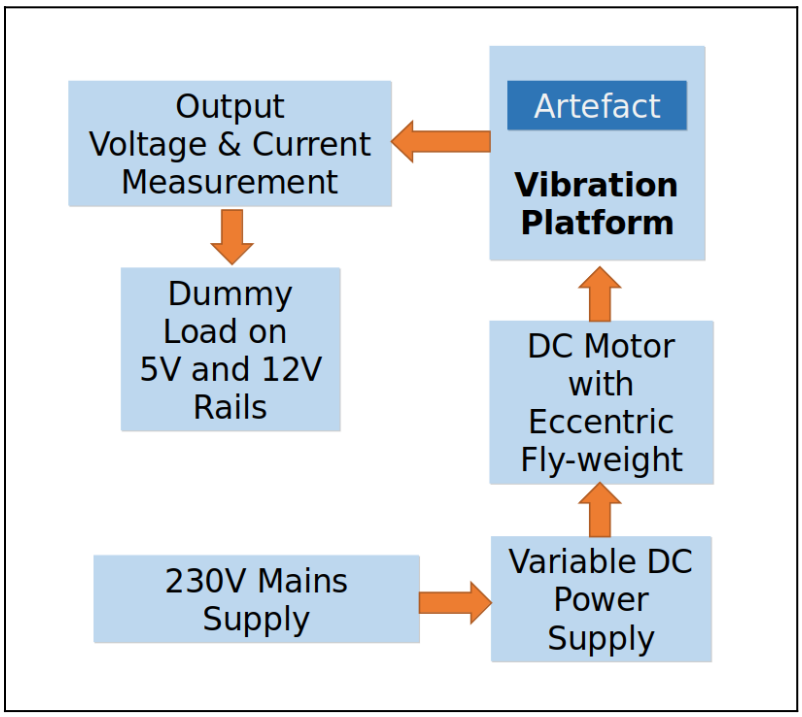


Figure 5.32 Artefact Vibration Endurance Test Platform Block Diagram

Although this is by no means a calibrated test, was it performed for 6 hours per axis at different frequencies in order to determine if any physical damage could be induced on the PSU. During vibration testing the artefact was also operated at 115% load in order to meet or exceed real-world deployment requirements.

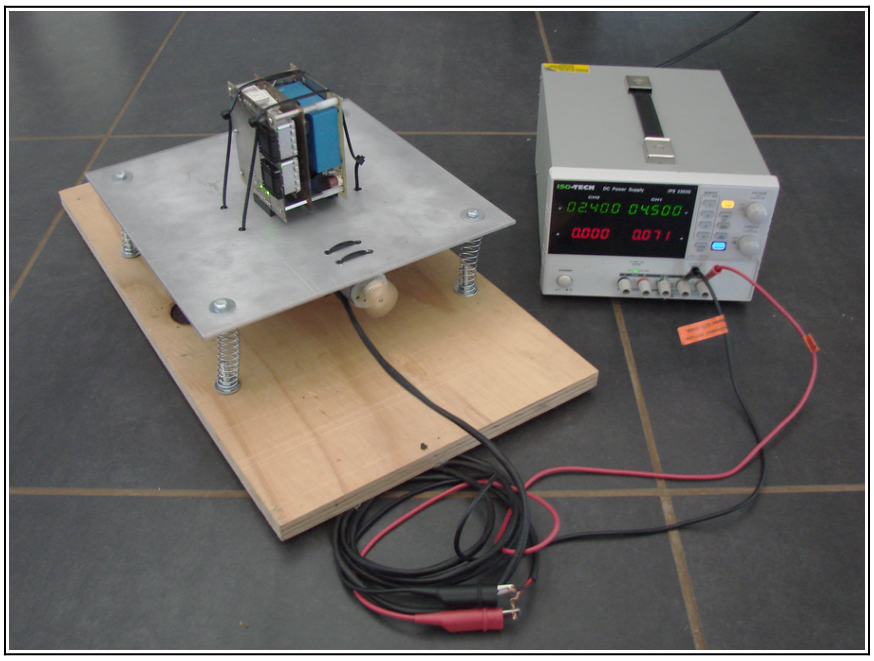


Figure 5.33 Power Supply Vibration Endurance Test Platform

Figure 5.33 shows the test setup of the extended vibration test. The DC motor with the lathed eccentric fly-weight can be seen on the front of the aluminium platform.

No visible damage to the artefact was observed upon completion of the 18 hours of vibration testing. The output of the artefact on both the 5V and 12V rails remained stable as can be seen from the following oscillograph:

