NWU®

The day the current disappeared

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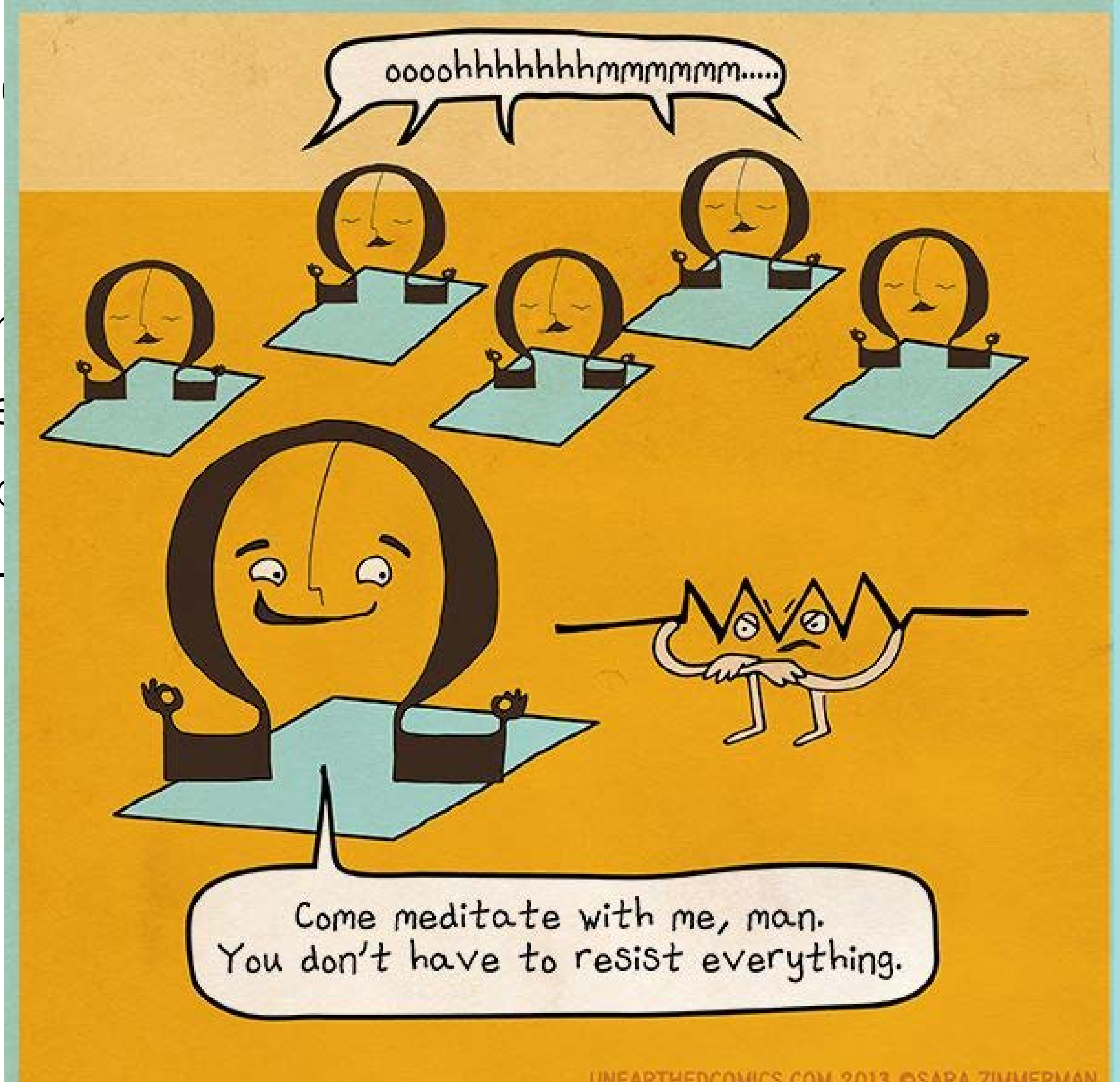
3 May 2019

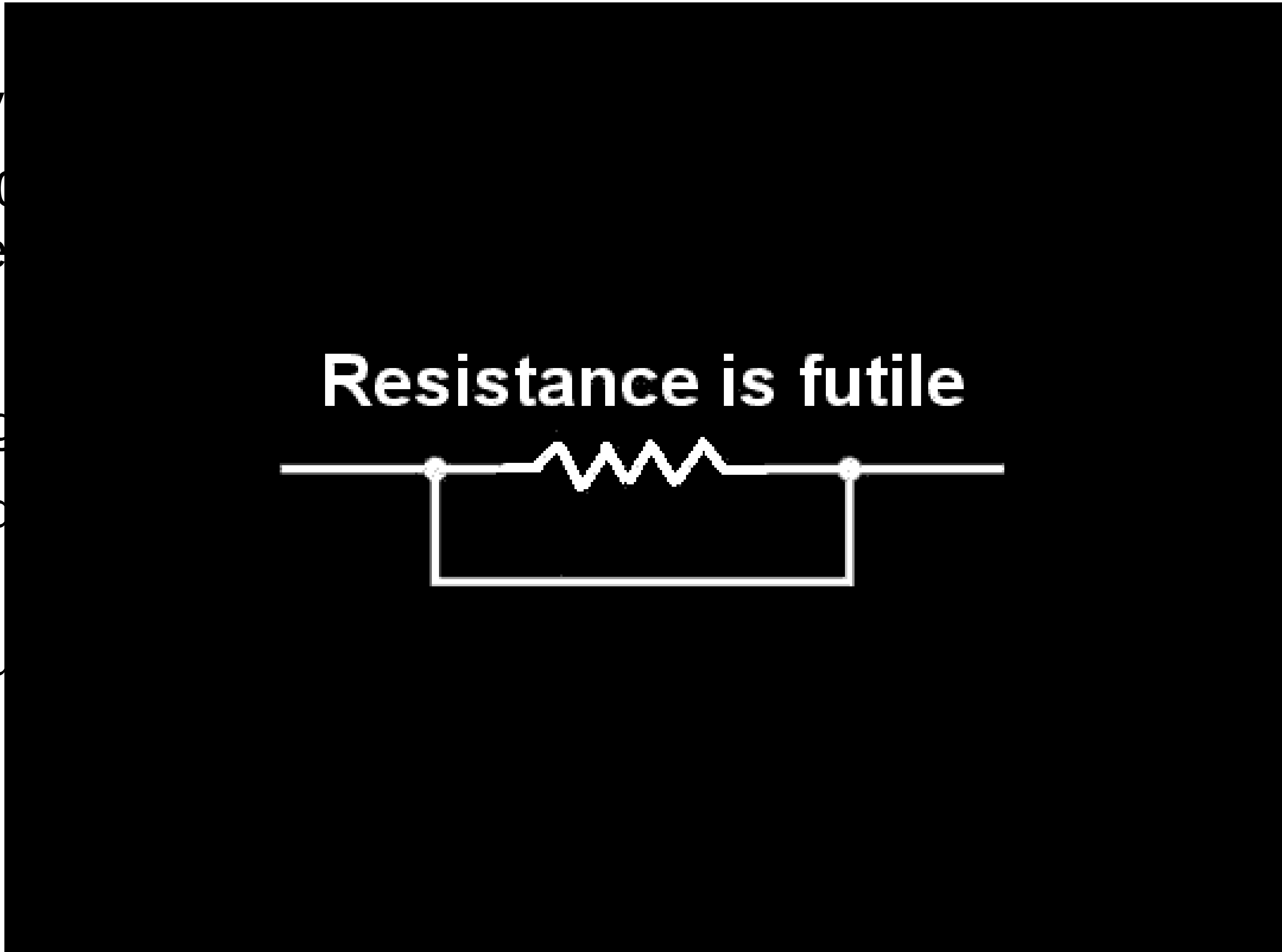
C

- Finding current: What did
- Why the Polish knight war
- That is why the current we
- Until sanity was restored b
- Application in impedance-

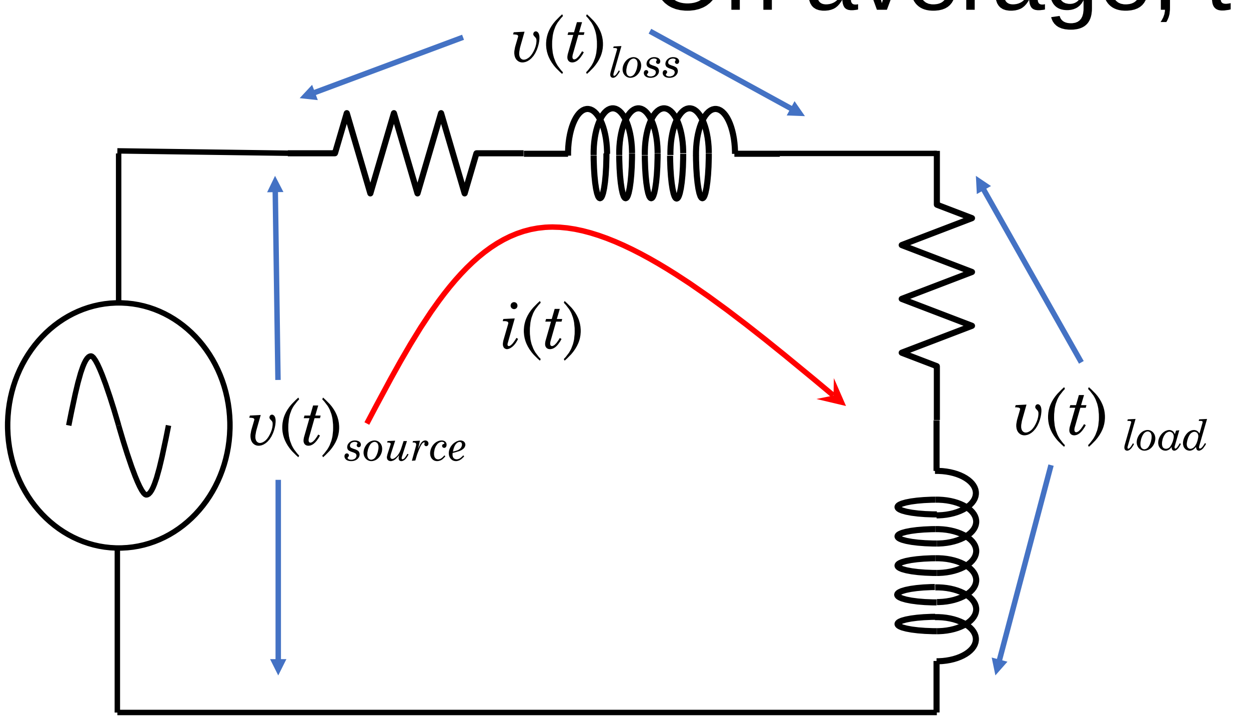


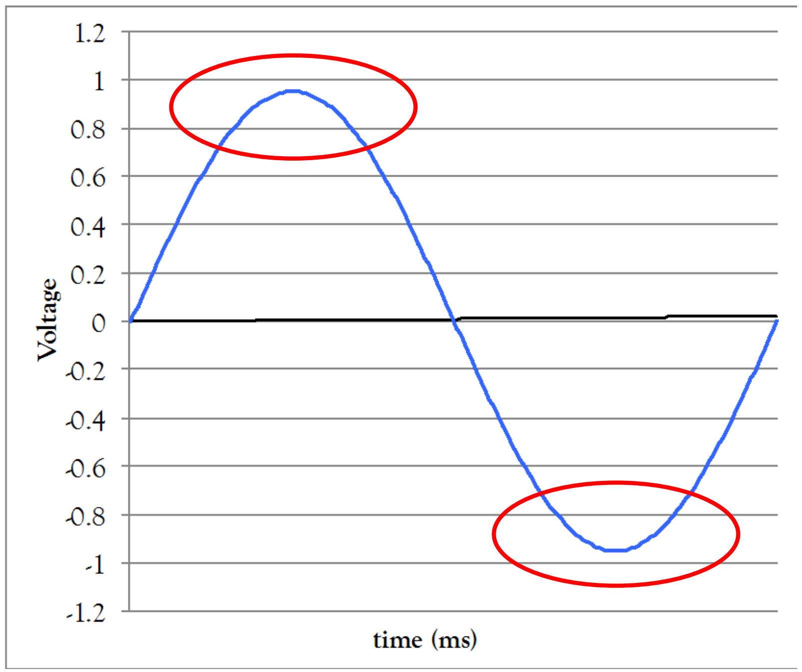
A brief history of nearly every electron

- Electricity as a matter of phy
- Found application during 180
  do “something”, mostly to be
- Moving electrically charged
- Mostly done in an alternating
- How well it is done governed
  Ohm
- And that misery made the cu



On average, the voltage remains shockingly





$$p(t) = v(t) * i(t)$$

$$= V_{\max} * I_{\max} * \cos(\omega t + \delta)\cos(\omega t + \beta)$$

$$= \frac{1}{2}\sqrt{2}V_{rms}\sqrt{2}I_{rms}\cos(\delta - \beta) + V_{rms}I_{rms}\cos(\delta - \beta)\cos\left[2(\omega t + \delta)\right] + V_{rms}I_{rms}\sin(\delta - \beta)\sin\left[2(\omega t + \delta)\right]$$

$$= \underbrace{V_{RMS}I_{RMS}\cos(\delta - \beta)\left\{1 + \cos\left[2(\omega t + \delta)\right]\right\}}_{\text{Resistive component of load}} + \underbrace{V_{RMS}I_{RMS}\sin(\delta - \beta)\sin\left[2(\omega t + \delta)\right]}_{\text{Reactive component: } L\text{, C or both}}$$

Resistive component of load

Reactive component: *L*, C or both

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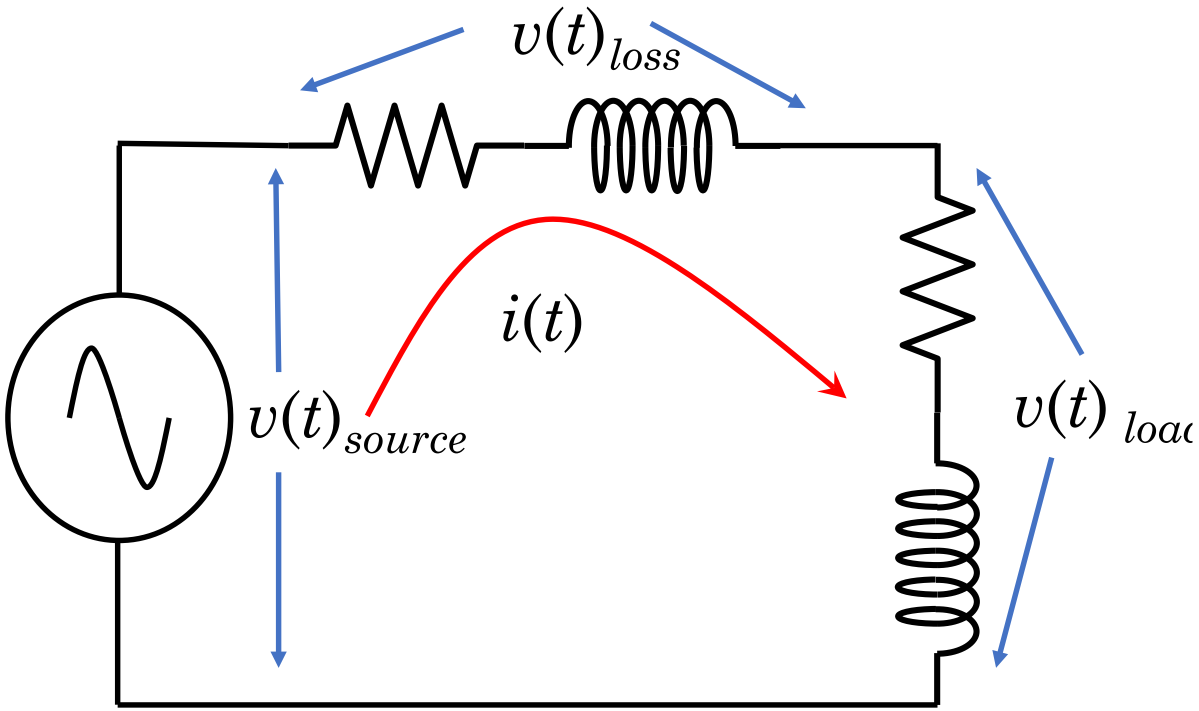
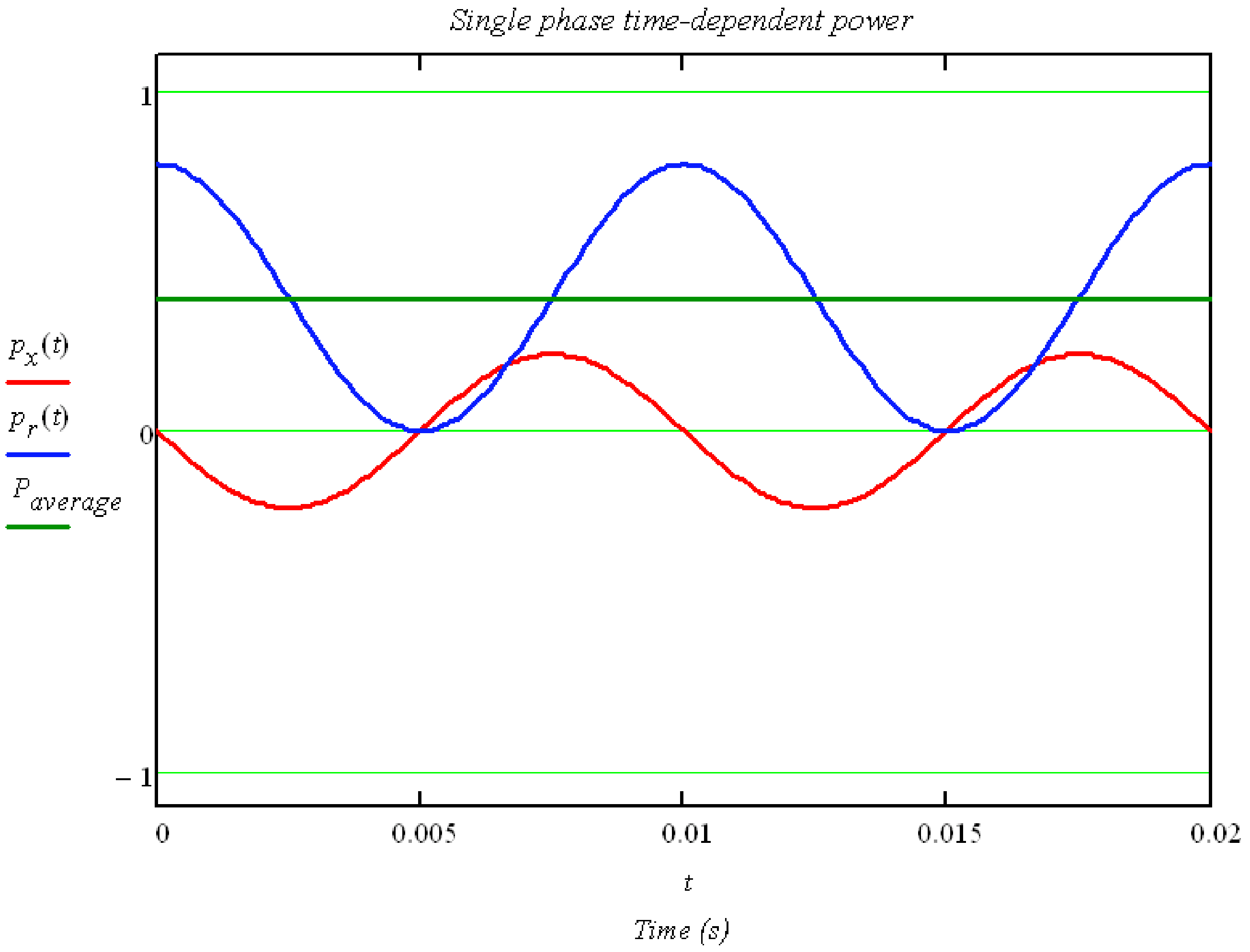
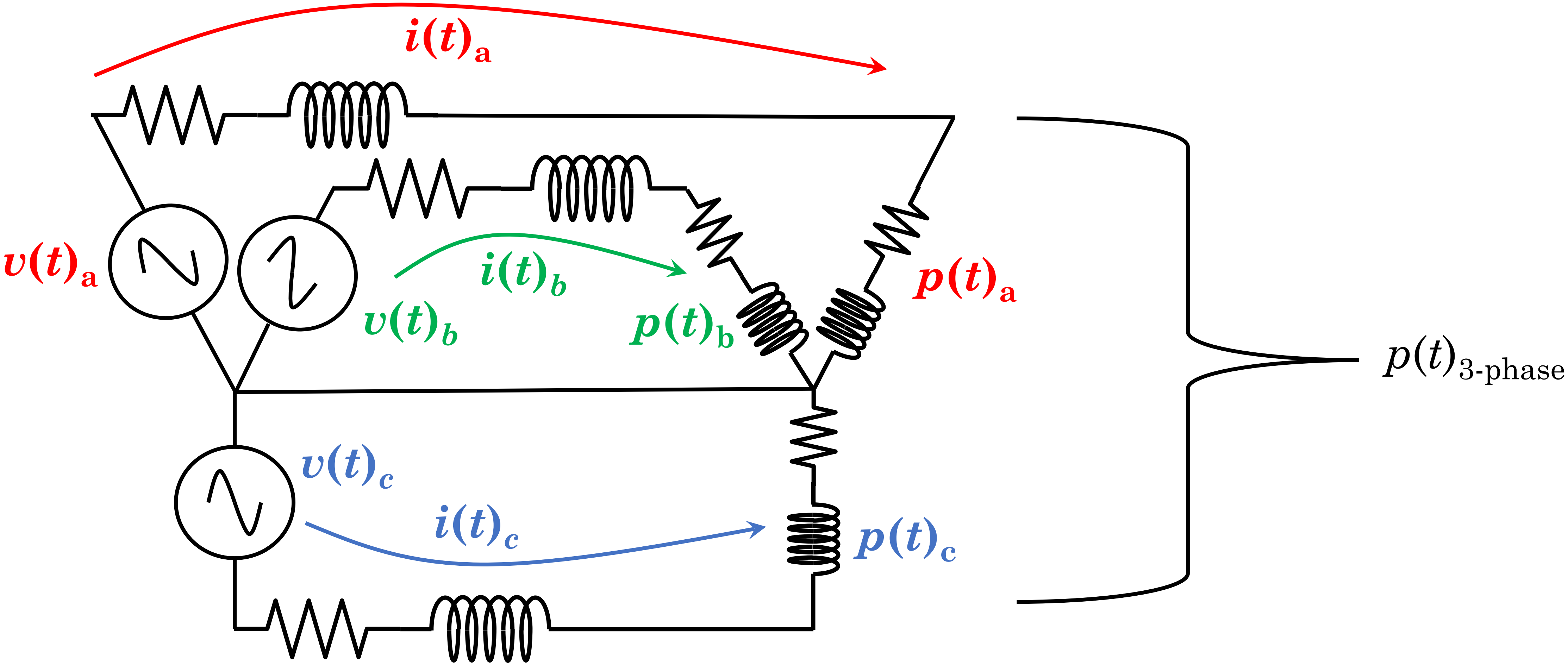
That is why that single-phase generator remained so s