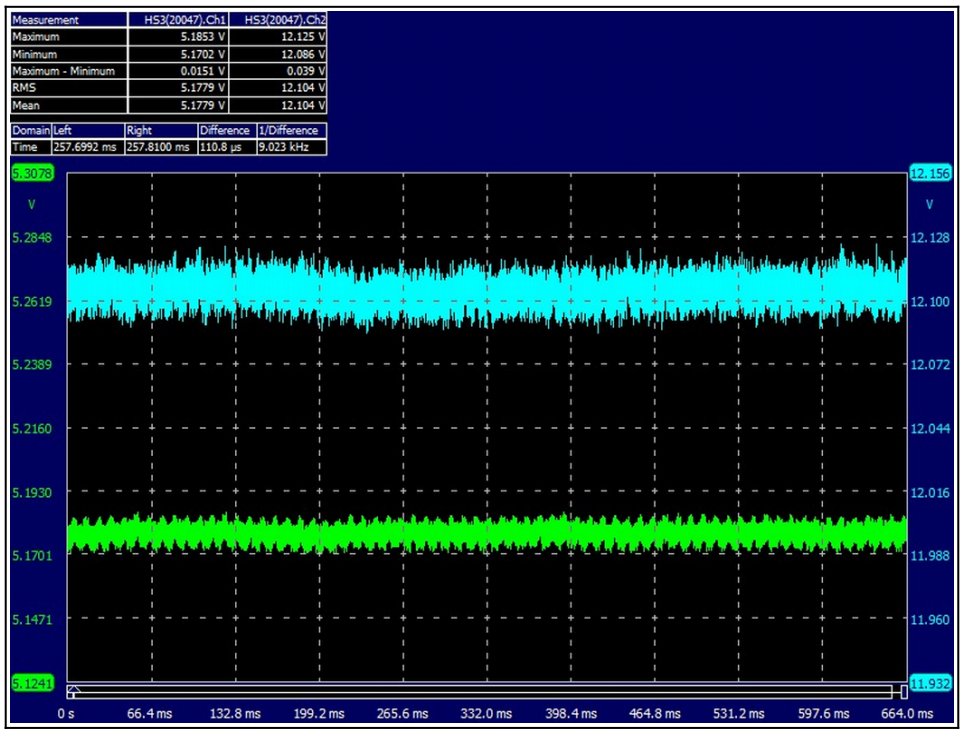


Figure 5.33 Output Rail Measurements After Vibration Test

5.3.14 Shock Test

For the shock test, the power supply was subjected to 3 falls in each orientation from a height of 300mm onto a hard table surface in order to simulate handling in a real-world scenario.

The output from the power supply was measured afterwards with an oscilloscope and was found to be within the requirements.

Figure 5.34 shows the measured output after the shock test.

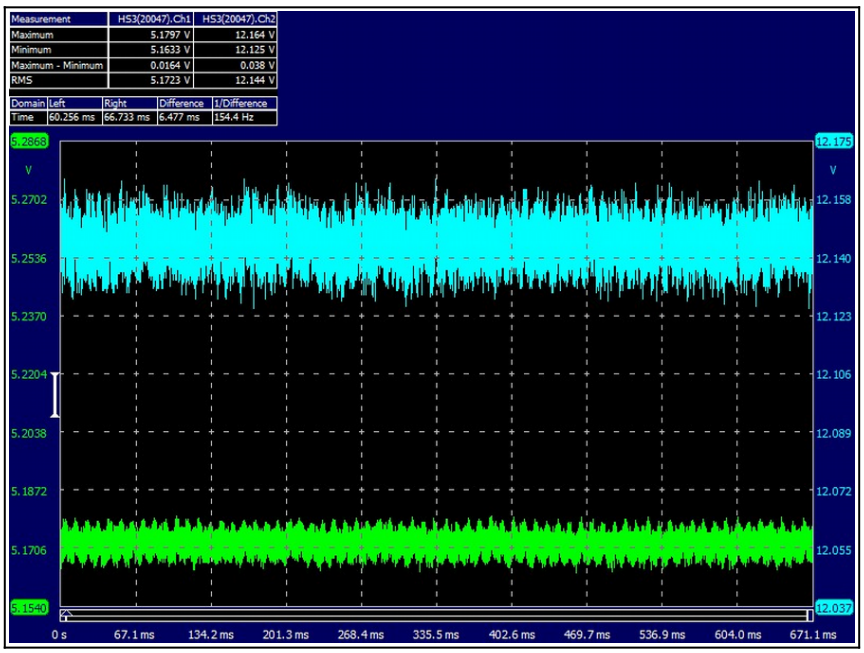


Figure 5.34 Output Rail Measurements After Shock Test

After the measurements for Figure 5.34 were taken, the power supply was completely dis-assembled into its three constituent parts and inspected with the 45X stereoscopic microscope. No signs of visible damage was observed.

5.4 Final Verification Conclusion

Since the artefact is a proof of concept design, and many improvements can be affected, it has been proven with these preceding tests that it is fully operational. The artefact was subjected to a number of electrical, mechanical and environmental tests with continuous measurements taken in order to verify the robustness of the power supply.

The results from these tests validates the design requirements as set out in the beginning of this dissertation. It is fully deployable in its current form as a robust power supply for harsh environments.

CHAPTER SIX

Conclusion

This concluding chapter summarises the results that were obtained during this investigation. Through an established research process, this dissertation serves as guideline for the design and synthesis of a robust power supply for neutron monitoring applications. In conclusion it can be said that the PSU provides proof-of-concept evidence that a single PSU Configuration Item can be deployed in all existing neutron monitoring applications.