Real work done: $P_{average} = V_{RMS} I_{RMS} \cos(\delta - \beta)$

That is why we have 3-phase electricity

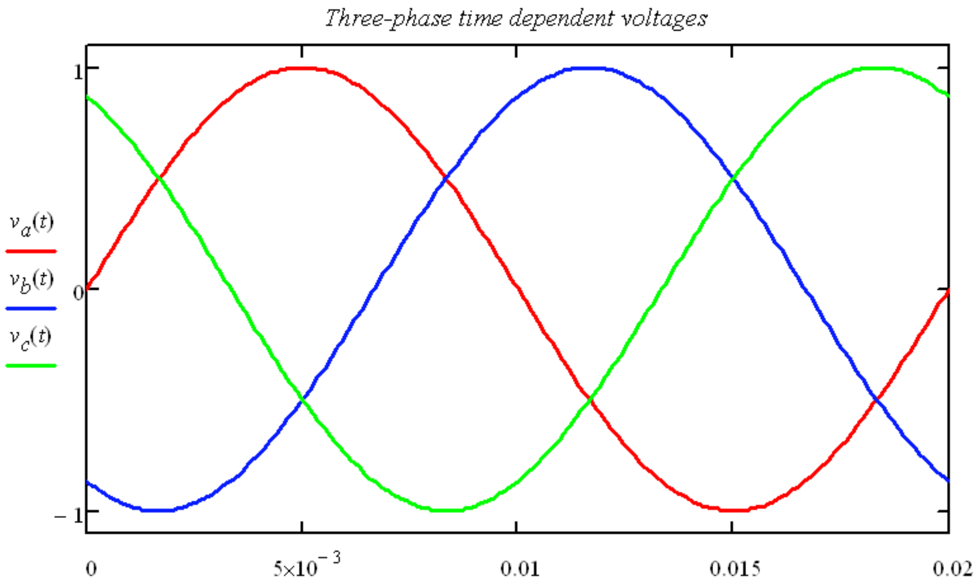


The War of Currents winner : George Westinghouse; 1886

$$v_a(t) = \sqrt{2}V_{LN}\cos(\omega t + \delta)$$

$$v_b(t) = \sqrt{2}V_{LN}\cos(\omega t + \delta - 120^0)$$

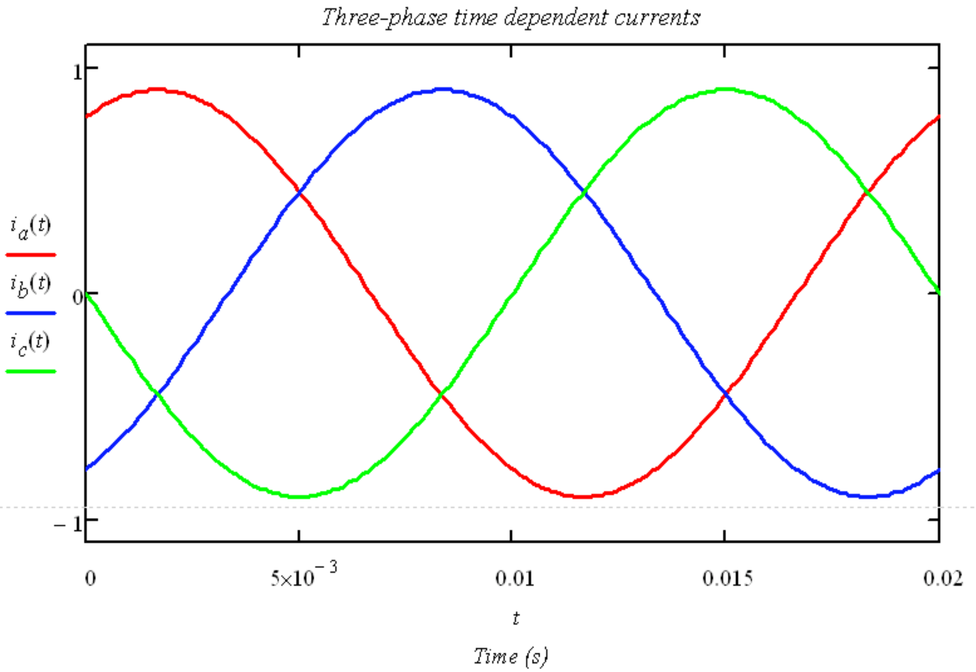
$$v_a(t) = \sqrt{2}V_{LN}\cos(\omega t + \delta - 240^0)$$



$$i_a(t) = \sqrt{2}I_L\cos(\omega t + \beta)$$

$$i_b(t) = \sqrt{2}I_L\cos(\omega t + \beta - 120^0)$$

$$i_c(t) = \sqrt{2}I_L\cos(\omega t + \beta - 240^0)$$



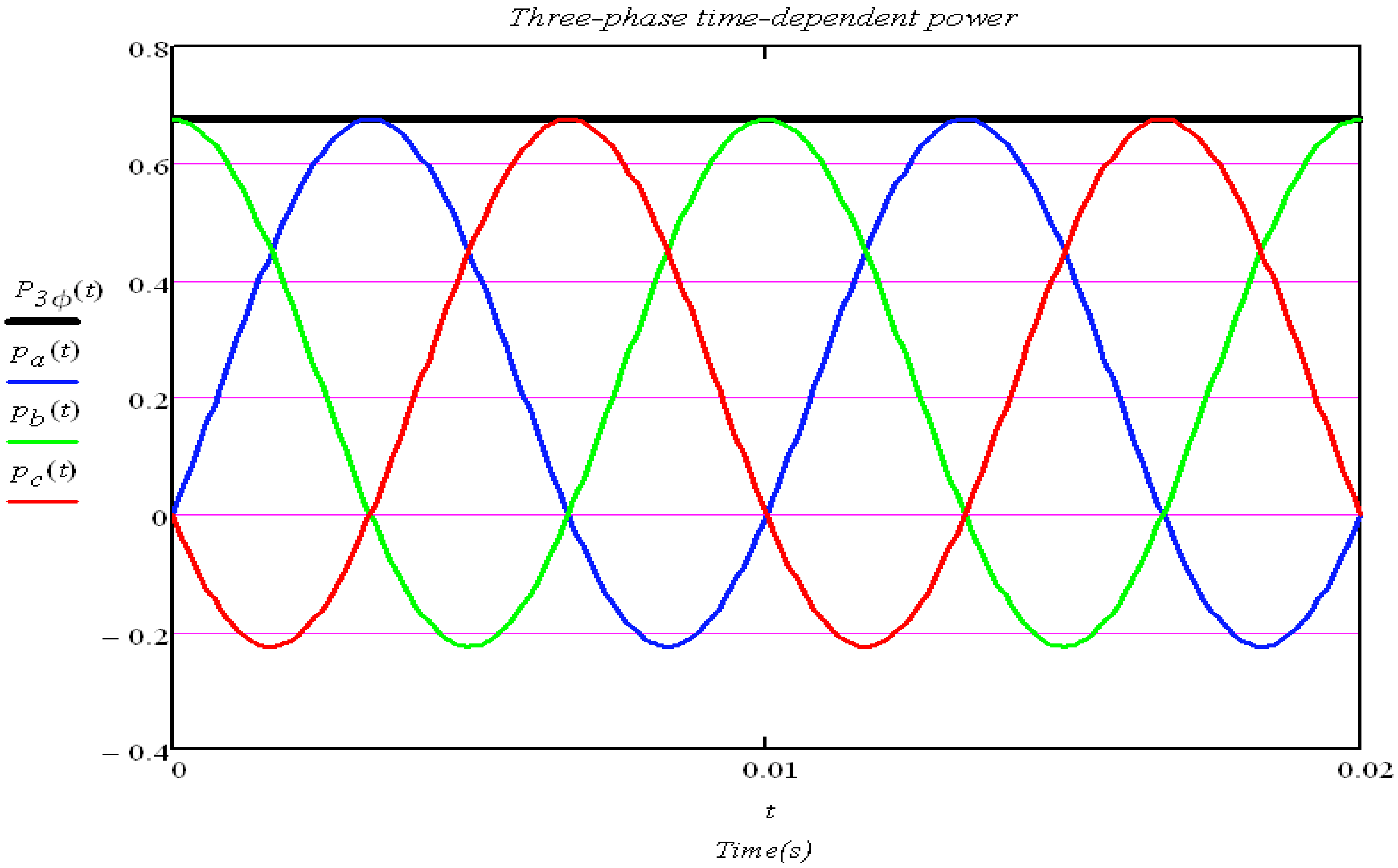
The War of Currents winner : George Westinghouse; 1886

$$p_{3\varphi}(t) = p_a(t) + p_b(t) + p_c(t)$$

$$= 3V_{LN}I_L\cos(\delta-\beta) + V_{LN}I_L\cos(\delta-\beta) + V_{LN}I_L[\cos(\delta-\beta) + V_{LN}I_L\cos(2\omega t+\delta+\beta) + \ldots\ldots$$

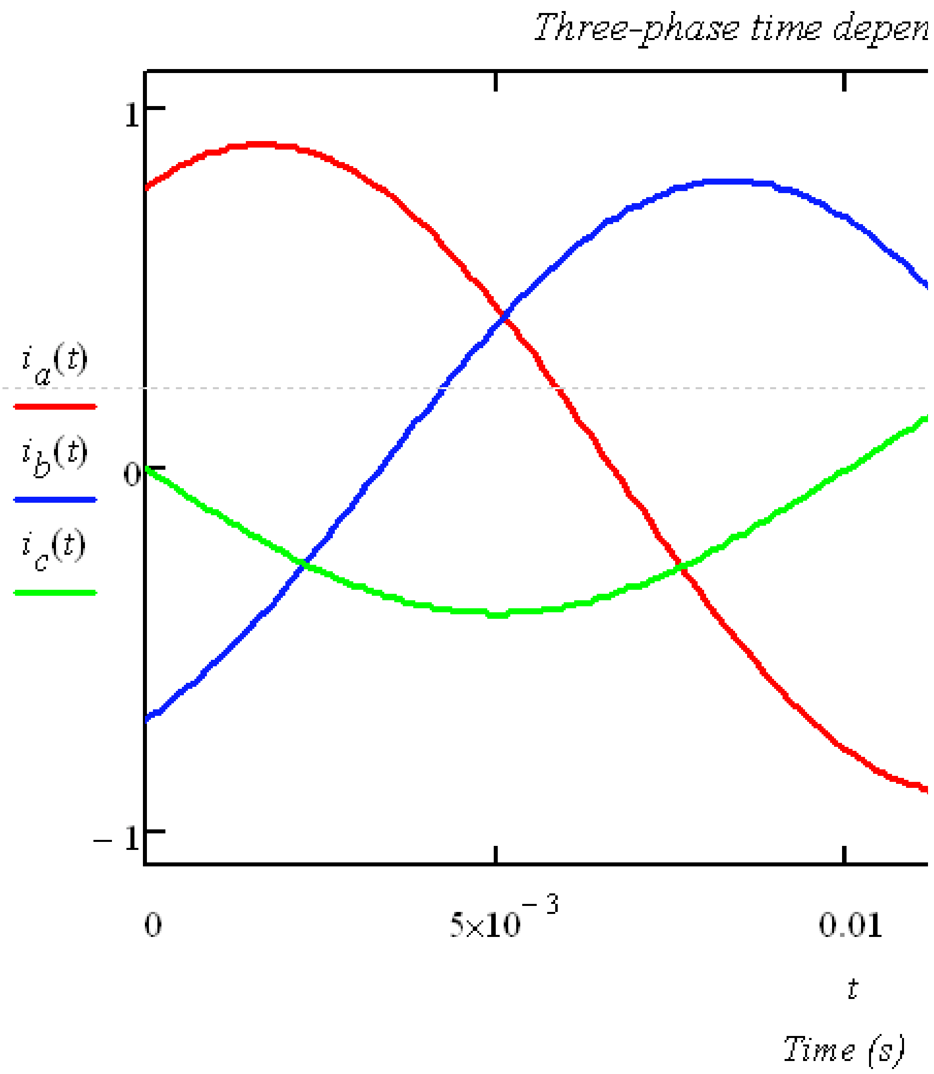
$$\ldots\ldots + \cos(2\omega t+\delta+\beta-240^0) + \cos(\delta-\beta) + V_{LN}I_L\cos(2\omega t+\delta+\beta+240^0)]$$

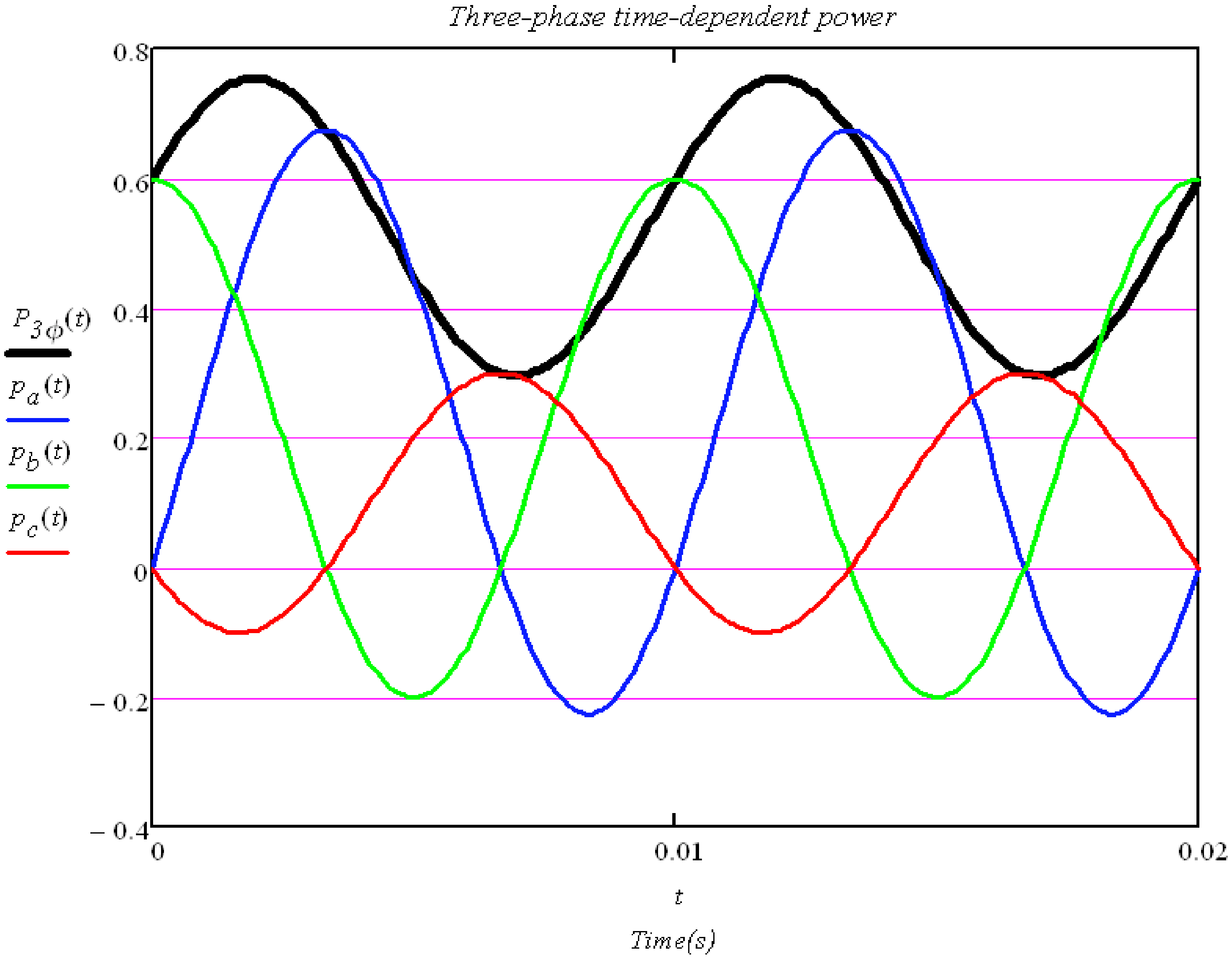
$$= 3V_{LN}I_L\cos(\delta-\beta) = P_{3\varphi}$$



And if those voltages are no longer symmetrical and those currents unbalanced?

The time-independent feature of three-phase energy transfer is lost……



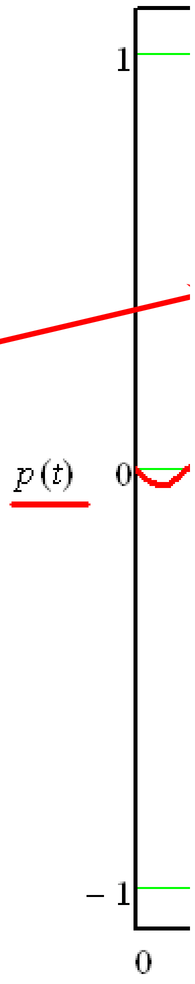


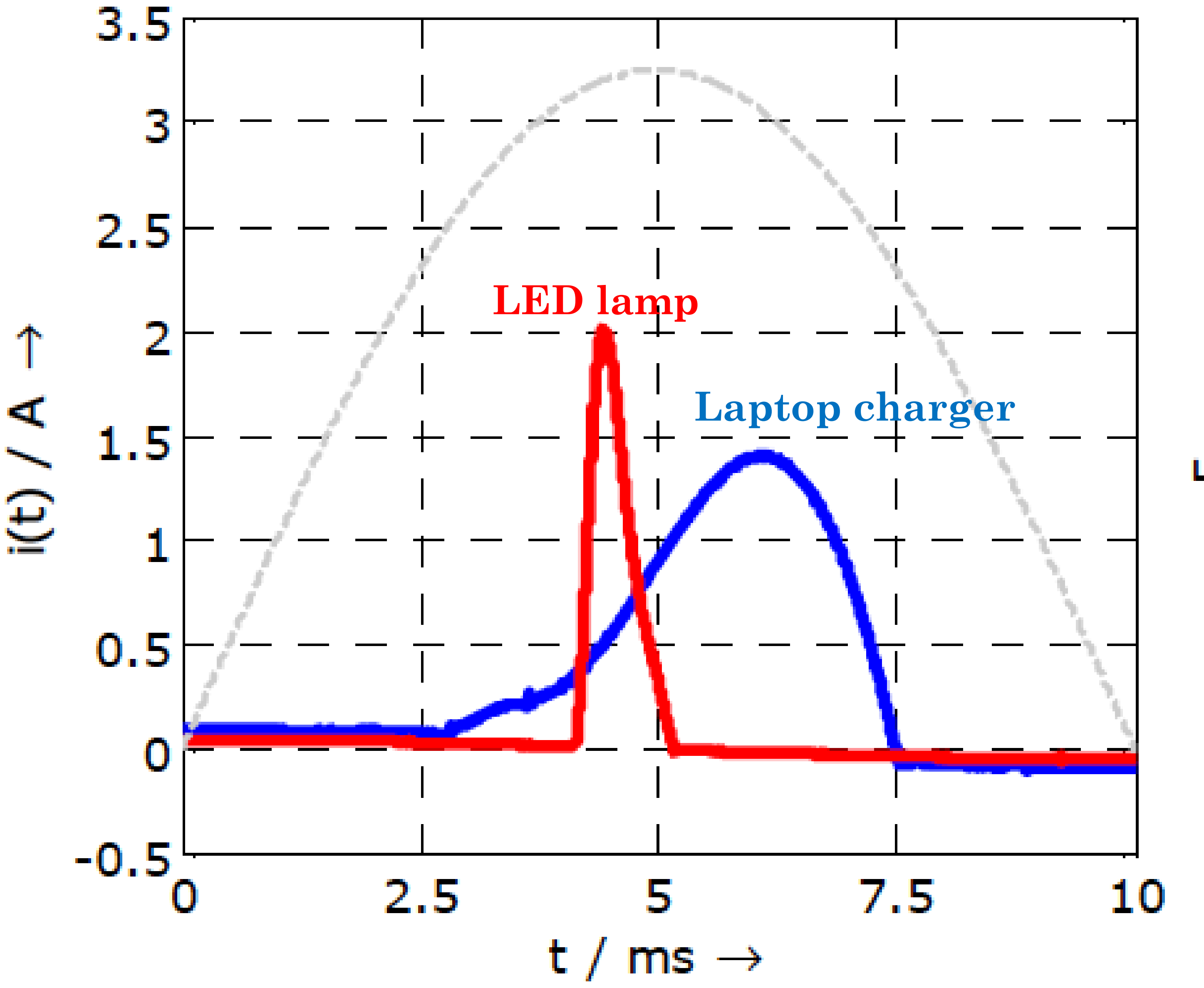
It get worse when the load is non-linear (and supply voltage non-sinusoidal)….

- What does non-linear loading mea
- More or less the modern way of co
- Such as in a LED lamp, a laptop cl
- Nowadays, MW's and kV's
- The energy transfer is impacted
- We are used to:

$$\boldsymbol{S} = P + jQ$$

$$\therefore S^2 = P^2 + Q^2$$





Not anymore….

$$S^2 > P^2 + Q^2$$

$$D^2 = S^2 - P^2 - Q^2$$

Now this is where the current got lost!