6.1 Summary

The primary research question (problem statement) as set out in Chapter 1 (Section 1.3) was stated as follows:

> *Is it possible to design and synthesise a single configuration item (i.e a robust, low voltage, power supply) – one capable of being deployed in all environments in which neutron monitors are deployed?*

This problem was logically divided into three sub problems or research objectives, viz.:

1. *Is it possible to design and synthesise a robust power supply which can withstand a range of specified harsh environments?*
2. *Can this envisaged PSU be designed with a view to ease manufacture by modular construction (including identification of readily obtainable components)?*
3. *How best may the envisaged artefact (PSU) be validated and verified in order to determine if the research parameters have been adequately addressed?*

As part of the research methodology set out in Chapter 1 (Figure 1.7), Chapter 2 was devoted to an in-depth literature study. In this context, the following topics received attention during the course of this literature study:

- Harsh Environments and what constitutes these;
- Stresses on electronic systems such as power supplies in harsh environments entailing electrical, mechanical, humidity and temperature stresses;
- Preventative and corrective actions during the design, construction and operation of power supplies in harsh environments;
- Various types of power supplies including Unregulated, Linear, Switch-mode and Hybrid power supplies and advantages versus disadvantages of each type;
- An in-depth discussion of a number fundamental types of switch-mode power supplies, examples of each and elementary functioning of each;
- Typical existing power supplies deployed in neutron monitoring applications and operated under harsh environmental conditions.

Chapter 3 dealt with the design of the physical artefact based on the research undertaken in Chapter 2. It outlined the system analysis that was performed in order to establish the design requirements. The system analysis process focussed on describing the problem, setting up an outline in terms of desired performance and provided the foundation for the designer to develop a basic design. Subsequently, the developed artefact was iteratively improved in terms of functionality and performance until a final artefact that wholly satisfied the requirements (i.e. as designated in the main research problem statement) was reached. An in-depth requirements analysis was performed, studying the various aspects of a power supply capable of operating in harsh environments. This requirements analysis consisted of an electrical requirements analysis and environmental requirements analysis. It also outlined the testing requirements for such a harsh environment power supply.

In order to perform the detailed design of the final artefact (as outlined in Chapter 3) specific components were selected that met or even exceeded the minimum requirements as to what was set out. This process was carefully documented in Chapter 4. The optimum combination of components was found based on a parameter search on the various suppliers' websites and a final bill of materials was produced. The circuit boards were manufactured with the use of a computer controlled PCB milling machine and were individually hand-soldered.

Chapter 5 details the validation and verification process undertaken. Through a cross-referenced matrix detailing the design-requirements and the measured characteristics, it was established that the artefact fully satisfies the research requirements; and it was verified as such. The validation process described in the latter part of Chapter 5, takes cognisance of the relevant MIL-STD tests for environmental testing as described in the literature study. These international standards were employed as guidelines and a test plan

was developed through which the research was validated. The individual tests were each planned and successfully executed. All associated results have been provided. Finally Chapter 5 summarises the results with regards to performance.

It can thus be concluded that, in theory, a singe configuration item (PSU) could be deployed to all existing neutron monitor sites. In this context, the current power supply (i.e. as an outcome of the current research project) is purely a functional prototype and valid proof of concept. Obviously, before it can be reproduced (mass production) commercially for installation in, *inter alia*, neutron monitors, it will need to be appropriately enhanced. Even so, issues pertaining to maintenance and repair as well as experimental failure due to power supply failure have been resolved.

6.2 Contributions

As previously stated, at the time of writing (2019) neutron monitoring for cosmic ray studies has been conducted for more than six decades. However, within a larger context, electronic systems have operated in harsh environments ever since the advent of electronics. It is generally accepted that modern electronics will continue to be, *inter alia*, miniaturised. Here, with the vast array of sensor and processing devices available to researchers and the general public, harsh environment deployment of said systems will become more commonplace.

The investigation conducted in this dissertation is the culmination of more than five years of research by the researcher in, *inter alia*, power supplies for harsh environments. Although the artefact produced through this research is a proof of concept design only, it can, with the minimum of additional research, be developed into a fully deployable and commercial product. This should be seen as an important contribution to the neutron monitoring field.

6.3 Further Research and Recommendations

The prototype artefact is a self-contained, fully-functional power supply that satisfies the design requirements as developed in this dissertation. As a large quantity of data on the performance of the synthesised artefact was amassed during this research, the following recommendations are made *apropos* possible future research.

6.3.1 Form Factor

Compared to previous PSUs, the size of the current artefact has a significantly reduced footprint. However, assumed future advances in electronic components (transformers) and battery technology may well be employed to reduce the already highly compact artefact without reducing performance or robustness. Regardless, the current size is wholly acceptable and significant future reductions will be minimal due to the nature of transformers.

6.3.2 Battery Management

A major improvement to the performance of the artefact would be gained by further research into the battery management of the built-in Li-Ion cells and battery as a whole. As with many electronic components, batteries and battery chemistries have made huge advances during the past years. Further research into the battery management sub-system of the artefact could entail the following points:

- Improved performance in sub-zero temperatures through the possible use of cells from a different manufacturer or specification.
- Support for other battery/storage chemistries such as Li-polymer cells and Electric Double Layer Capacitors (Super Capacitors) should also be considered in any future iterations of the artefact. This will greatly enhance the adaptability of the PSU with increased deployment capabilities and robustness in especially harsh environments where batteries are often exposed to less-than ideal conditions.
- Although not directly related to the battery management system, the use of a programmable micro-controller with the corresponding charging algorithm for various chemistries is highly recommended. This will add to the flexibility of the power supply and overall modular design approach of the artefact

6.3.3 Diagnostic Capability

Since the artefact will mostly be deployed in remote locations where physical supervision is not always available or regularly possible, it is suggested that a completely isolated diagnostic and fault reporting sub-system be developed and integrated into the artefact.

Such a sub-system might well contain a micro-controller and would add to the autonomous operation of the PSU and NM by extension. The integration of this diagnostic system should however not interfere with the

reliability of the existing PSU. Any failure of this sub-system should not compromise the main function of the power supply. Specifically, to effectively power a load under all harsh conditions as set out in this dissertation.

6.3.4 Efficiency

As part of the passive filtering of high frequency noise that occurs on the mains supply, a low loss, iron-core toroidal transformer was used as a bulk conversion element. Although toroidal transformers are very efficient, this transformer had been designed for 50 Hz operation, and is therefore relatively bulky in size.

With possible future advances in power electronics, it is suggested that further research be done into the feasibility of replacing the existing transformer with a highly efficient, robust switch-mode power supply. This will also decrease the physical size and weight of the PSU without necessarily compromising the robustness or galvanic isolation of the artefact.

6.3.5 Cost

As cost is always a factor in any industry it is suggested that different construction techniques be investigated in the design of future iterations of robust power supplies based on the artefact synthesised in this dissertation. Additional research is suggested on the physical lay-out of the printed circuit boards in order to speed up the assembly process. This is especially true when automated assembly and soldering processes are to be implemented during mass production of said artefact.

6.4 Conclusion

It can be safely stated that this investigation provides substantiated information regarding research into low voltage power supplies as employed in harsh environments. Based on the research conducted into these aforementioned topics, this study resulted with the development of a harsh environment power supply in answer to the initial research question set down at the onset of this dissertation. The synthesised artefact is developed for typical deployment in a neutron monitoring environment and can be applied in any application where operating conditions constitute a similar harsh environment. A relevant and applicable validation and verification process was followed and all results were reported.

In conclusion this low voltage power supply readily meets or exceeds the design criteria as set out in Chapter 3, except in terms of the stand-by time during input power-source failures. This short-coming

should be addressed through further research as outlined in section 6.3 above. Furthermore it must be kept in mind that the artefact which has been synthesised in this dissertation, is only a prototype and enhancements can be made to it through further research.

Source List

1. Journal of Telecommunications System & Management, ISSN: 2167-0919, Accessed 14 March 2019 from https://www.omicsonline.org/scholarly /satellite-communication-journals-articles-ppts-list.php

2. Federal State Unitary Enterprise – Morsviazsputnik Website (Iridium and Inmarsat Operators, Russia), Accessed 14 March 2019 from https://www.marsat.ru/ en/technologies-iridiumnetwork

3. NASA Website, Accessed 5 February 2016 from https://www.nasa.gov/sites /default/files/thumbnails/ image/faq13.jpg

4. Idris A.N., et al., *Effect of Radio Frequency Interference (RFI) on the Precision of GPS Relative Positioning*, 8th International Symposium of the Digital Earth (ISDE8), IOP Conf. Series: Earth and Environmental Science 18 (2014) 012035 doi:10.10 88/1755-1315/18/1/012035

5. Z.S.Hamidi, et al., *Influence Factors of Radio Frequency Interference (RFI) for Solar Radio Astronomy Purpose at National Space Centre*, Malaysia, HAI JOURNAL OF PHYSICS, SERIES 8, (2012)

6. Spaceweather Website, Accessed 19 April 2016 from http://www.space weather.gc.ca/sbg-en.php

7. Barbara B. Poppe, Kristen P., *Sentinels of the Sun - Forecasting Space Weather*, Johnson Books, Boulder Colorado, p. 10, 2006.

8. Ian Morison, *Introduction to Astronomy and Cosmology*, John Wiley & Sons, p. 198, 2008.

9. H. Kruger, *A Calibration Neutron Monitor for Long-term Cosmic Ray Modulation Studies*, unpublished Ph.D. thesis, Potchefstroom: North-West University, 2006.

10. NWU Neutron Monitor Data Website, Accessed 4 August 2017 from http://naturalsciences.nwu.ac.za/ neutron-monitor-data

11. Neutron Monitor Database Website, Accessed 27 January 2017 from www. nmdb.eu

12. Neutron Monitor Database Website, Accessed 27 January 2017 from http:// www01.nmdb.eu/ public_outreach/en/06/

13. Danie de Villiers, *Calibration Neutron Monitor*, Potchefstroom: North-West University, Volume 1, April 2003.

14. Benadé GJJ, *Mini Neutron Monitor User Manua*l, September 2014, NWU, Potchefstroom

15. J.G.J. Krige, *A Testbed Implementation of Energy Efficient Wireless Sensor Network Routing Protocols*, unpublished M.Ing dissertation, Potchefstroom: North-West University, p. 5, 2013.

16. Benjamin S., et al., *Systems Engineering and Analysis*, Second Edition, New Jersey: Prentice Hall, p. 23, 1980.

17. Huang H. et al., *Passive device degradation models for a electromagnetic emission robustness study of a buck DC-DC converter.* EMC Europe 2015, Aug 2015, Dresden, Germany. 6p., 2015 Accessed 5 February 2019 from https://hal.archives-ouvertes.fr/hal-01225350/document

18. Crocomibette C. et. al., *Instrumentation and Control Ageing Management: a Focus on Electronic Parts and Boards*, Accessed 5 February 2019 from https://www.epri.com/#/ pages/product /1008166/?lang=en-US and https://inis.iaea.org/collection/NCLCollection Store/_Public/34/ 005/34005315.pdf?r=1&r=1

19. Alexandre Boyer, et. al., *Characterization of the Evolution of IC Emissions after Accelerated Aging*. IEEE Transactions on Electromagnetic Compatibility, Institute of Electrical and Electronics Engineers, 2009, 51 (4), pp.892. <10.1109>. Accessed 5 February 2019 from https:// hal.archives-ouvertes. fr/file/index/docid/669519/filenameBoyer_2009_Evolution_of_IC_Emission_Spectrum_after_Ageing_-_for_publication.pdf