- Distortion power?
- What is that?
- Something missing in power theory?
- Budeanu defined the concept of distortion power – as "distortion" is the cause
- Many contributions to power theory followed
- Modern power phenomena required new definition
- Engineers have to design, specify and operate power system in which energy phenomena has physical intrepetation
- Why is the term "distortion power" then still in use?
- Discussion became intense.........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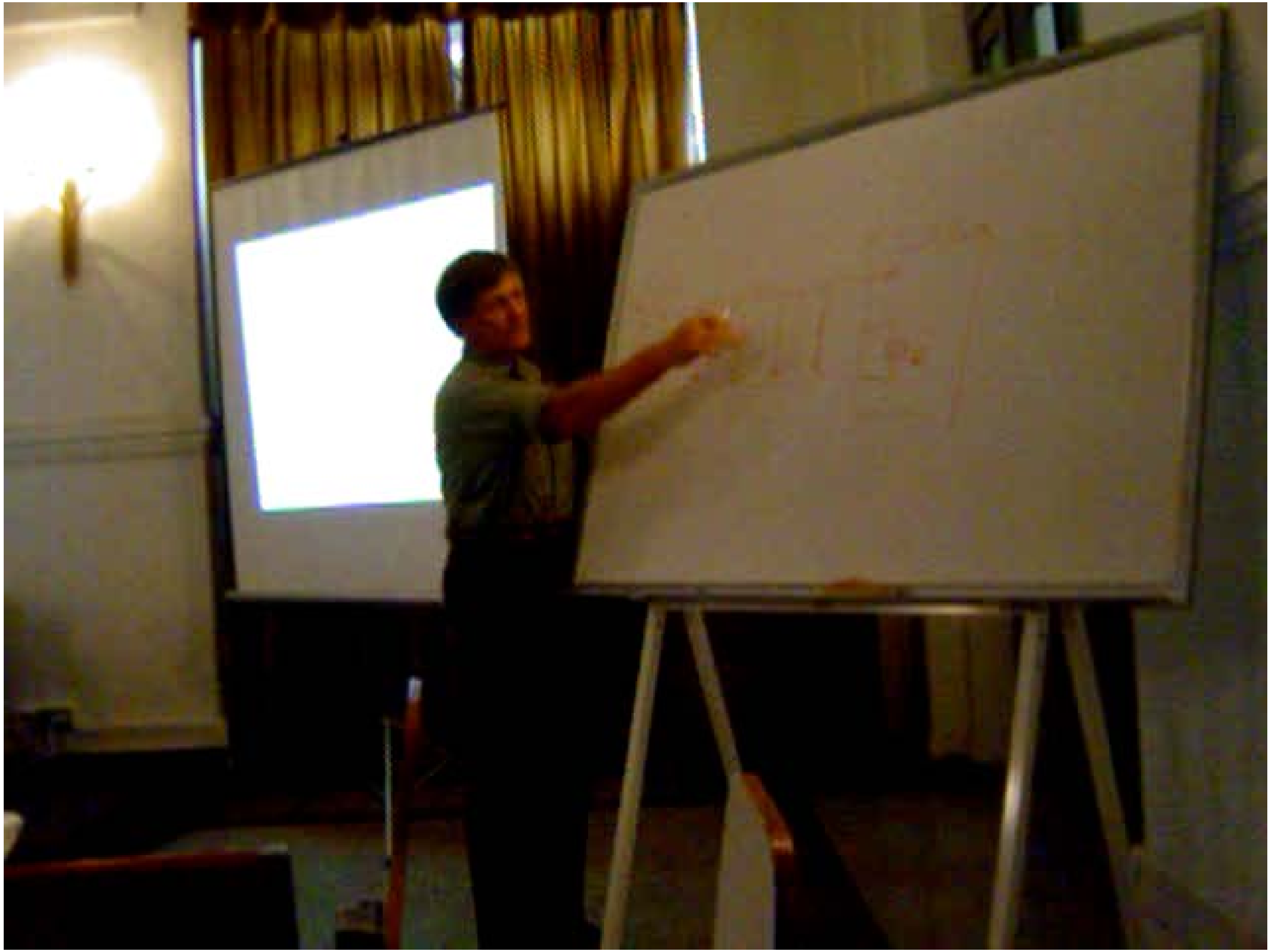
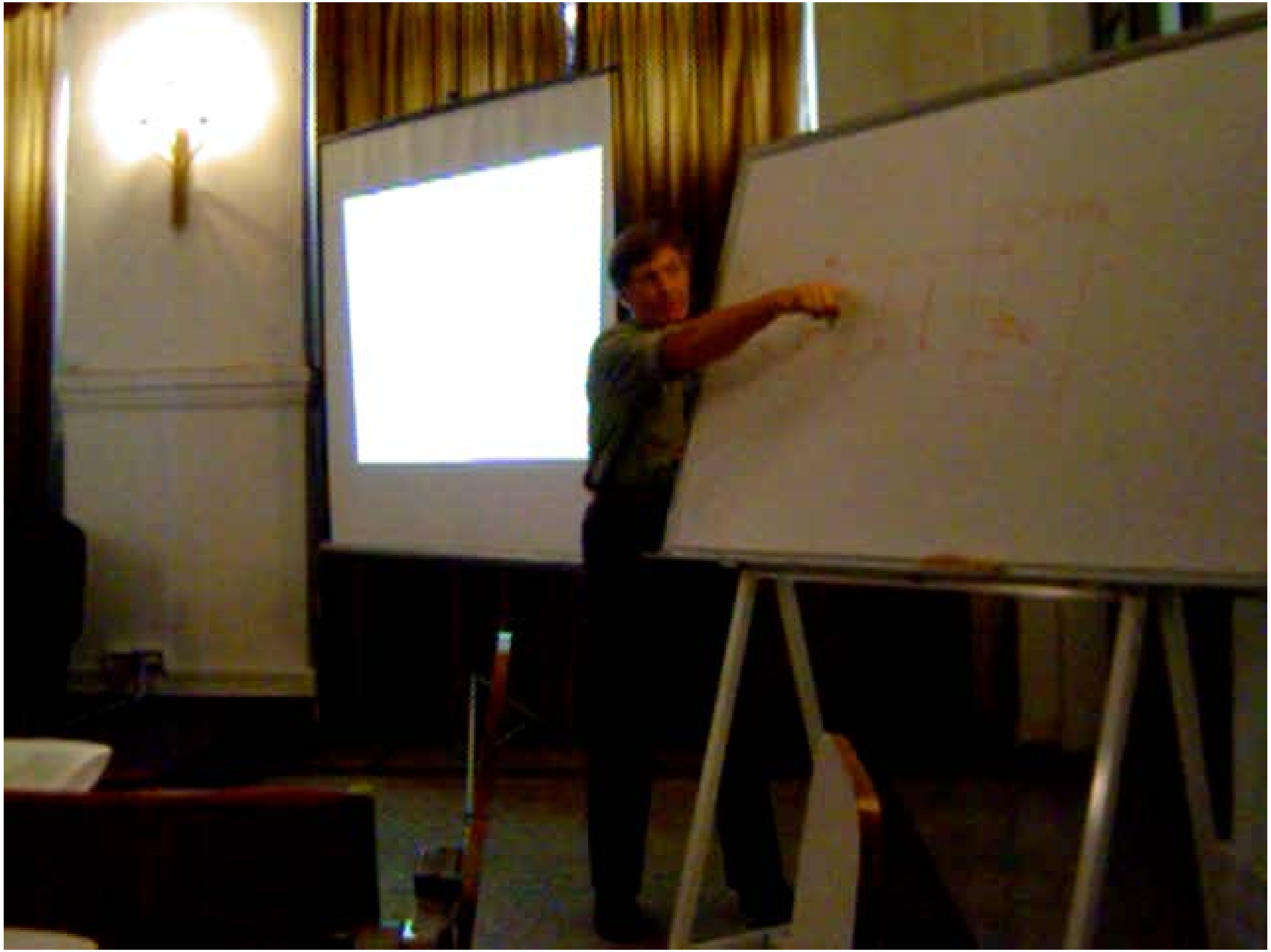
And then the Polish knight arrived…





834 IEEE TRANSAC

What is Wrong
Reactive and Distort

LESZEK S.

Shouldn't we ra

Displaying results **1-25** of **34** for **Czarnecki three phase power** ×

Journals & Magazines (23)

Conferences (11)

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Year

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1988 2017

From 1988 To 2017

Author

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Investigating the validity of the Czarnecki three phase power definitions
A.P.J. Rens ; P.H. Swart
IEEE AFRICON. 6th Africon Conference in Africa,
Year: 2002 , Volume: 2
Pages: 815 - 821 vol.2
IEEE Conferences
Abstract (html) (349 Kb)

Closure on "Instantaneous Reactive Power p-q Theory and Power Properties of Three-Phase Systems"
Leszek S. Czarnecki
IEEE Transactions on Power Delivery
Year: 2008 , Volume: 23 , Issue: 3
Pages: 1695 - 1696
Cited by: Papers (8)
IEEE Journals & Magazines
Abstract (html) (64 Kb)

Closure on "Could Power Properties of Three-Phase Systems Be Described in Terms of Poynting Vector?"
Leszek S. Czarnecki
IEEE Transactions on Power Delivery
Year: 2007 , Volume: 22 , Issue: 2
Pages: 1269 - 1270
Cited by: Papers (2)
IEEE Journals & Magazines
Abstract (html) (71 Kb)

Instantaneous reactive power p-q theory and power properties of three-phase systems
L.S. Czarnecki
IEEE Transactions on Power Delivery
Year: 2006 , Volume: 21 , Issue: 1
Pages: 362 - 367
Cited by: Papers (103)

But what is the problem?

- Steinmetz (1892): Ratio of active to apparent power decrease when waveform becomes more distorted such as electric arc (lighting application).
- Impact of distortion and unbalance new phenomena
- Power factor reduction a concern -
- **Unbalance in loading, asymmetry in supply voltages**, AND **distortion in voltage** and/or **current** contributes to the degradation of power factor (the effiency in the transfer of real energy)
- Classical power theory can only deal with perfectly sinusoidal voltages, perfectly symmetrical between phases and perfectly linear loads that withdraw perfectly balanced currents
- Budeanu (1927) described $S^2 > P^2+Q^2$ when waveforms are non-sinusoidal

➢ IEEE-1459-2010 attempted to further practical formulations universally acceptable for engineers to deal with modern power systems

Lyon	1920	**Depenbrock**	1977-2003
Bucholz	1922	**Kusters and Moore**	1980
Budeanu	1927	Page	1980
Fryze	1932	**Nomowiesjki**	1981
Goodhue	1933	**Akagi-Nabae**	1983…..
Quade	1937	**Filipski**	1984
Nudelcu	1963	Sawicki	1986
Sharon	1972	**Czarnecki**	1987-…..
Shepherd-Zakikhani	1972	Enslin	1988
Emanuel	1974	**Tenti**	1990
Harashima	1976	**Ferrero**	1991-…..
		Willems	1992-…..
		IEEE, Emanuel	1996-…..

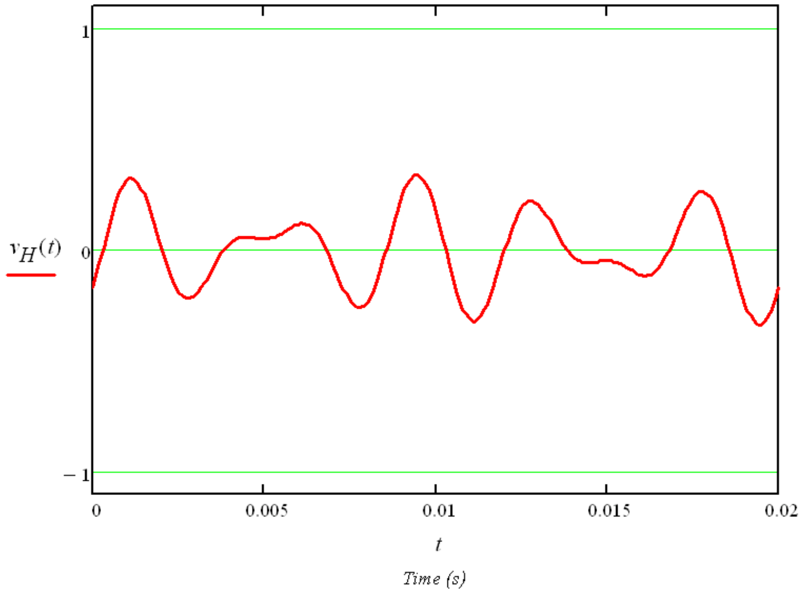
Effective values: nonsinusoidal waveform conditions (1)

- The IEEE 1459-2000 document further practical guidelines on power definitions
- The time-domain or the frequency domain can be used for power definitions
- Focus will be on frequency domain power definitions in this presentation
- A non-sinusoidal, single-phase, time-dependent voltage $v(t)_{1\varphi}$ with fixed and repetitive period T is applied to a load - represented as a finite series of harmonic components: h=1, 5, 7
- Single phase distortion component of $v(t)_{1\varphi}$ can be isolated as $v_H(t)_{1\varphi}$:

$$v(t)_{1\phi} = \sum_{h=1}^{N} v_h(t) = \sum_{h=1}^{N} \sqrt{2} V_h \sin(h\omega t + \alpha_h)$$

$$v(t)_{1\phi} = \sin(\omega t + \theta_1) + \frac{1}{5}\sin(5\omega t + \theta_5) + \frac{1}{7}\sin(7\omega t + \theta_7)$$

$$v_H(t)_{1\phi} = \sum_{h \neq 1}^{N} v_h(t)_{1\phi} = \frac{1}{5}\sin(5\omega t + \theta_5) + \frac{1}{7}\sin(7\omega t + \theta_7)$$



Effective values: nonsinusoidal waveform conditions (2)

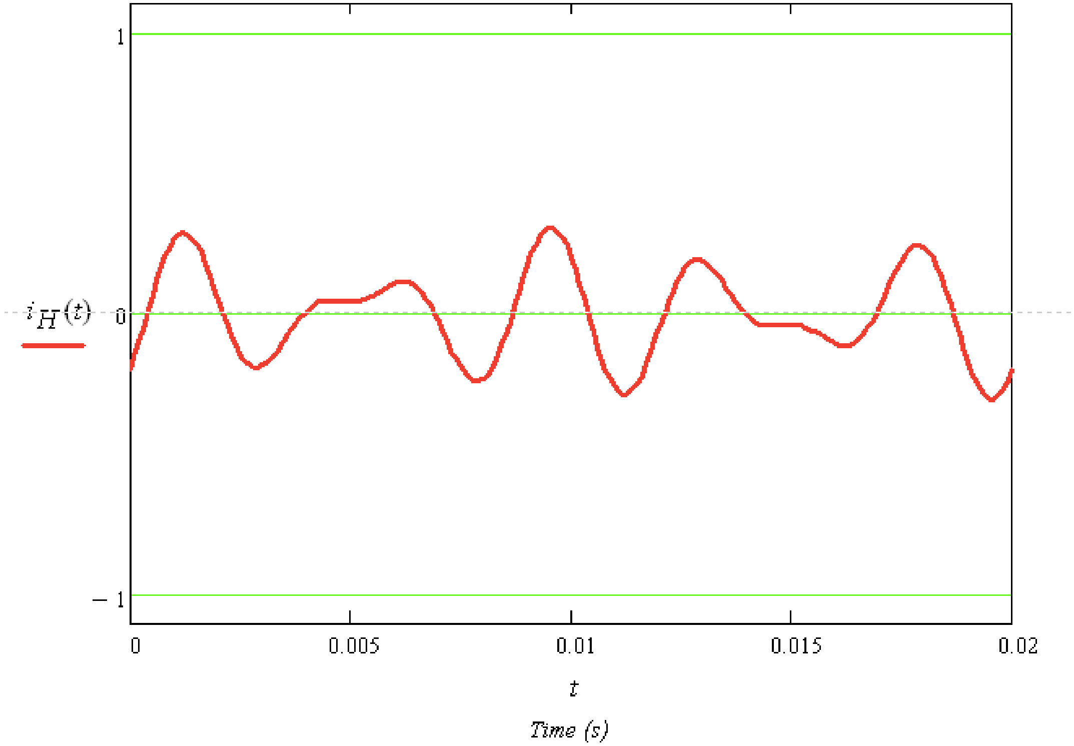
- $i(t)_{1\varphi}$ when $v(t)_{1\varphi}$ is applied to frequency dependent impedance load:

$$i(t)_{1\phi} = \sum_{h=1}^{N} i_h(t)_{1\phi} = \sum_{h=1}^{N} \sqrt{2} I_{h,1\phi} \sin\left(h\omega_1 t + \beta_h\right)$$