20. Private communication Prof. H Moraal, July 2009

21. Private communication Prof. H Moraal, December 2014

22. Private communication with Dr. H Kruger, SANAE IV Station, Antarctica, December 2006

23. Private Communication with C. Steyn, SANAE IV Station, Antarctica, 2007

24. Holboell J., Sverrisson S., *The influence of temperature differences in moist environments on surface discharges on solid insulation*, 24th Nordic Insulation Symposium on Materials, Components and Diagnostics

25. Maskell B. R., *The effect of humidity on a corona discharge in air*, Royal Aircraft Establishment Technical Report 70106 June 1970, Accessed 21 December 2018 from https://apps.dtic.mil/dtic/tr/fulltext/u2/720090.pdf

26. ELNA Capacitor Product Guide. *Cautions for Using Aluminium Electrolytic Capacitors*, CAT.No.2015/2016E, ELNA Website, Accessed 4 August 2016 from http://www.elna.co.jp/en/capacitor/alumi/catalog/pdf/poly_caution_e_p24-26.pdf

27. Nichicon General Descriptions of Aluminum Electrolytic Capacitors, Technical Notes CAT 8101E, p.18 Nichicon Website, Accessed 9 September 2016 from http://www.nichicon.co.jp/ english/products /pdf/aluminum.pdf

28. Tektronix Application Note, *Power Measurements on AC-DC Power Supplies*, Accessed 16 February 2019 from https://www.mouser.com/pdfdocs/55W_29 828_1_Power20Measurements 20on%20AC-DC.pdf

29. Tektronix, *Power Supply Measurement and Analysis Primer, November 2015, Accessed 16 February 2019 from* https://www.tek.com/document/primer/ power-supply-measurement-and-analysis-primer

30. Keysight Technologies, *Power Supply Testing – Application Note 372-1,* 4 December 2017, Accessed 15 February 2019 from http://literature.cdn.key sight.com/litweb/pdf/5952-4190.pdf

31. Texas Instruments, *How to Measure the Loop Transfer Function of Power Supplies – Application Note AN-1889,* April 2014, Accessed 15 February 2019 from http://www.ti.com/lit/an/snva364a/snva364a.pdf

32. CUI Inc., *Glossary of Power Supply Terms,* Accessed 14 February 2019 from https://www.cui.com/catalog /resource/power-supply-glossary.pdf

33. ON Semiconductor, *Switch-Mode Power Supply Reference Manual*, Accessed 14 February 2019 from https://www. onsemi.com/pub/Collateral/SMPSRM-D.PDF

34. Acopian Power Supplies, *Power Supply Comparisons*, Accessed 23 December 2018 from https://www. acopian.com/linear-power-supply-vs-switching-power-supply-vs-unregulated-power-supply.html

35. ELPROCUS Website, *Classification of Power Supply and Its Different Types*, Accessed 19 February 2019 from https://www.elprocus.com/classification-power-supply-different-types/

36. Floyd T.L., *Electronics Fundamentals,* Fifth Edition, New Jersey: Prentice Hall, p. 770-786, 1980.

37. Microchip*, PIC32MX795F512L Datasheet,* Accessed 29 February 2017 from http://ww1.microchip.com/ downloads/en/DeviceDoc/6000 1156J.pdf

38. Linear Technology, *LT4320 Datasheet: Ideal Diode Bridge Controller*, Accessed 19 November 2017 from http://cds.linear.com/docs/en/datasheet/ 4320fb.pdf

39. ST Micro Electronics, *L78 Linear Regulator Datasheet*, Accessed 8 January 2019 from https://www. st.com /resource/en/datasheet/l78.pdf

40. Analog.com Training and Seminars, *Basic Linear Design: Printed Circuit Board (PCB) Design Issues,* Accessed 11 February 2019 from https://www. analog.com/media/en /training-seminars/design-handbooks/Basic-Linear-Design/Chapter12.pdf

41. Maxim Integrated, Tutorial 751: *Linear Regulators in Portable Applications*, Online article accessed 19 February 2019 from https://pdfserv.maximinteg rated.com/en/an /AN751.pdf

42. Patel A.P., Knoth S., *When is it best to use LDO regulators?,* Online article, published 21st March 2017, Accessed 19 February 2019 from https://www. electronicsweekly.com /news/best-use-ldo-regulators-2017-03/

43. Zhang H.J., *Basic Concepts of Linear Regulator and Switching Mode Power Supplies,* Linear Technology, Application Note 140, Accessed 23 February 2019 from https://pdfs.semanticscholar.org/794c/1ba2 e5027f03eba7c2ce3 d1e63e639741b14.pdf

44. Linear Technology, *LT1377 Datasheet*, Accessed 29 February 2017 from https://www.analog.com/en/ products/lt1377.html

45. Zehendner M., Ulmann M., *Power Topologies Handbook,* Accessed 20 February 2019 from http://www. ti.com/tool/powerstage-designer?HQS=pwr-null-null-pwrtopologies-bs-evm-null-wwe#Technical %20Documents

46. National Instruments, *Linear versus Switch-mode Power Supplies Comparison*, Accessed 5 Augustus 2018 from http://digital.ni.com/public.nsf/allkb/7438e77138bddf1b86256f660008e9cc/$FILE linear_versus_switch ing.pdf