- Distortion components $i_H(t)_{1\varphi}$:

$$i_H(t)_{1\phi} = \sum_{h \neq 1}^{N} \sqrt{2} I_h \sin(h\omega_1 t + \beta_h)$$

$$h = [1, 5, 7]$$



Active Power: nonsinusoidal waveform conditions

- The *effective* or *RMS* values: $V_{1\phi} = \sqrt{\sum_{h=1}^{N} \left| \boldsymbol{V}_{h,1\phi}^2 \right|}$; $\quad I_{1\phi} = \sqrt{\sum_{h=1}^{N} \left| \boldsymbol{I}_{h,1\phi}^2 \right|}$

- The single phase power: $p_{1\phi}(t) = v(t)_{1\phi}\, i(t)_{1\phi} = \left(\sum_{h=1}^{N} v_h(t)_{1\phi} \right) \left(\sum_{h=1}^{N} i_h(t)_{1\phi} \right)$

- Classical power theory formulates ***Time-dependent Active Power*** (per harmonic order *h*):

$$p_h(t)_{1\phi} = \mathrm{Re}\left[\sqrt{2} \boldsymbol{v}_h(t)_{1\phi} \right] \mathrm{Re}\left[\sqrt{2} \boldsymbol{i}_h(t)_{1\phi} \right]$$

- The ***Time-dependent Total Active Power*** of a circuit under distorted waveform conditions:

$$p(t)_{1\phi} = \sum_{h=1}^{N} p_h(t)_{1\phi}$$

- ***Total*** (or ***Joint***) ***Average Active Power*** requires integration over a period *T*:

$$P_{1\phi} = \frac{1}{T} \int_T p(t)_{1\phi}\, dt = \sum_{h=1}^{N} V_{h,1\phi} I_{h,1\phi} \cos(\alpha_h - \beta_h)$$

Reactive Power: nonsinusoidal waveform conditions

• Classical power theory formulates ***Time-dependent Reactive Power*** (per harmonic order *h*):

$$q(t)_h = \mathrm{Re}\left[\sqrt{2}\boldsymbol{v}(t)_h\right]\mathrm{Im}\left[\sqrt{2}\boldsymbol{i}(t)_h\right]$$

• The ***Time-dependent Total Reactive Power*** of a circuit under distorted waveform conditions:

$$q(t) = \sum_{h=1}^{N} q(t)_h$$

Does it make sense?

☞ **It does not make sense!**

• ***Total*** (or ***Joint***) ***Average Reactive Power*** requires integration over a period *T*:

$$Q_B = \frac{1}{T}\int_T q(t) = \frac{1}{T}\int_T \sum_{h=1}^{N} q(t)_h = \sum_{h=1}^{\infty} V_{h,1\phi} I_{h,1\phi} \sin(\alpha_h - \beta_h)$$

$$p(t)_{1\phi} = v(t)_{1\phi}\, i(t)_{1\phi}$$

$$= \sum_{h=1}^{N} v_h(t)_{1\phi} \sum_{h=1}^{N} i_h(t)_{1\phi}$$

$$p(t)_{1\phi} = \sum_{h=1}^{N} \sqrt{2} V_{h,1\phi} \sin\left(h\omega_1 t + \alpha_h\right) * \sum_{h=1}^{N} \sqrt{2} I_{h,1\phi} \sin\left(h\omega_1 t + \beta_h\right)$$

$$= \sqrt{\left(\sum_{h=1}^{N} P_{h,1\phi}\right)^2 + \left(\sum_{h=1}^{N} Q_B\right)^2 + \left(\sum_{h,k=1(h\neq k)}^{N} \left|\boldsymbol{V}_{h,1\phi}\right|\left|\boldsymbol{I}_{k,1\phi}\right|\right)^2}$$

$$= P_H + Q_B + D_B$$

Budeanu's Distortion Power

Total Active Power   Total Reactive Power (Budeanu's Reactive Power)

What is wrong with Q_B – the Budeanu Reactive Power?

• Physical nature of reactive power follows from the application of field theory (Maxwell's equations)

• Reactive Power not to contribute to real energy transfer

• Physical nature of reactive power - energy accumulation in electric and magnetic fields of reactive components in the load and source

• Results in oscillatory exchange of energy between these reactive components

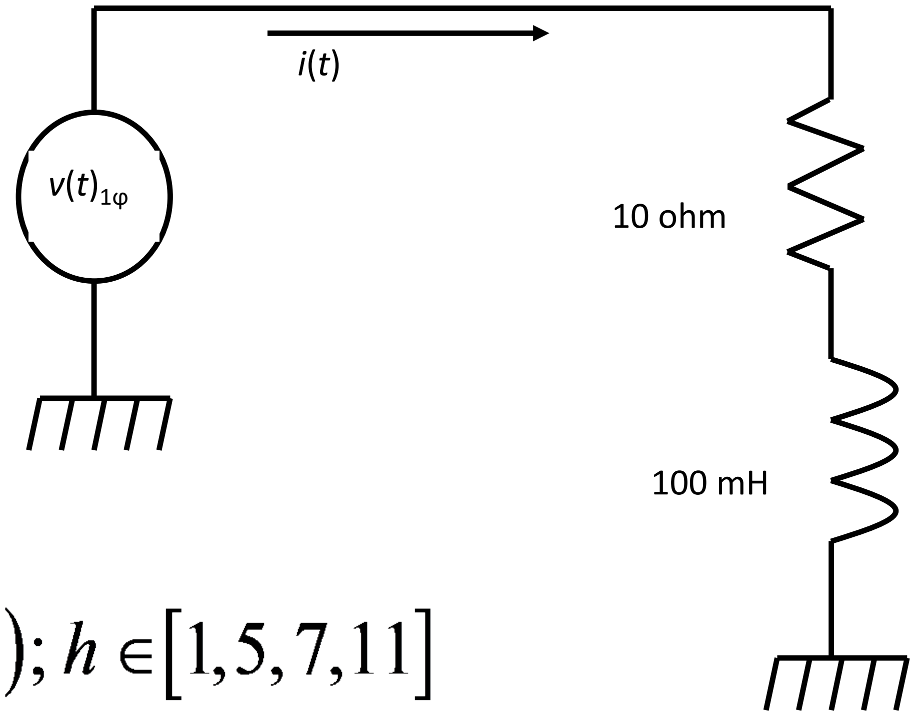
• Similar explanation assigned to harmonic reactive power Q_h at each harmonic order h

• Is Q_B (Joint/Total Reactive Power) a useful concept?

  • Let's investigate……

$$Q_B = \frac{1}{T}\int_T q(t) = \frac{1}{T}\int_T \sum_{h=1}^{N} q(t)_h = \sum_{h=1}^{\infty} V_{h,1\phi} I_{h,1\phi} \sin(\alpha_h - \beta_h)$$

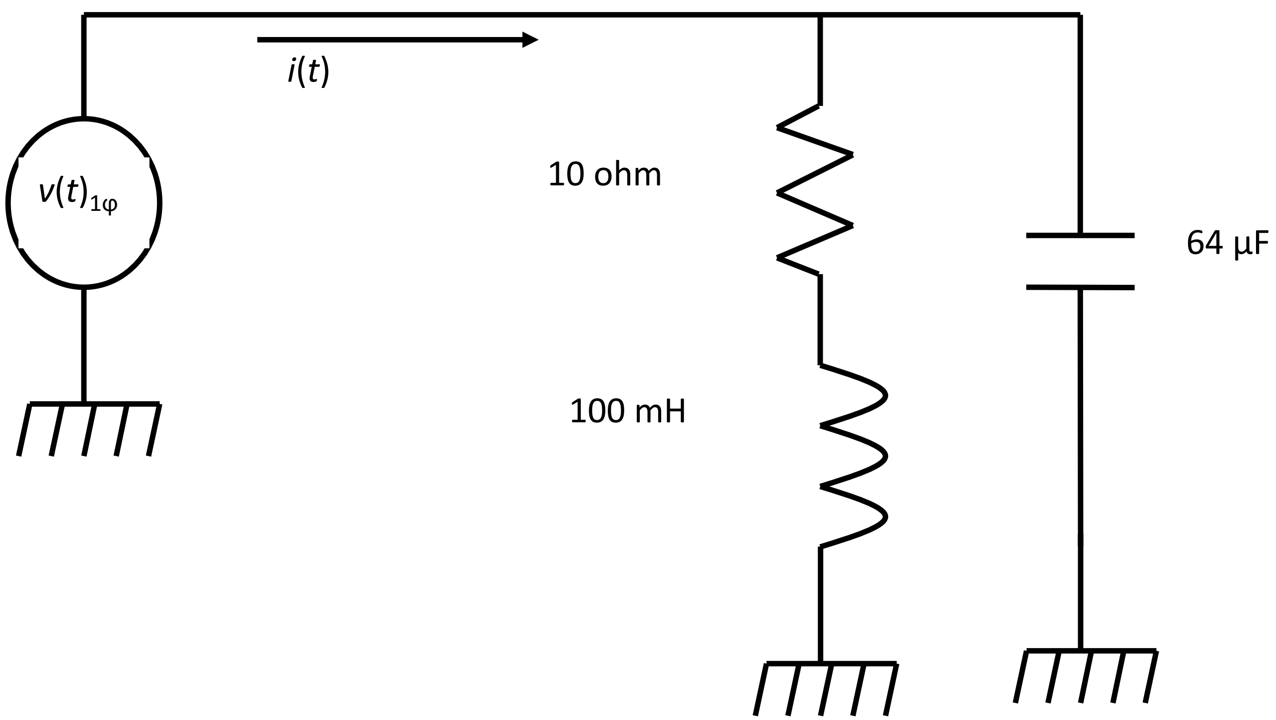
Application of Q_B in power factor correction (1)



$$v(t)_{1\phi} = \frac{100}{h}\sin\left(2\cdot\pi\cdot 50\cdot h\cdot t\right);\ h\in[1,5,7,11]$$

- PF = 0.3 based on Q_B

Application of Q_B in power factor correction (2)



- Calculate the capacitance in parallel to compensate Q_B

$$C = \frac{Q_B}{V_1^2\omega_1 + V_5^2\omega_5 + V_7^2\omega_7 + V_{11}^2\omega_{11}}$$

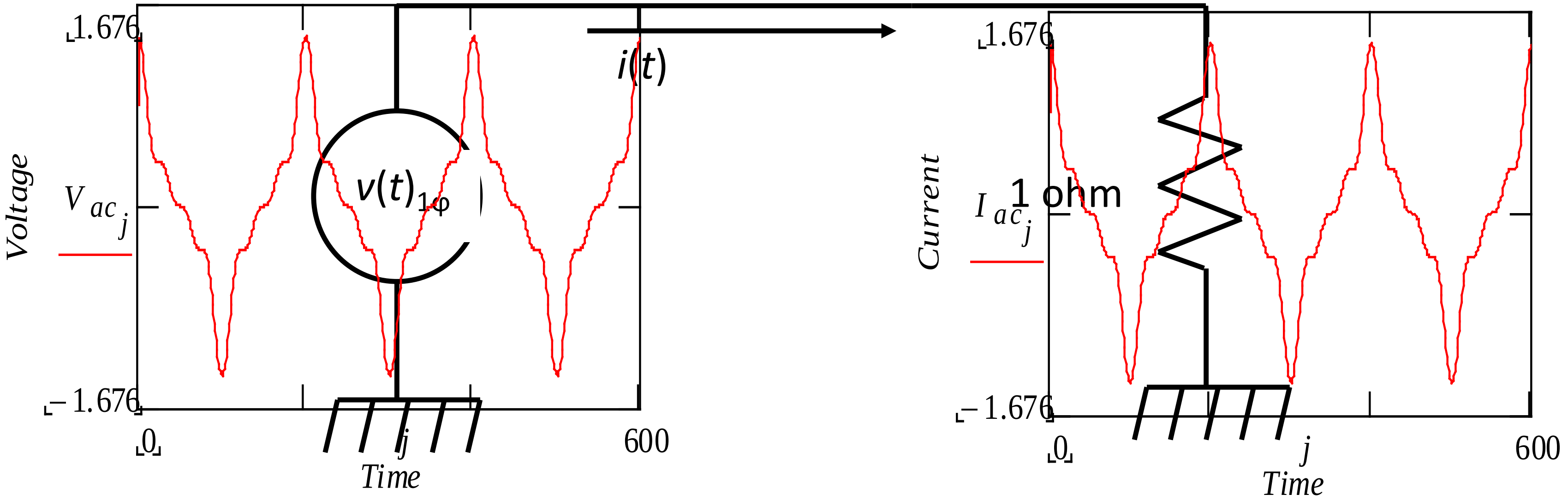
Application of Q_B in power factor correction (3)

Symbol	Without a capacitor	Compensated	Units
$S_{1\phi}$	602	412	VA
$P_{1\phi}$	180.	181	Watt
Q_B	574	4	VAr
D_B	16	370	VAr
PF	0.3	0.4	
C	0	65	μF

- Q_B completely compensated by capacitor, but- power factor of compensated circuit did not change significantly.
- Apparent power is less in compensated circuit but unnecessary loading remains (difference between apparent power and real power).

Remark

- Budeanu's reactive power (Q_B) not useful for power factor compensation.
- Power factor correction results in "distortion power" (D_B) to increase significantly due to increased interaction between uneven harmonic voltage and current components.



$$v(t)_{1\phi} = \frac{1}{h}\sin(2\cdot\pi\cdot 50\cdot h\cdot t);\ h\in[1,3,5,7]$$

$S_{1\phi}$	1.194 VA
$P_{1\phi}$	1.194 Watt
Q_B	0 VAr
D_B	0 VAr

- D_B has zero value: waveforms perfectly sinusoidal?
- Both voltage and current are distorted!
- D_B does not relate to degree of waveform distortion.

Summary: Power theory in a modern power system

- It must, as far as possible consist of a generalisation of the classic single-frequency power theory that has by now been universally accepted.
- It must be as amenable to conventional measurement techniques as possible and require the minimum of sophistication in instrumentation.
- It’s different defined components must be relatable to physically observable or ascribable phenomena and not to hypothetical or abstract mathematical definition.
- It must present a suitable basis for quantifiable measurement, control, tariff systems and design.
- It must cater for every conceivable practical situation and never violate circuit laws, regardless of which domain it is transformed into.
- It must be useful to the engineer who has to apply these definitions in design, specification and operation of the power system.

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Modern Power Theory

2. The IEEE 1459 made easy

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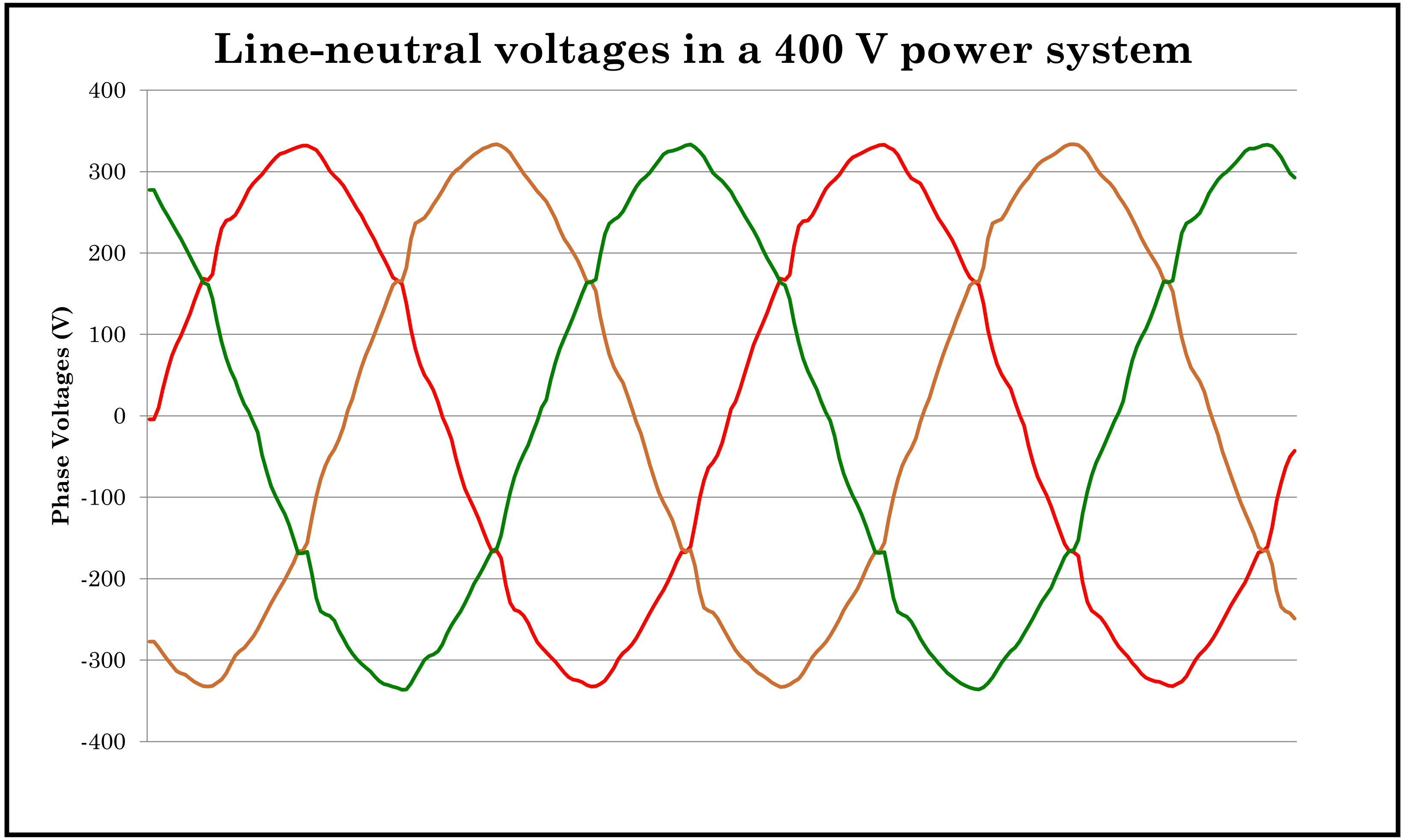
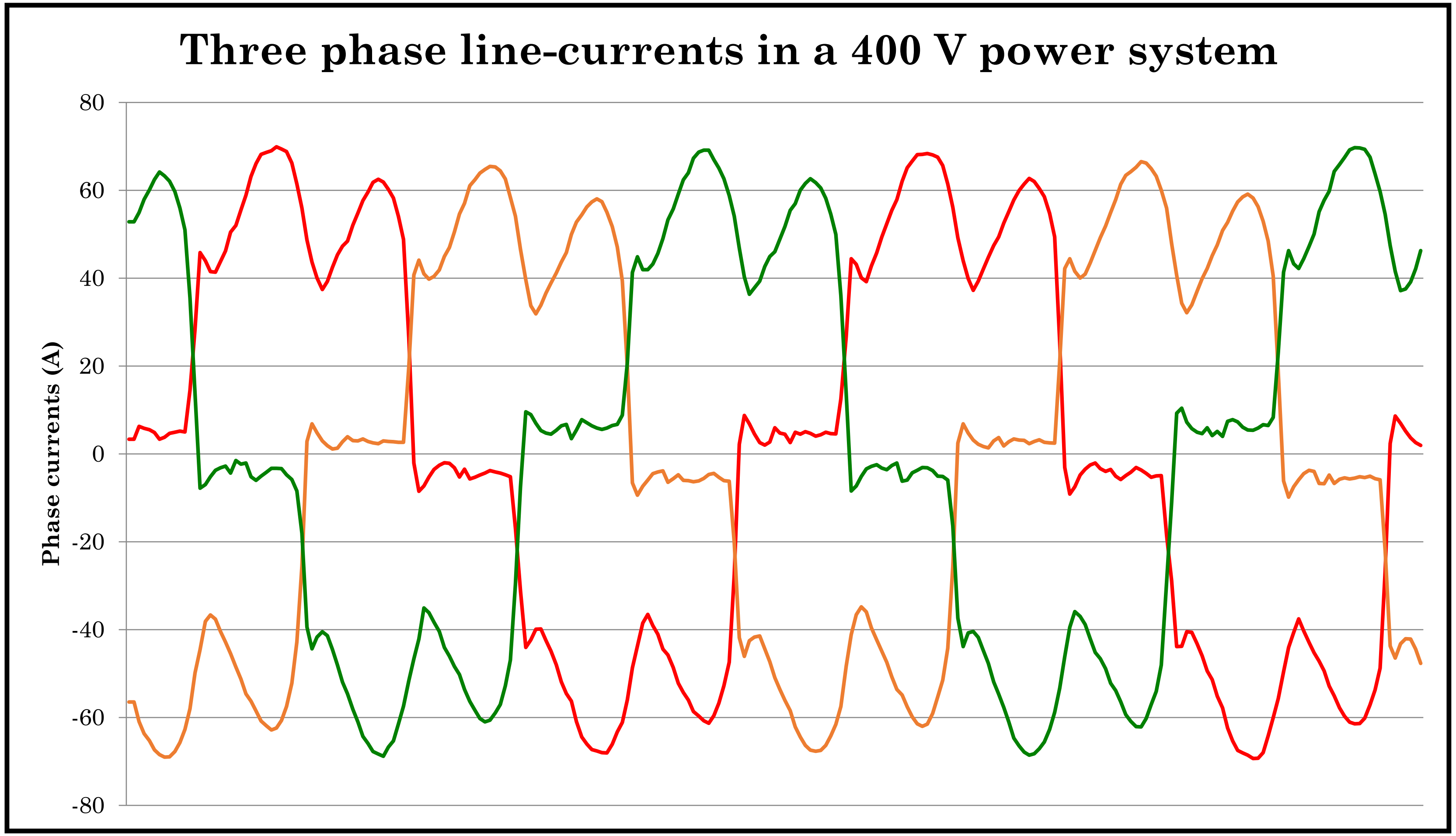
What is a modern Power System? (1)