47. Texas Instruments, *Power Supply Information Poster*, Accessed 8 May 2018 from http://www. ti.com/lit/sg/sluw001f/sluw001f.pdf

48. Falin J., Texas Instruments, *Designing DC/DC converters based on SEPIC topology*, Video accessed 7 December 2018 from https://www.youtube.com/watch?v=pJRC77j_91k

49. Falin J., Texas Instruments, *Designing DC/DC converters based on SEPIC topology*, Accessed 8 December 2018 from https://e2echina.ti.com/cfs-file /key/telligent-evolution-componentsattach ments/13-112-00-00-00-00-58-20/Designing-DC-DC-converters-based-on-SEPIC-topology.pdf

50. Zhang D., *Designing A SEPIC Converter*, Texas Instruments Application Note AN-1484, Accessed 24 February 2019 from http://www.ti.com/lit/an/snva16 8e/snva168e.pdf

51. Condit R., *Transformerless Power Supplies: Resistive and Capacitive,* Microchip Technology Inc Application Note AN954, Accessed 25 February 2019 from http://ww1.microchip.com/downloads/en/ appnotes/00954A.pdf

52. Article: *Opto-coupler vs. Opto-Isolator*, Accessed 23 December 2018 from https://www.electronicproducts.com/Optoelectronics/Optocouplers_and_OptoisolatorsOptocoupler_vs_optoisolator.aspx

53. Analog Devices, *Analog Isolation Amplifiers*, TUTORIAL MT-071, Accessed 24 February 2019 from https://www.analog.com/media/en/trainingseminars /tutorials/mt-071.pdf

54. Whitlock B*., Understanding, Finding and Eliminating Ground Loops,* MIT CEDIA Class EST016 Handout, Accessed 24 February 2019 from http://web.mit.edu/jhawk/tmp/p/EST016_Ground_Loops_hand out.pdf

55. D&B Power Associates Inc., *Understanding Power Disturbances*, Illinois, Accessed 21 December 2016 from www.dbpowerinc.com

56. Kansas City Power & Light Company, *Understanding and Avoiding Commercial Power Disturbances,* Online Brochure, Published 29 November 2001, Accessed 1 January 2016 from www.kcpl.com

57. MIL-STD-883-Rev-K. *Test Method 1014.15 for Microcircuits*, Accessed 13 October 2017 from https://www.navsea.navy.mil/Portals/103/Documents/NSWC_Crane/SD-18/Test%20Methods/MILSTD883.pdf

58. United States of America Department of Defence Website, Accessed 24 October 2016 from https://landandmaritimeapps.dla.mil/Downloads/MilSpec/Docs/MIL-STD-883/std883.pdf

59. ST Micro Electronics, Application Note AN3353, *IEC61000-4-2 Standard Testing*, Accessed 19 April 2017 from https://www.st.com/content/ccc/resource/technical/document/application_note/b3/42/28/d8/e2/db/44/f5/DM00 023467.pdf/files/DM00023467.pdf/jcr:content/translations/en.DM00023467.pdf

60. ESDA/JEDEC *Joint Standard for Electrostatic Discharge Sensitivity Testing - Human Body Model (HBM) – Component Level*, ANSI/ANSI/ESDA/JEDEC JS-001-2010, April 2010

61. IEC Website, Accessed 7 May 2017 from https://webstore.iec.ch/preview/info_iec61000-42%7Bed 2.0%7Db.pdf

62. Siswanto W.A., et al*., General Purpose Vibration Test System for Electronic Devices*, Proceedings of Malaysian Technical Universities Conference on Engineering and Technology, June 28-29, 2010, Accessed 5 February 2019 from https://www.researchgate.net/publication /216242497_General_Purpose_Vibration_Test_System_for_Electronic_Devices

63. Nelson C., *Vibration Test Evolution; Single-Axis, Single-Shaker to 6DoF*, TEAM Vibration Testing Corporation,2002, Accessed 12 February 2019 from https://www.teamcorporation.com/images/ technical_documents/pdf/Vibration-Test-Evolution.pdf

64. *Vibration Testing*, Accessed 12 February 2019 from http://www2.me.rochester.edu/courses/ME443/ Assignments/VibrationTesting.pdf

65. Bruel & Kjær, *Vibration Introduction Booklet*, Accessed 12 February 2019 from https://www. bksv.com/ media/doc/br0227.pdf

66. Delserro Engineering Solutions, S*inusoidal and Random Vibration* Testing, Accessed 16 November 2018 from https://www.desolutions.com/blog/2013 /04/sinusoidal-and-random-vibration-testing-primer

67. Allen J.et al., *Selection and Performance of Vibration Tests*, Hughes Aircraft Company, 1971, Accessed 12 February 2019 from https://apps. dtic.mil/dtic/tr/fulltext/u2/737830.pdf

68. MIL-STD 810G-1 Standard, United States of America Department of Defence Website: Accessed 16 November 2016 from http://quicksearch.dla.mil/Transient/1BC9167BC023403BA375CAFB58FE 70B3.pdf

69. Clemens J.M. Lasance, T*emperature and Reliability-in-Electronics-Systems* Online article, Accessed 17 December 2018, https://www.electronics-cooling.com/2001/11/temperature-and-reliability-in-electronics-systems-the-missing-link/

70. Lall P., Pecht M., Hakim E., *Influence of temperature on Microelectronics and System reliability*, CRC Press, New York, 1997

71. Mohammad Motalab, et al., *Correlation of Reliability Models Including Aging Effects with Thermal Cycling Reliability,* Centre for Advanced Vehicle and Extreme Environment Electronics, Conference Paper in Proceedings Electronic Components and Technology Conference , May 2013, DOI:10.110 9/ECTC.2013.6575694, Accessed 25 December 2018 from https://www.researchgate.net/publication/ 261310772

72. Lee W.W., et al., *Solder joint fatigue models: review and applicability to chip scale packages*, Introductory invited paper, Microelectronics Reliability 40 (2000) 231-244, Accessed 13 February 2019 from https://pdfs.semantic scholar.org/3b60/d4055ea195f379326ae60f0e5c5aed41fba7.pdf

73. Shi X.Q., *Low cycle fatigue analysis of temperature and frequency effects in eutectic solder alloy,* International Journal of Fatigue 22 (2000) 217–228, Accessed 14 February 2019 from http://www3.ntu.edu.sg/home/mwzhou /Papers /Zhou%2020 00%20-%20Inter%20J%20Fatigue.pdf

74. Blattau N., Hillman C., *Failure Mechanisms in Electronic Products at High Altitudes*, CALCE Electronic Products and Systems Center, University of Maryland, Accessed 16 November 2018 form https://pdfs.semanticscholar. org/6046/529f05a65e182ac9323ef8eb26b2 075d0e13.pdf20and20 Report 201235%20Standard20atmosphere20%E2%80%93%20tables%20and20 data%20for %20altitudes20to2065800%20feet,%20US

75. Norton D., *How does altitude affect AC-DC power supplies?*, 5 December 2012, Accessed 18 December 2018 from https://www.edn.com/electronics-blogs/power-supply-notes/4402833 /How-does-altitude-affect-AC-DC-power-supplies-]

76. Parmenter K., *Design Considerations for Power Supplies in High-Altitude Applications*, Excelsys Technologies, Accessed 13 February 2019 from https://www.psma.com/sites/default/files/uploads/tech-forums-safety-compliance/presentations/is63-design-considerations-power-supplies-high-altitude-applications.pdf

77. ABB Instrument Transformers, *Installation of instrument transformers at high altitude – Effects, Problems and Solutions,* Accessed 14 February 2019 from https://library.e.abb.com/public/3e38c42df4a74bb49821665f6ff3ca9f installation20of20Instrument 20 Transformers%20at%20high%20altitude20-%20Ed1%202015-06-10% 201HSM%209543%2041-02en.pdf

78. ABB Instrument Transformers, *White Paper: Low voltage products in high altitudes - Information and technical guidance for applications above 2000m sea level*, Accessed 13 February 2019 from https://library.e.abb.com/public/ e4bc987d3b3a4e45a025161863ca67c1/2 CDC131118D0201%20Rev.%20A%20White%20Paper%20LVP%20in%20high%20altitudes.pdf

79. Lin D, *Effect of Hight Altitude for Electronical Cooling*, 10-11-2017, Presentation Accessed 15 February 2019 from http://www.efd.com.tw/uploads/1/3/2/1/13213742/effects_of_high_altitude_forelectronic_cooling.pdf

80. Littelfuse, *Transient Suppression Devices and Principles*, Application Note 9768, Accessed 7 May 2017 from www.littlefuse.com

81. ON Semiconductor, *An Introduction to Transient Voltage Suppression Devices*, Application Note AND8229/D, Accessed 19 November 2017 from https://www.onsemi.com/pub/Collateral/AND 8229-D.PDF

82. KEMET Electronic Components, *Safety Disk Capacitors- Product Training Module*, Accessed 19 November 2017 from http://www.kemet.com/Lists /FileStore/900%20Series%20Product%20Training%20Module.pdf

83. Rajaram M. P., *PCB Protection - Conformal Coating, Potting, & Encapsulation*, Henkel Adhesive Technologies India (Ltd), Presentation for Surface Mount Technology Association (SMTA), Accessed 15 February 2018 from https:// www.smta.org/chapters/files/SMTA_India_ Chapter_Henkel_SMTA_India_Presentation.pdf

84. Kinner P., Little A., *Conformal Coatings Vs Potting Compounds: Which is better to protect my PCB, a coating or a resin?* Accessed 12 February 2019 from https://www.electrolube.com/technical-articles/conformal-coatings-vs-potting-compounds-which-is-better-to-protect-my-pcb-a-coating-or-a-resin/

85. Penn Engineering Catalogue, *Printed Circuit Board Fasteners*, Accessed 14 February 2019 from https://www.pemnet.com/fastening_products/pdf/index data.pdf

86. Panacol Adhesives Catalogue, *Solutions for printed circuit boards:Innovative adhesives and sealants for effective production*, Accessed 15 February 2019 from https://www.panacol.com/fileadmin/flyer/Adhesive-Solutions-for-printed -Circuit-Boards.pdf

87. Hewlett-Packard, *Thermal Stress Management*, Accessed 21 December 2018 from https://support.hp.com/za-en/document/c01657439

88. Kamat S.P., *Thermal Management in Embedded Systems: A Software Approach,* Published in: IEEE Potentials (Volume: 32, Issue: 1, Jan.-Feb. 2013), pages 23 – 26; DOI: 10.1109/ MPOT.2012.2220036

89. Benson M. *The Art of Software Thermal Management for Embedded Systems,* page 3 – 5, 79-80; ISBN 978-1-4939-0298-9

90. Kumar A. et al., HybDTM: *A Coordinated Hardware-Software Approach for Dynamic Thermal Management,* Proceedings of the 43rd Design Automation Conference, DAC 2006, San Francisco, CA, USA, July 24-28, 2006, DOI: 10.11 09/DAC.2006.229219, Accessed 16 January 2019 from https://ieee xplore. ieee.org/document/1688858

91. Brooks D., Martonosi M., *Dynamic Thermal Management for High Performance Microprocessors,* Proceedings of the 7th International Symposium on High-Performance Computer Architecture, Monterrey, Mexico, January 2001, DOI: 10.1109/HPCA.2001.903261, Accessed 17 January 2019 from https://www.researchgate.net/publication/3888033_Dy namic_Thermal_Management_for_High-Performance_Microprocessors

92. Yeo I. et al., *Predictive Dynamic Thermal Management for Multi-core Systems,* Department of Computer Science, Texas A&M University, Conference paper presented June 8-13, 2008 at Design Automation Conference, Anaheim, California, USA, Accessed 17 January 2019, ISBN: 978-1-60558-115-6 from https://ieeexplore.ieee.org/document/4555916

93. DSM&T Manufacturers, *Harsh Environment Connectors & Wire Harnessing,* Accessed 26 December 2018 from http://www.dsmt.com/re sources/ip-rating-chart/

94. OMRON, *IP Ratings*, Accessed 16 November 2018 from https://www.components.omron.com/ documents/35736/704697/protection.pdf

95. IEC Website, Accessed 16 November 2018 from https://webstore.iec.ch /preview/info_iec60529%7Bed 2.2%7Db.pdf

96. International Organization for Standardization, *IP Ratings*, Accessed 16 November 2018 from https://www.iso.org/obp/ui/#!so:std:58048:e

97. Gates Energy Products, *Rechargable Batteries – Applications Handbook,* First Edition, Newton Massachusetts, Butterworth-Heineman, p. 6-11, 1998

98. Scrosati B., Garche J., *Lithium batteries: Status, Prospects and Future*. Journal of Power Sources, doi:10.1016/j.jpowsour.2009.11.048, Accessed 28 February 2019 from https://www.research gate.net/ profile/Juergen_Garche/publication/223709919_Lithium_Batteries_Status_Prospects_and_Future/ links/5a6b319e458515b2d0539be9/Lithium-Batteries-Status-pros pects-and-Future.pdf? origin=publication_detail

99. Hiscocks P.D., *Notes on the Nickel Cadmium Battery*, Department of Elec-trical and Computer Engineering Ryerson Polytechnic University,March 21, 2002, Accessed 29 March 2019 from https:// www.ee.ryerson.ca/~phiscock/papers/nicad-battery.pdf

100. Electrochem, *Li-ion Battery Temperature Trends During Charge and Dis-charge,* Accessed 28 February 2019 from https://electrochemsolutions.com /wp-content/uploads/sites/3/2017/09/Battery-Chemistry-Comparison Chart.pdf

101. Wang Q., *Thermal response of lithium-ion battery during charging and discharging under adiabatic conditions,* Published in the Journal of Thermal Analysis and Calorimetry · October 2015, DOI: 10.1007/s10973-015-5100-4 Accessed 28 February 2019 from https://www.researchgate.net/profile / Qingsong_Wang4/publication/284076006_Thermal_response_of_lithium-ion_battery_during _charging_and_discharging_under_adiabatic_conditions/links/5701424b08aee995dde8d7e7/ Thermal-response-of-lithium-ion-bat tery-during-charging-and-discharging-under-adiabatic-conditions.pdforigin =publication_detail

102. Britton D. et al., *Thermal Characterization Study of Lithium-Ion Cells,* Accessed 28 February 2019 from Nasa Technical Reports Server at https://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/2007003 2054.pdf

103. Shearing P., *How Does That Work? - Lithium Ion Batteries,* Information Brochure, Accessed 29 February 2019 from https://www.ingenia.org.uk/ getattachment/Ingenia/Issue-69/HOW-DOES-THAT-WORK-Lithiumion-batteries/How-does-that-work-69.pdf

104. Vishay General Semiconductor, *MBR(F,B)2060CT Dual Common-Cathode Schottky Rectifier Datasheet,* Accessed 5 February 2017 from https://www. vishay.com/docs/96405/vs-mbrb20ct-m3.pdf

105. IN COMPLIANCE Magazine*, Noise Mitigation Analysis of a π-filter for an Automotive Control Module, Published 1 May 2011,* Accessed 3 March 2019 from https://incompliancemag.com/article/noise-mitigation-analysis-of-a-filter-for-an-automotive-control-module/

106. ON Semiconductor, *Human Body Model (HBM) vs. IEC 61000−4−2,* Publication number: TND410/D, September 2010, Accessed 5 March 2019 from https://www.onsemi.com/pub/Collateral/TND410-D.PDF

107. Hansford Sensors, *Online Vibration Resources*, Accessed 1 January 2019 from https://www. hansford sensors.com/resources/vibration-calculator/

108. Kipp W.I., *Vibration Testing Equivalence*, presented at International Safe Transit Association (ISTA), Conference Proceedings in 2000, Updated December 2008, Accessed 17 January 2019 from http://www.wikippco.com/Vib%20Test%20Equivalence.pdf