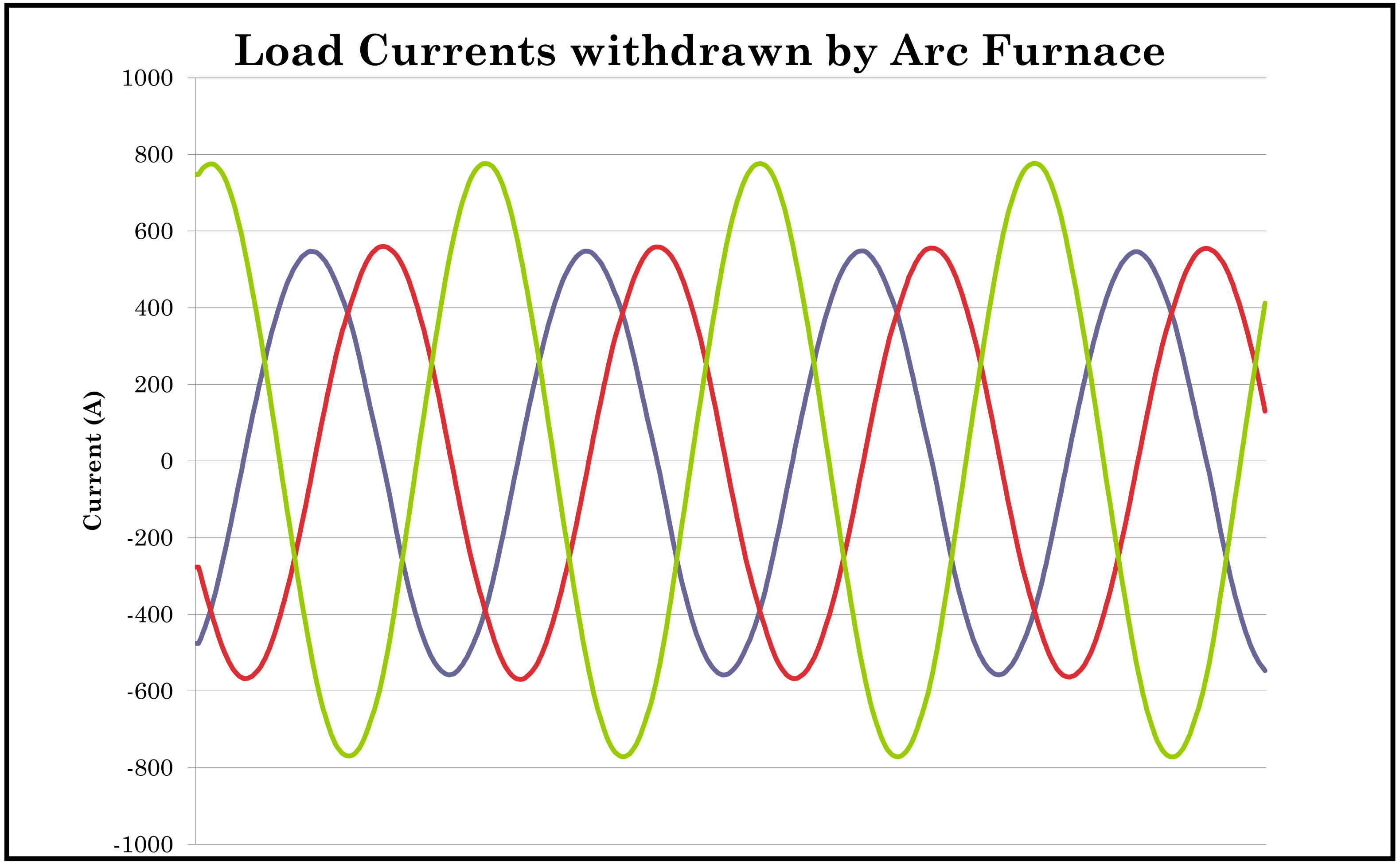
Condition 1: Non-sinusoidal supply voltages at a PCC…..



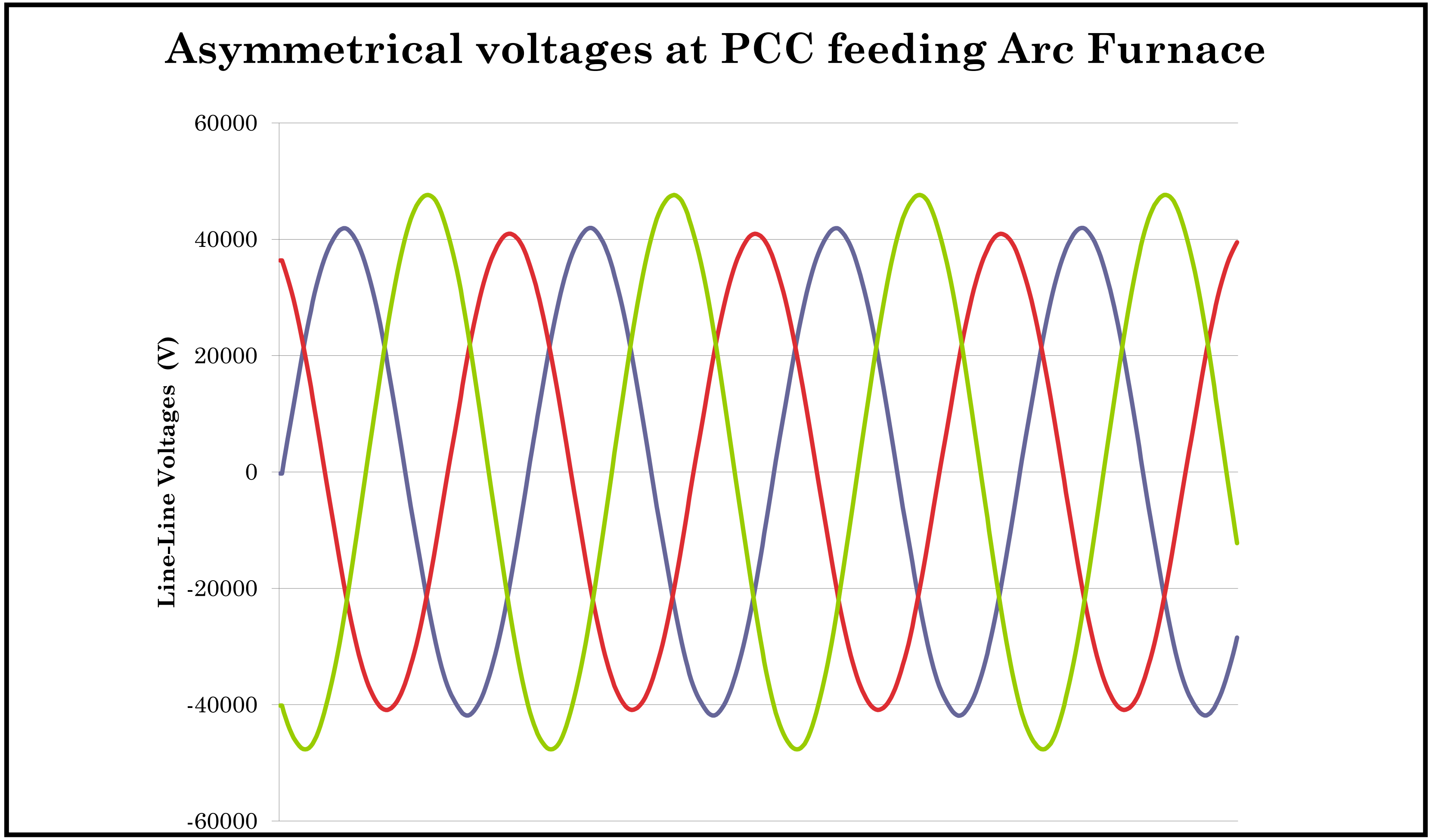
Condition 2: Nonlinear load current …..



Condition 3: Unbalance in loading…



Condition 4: Asymmetrical supply voltages….



- A Three-phase power system under non-sinusoidal waveform conditions, unbalanced loading and asymmetrical supply voltages is considered.
- Sinusoidal, balanced and single-phase power system operation is easily introduced as a simplification

Define nonsinusoidal line-neutral voltages and line currents:

$$v_a(t) = \sqrt{2}\sum_{h\neq 0}^{\infty} V_{a,h}\sin(h\omega t + \alpha_{a,h})$$

$$v_b(t) = \sqrt{2}\sum_{h\neq 0}^{\infty} V_{b,h}\sin(h\omega t + \alpha_{a,h} - 120^0 h)$$

$$v_c(t) = \sqrt{2}\sum_{h\neq 0}^{\infty} V_{c,h}\sin(h\omega t + \alpha_{c,h} + 120^0 h)$$

$$i_a(t) = I_{a0} + \sqrt{2}\sum_{h\neq 0}^{\infty} I_{a,h}\sin(h\omega t + \beta_{a,h})$$

$$i_b(t) = I_{b0} + \sqrt{2}\sum_{h\neq 0}^{\infty} I_{b,h}\sin(h\omega t + \beta_{a,h} - 120^0 h)$$

$$i_c(t) = I_{c0} + \sqrt{2}\sum_{h\neq 0}^{\infty} I_{c,h}\sin(h\omega t + \beta_{c,h} + 120^0 h)$$

- DC components in voltage, (V_{a0}, V_{b0} and V_{c0}) **should always be zero**.
- DC values in line currents (I_{a0}, I_{b0} and I_{c0}) **could be nonzero** depending on nature of load.

- The *RMS line-neutral voltage* V_a and RMS line current I_a (similarly for phase *b* and *c*) are related to harmonic components by:

$$V_a^2 = V_{a,1}^2 + \sum_{h\neq 2}^{\infty} V_{a,h}^2 = V_{a,1}^2 + V_{aH}^2 \quad \left(V_{aH}^2 = \sum_{h\neq 2}^{\infty} V_{a,h}^2\right)$$

$$I_a^2 = I_{a,1}^2 + \sum_{h\neq 2}^{\infty} I_{a,h}^2 = I_{a,1}^2 + I_{aH}^2 \quad \left(I_{aH}^2 = \sum_{h\neq 2}^{\infty} I_{a,h}^2\right)$$

- Fundamental frequency and the nonfundamental frequency (harmonic frequencies grouped)

☝ What is the “effect” of three-phase voltages and three-phase currents in terms of the three-phase power system?

“Effective” voltage and **“effective” current** to represent the state of the three-phase power system:

$$V_e^2 = V_{e1}^2 + V_{eH}^2$$

$$I_e^2 = I_{e1}^2 + I_{eH}^2$$

“Effective” voltage and **“effective” current** in a 3-wire three-phase power system:

$$V_e = \sqrt{\frac{V_a^2 + V_b^2 + V_c^2}{3}}$$

$$I_e = \sqrt{\frac{I_a^2 + I_b^2 + I_c^2}{3}}$$

☝ If an artificial neutral point in a **3-wire three-phase system** is not used to find the line-neutral voltage values, the *effective three-phase voltage* can be calculated from the **RMS phase-phase voltage** values as:

$$V_e = \sqrt{\frac{V_{ab}^2 + V_{bc}^2 + V_{ca}^2}{9}}$$

- The **fundamental frequency componens** of the *effective voltage* and *current* in a **3-wire three-phase power system**:

$$V_{e,1} = \sqrt{\frac{V_{ab,1}^2 + V_{bc,1}^2 + V_{ca,1}^2}{9}}$$

$$I_{e,1} = \sqrt{\frac{I_{a,1}^2 + I_{b,1}^2 + I_{c,1}^2}{3}}$$

- **Non-fundamental frequency** components of the *effective voltage* and *current* in a 3-wire three-phase power system:

$$V_{eH} = \sqrt{\frac{V_{abH}^2 + V_{bcH}^2 + V_{caH}^2}{9}}$$

$$I_{eH} = \sqrt{\frac{I_{aH}^2 + I_{bH}^2 + I_{cH}^2}{3}}$$

- **Non-fundamental frequency** components relates to the harmonic components (line-neutral voltages assumed):

$$V_{eH} = \sqrt{\frac{\sum_{h \neq 1}^{\infty} \left(V_{a,h}^2 + V_{b,h}^2 + V_{c,h}^2 \right)}{3}}$$

$$I_{eH} = \sqrt{\frac{\sum_{h \neq 1}^{\infty} \left(I_{a,h}^2 + I_{b,h}^2 + I_{c,h}^2 \right)}{3}}$$

- **Unbalanced** condition in a **4-wire three-phase power** system requries reformulation of the *effective voltage* and *current* :

$$V_e = \sqrt{\frac{1}{18}\left[3\left(V_a^2 + V_b^2 + V_c^2\right) + V_{ab}^2 + V_{bc}^2 + V_{ca}^2\right]}$$

$$I_e = \sqrt{\frac{I_a^2 + I_b^2 + I_c^2 + I_n^2}{3}}$$

- The **fundamental frequency** components of the *effective voltage* and *current* in a **4-wire three-phase power system**:

$$V_{e,1} = \sqrt{\frac{1}{18}\left[3\left(V_{a,1}^2 + V_{b,1}^2 + V_{c,1}^2\right) + V_{ab,1}^2 + V_{bc,1}^2 + V_{ca,1}^2\right]}$$

$$I_{e,1} = \sqrt{\frac{I_{a,1}^2 + I_{b,1}^2 + I_{c,1}^2 + I_{n,1}^2}{3}}$$

- The **non-fundamental** frequency components of the *effective voltage* and *current* in a **4-wire three-phase power system**:

$$V_{eH} = \sqrt{\frac{1}{18}\left[3\left(V_{aH}^2 + V_{bH}^2 + V_{cH}^2\right) + V_{abH}^2 + V_{bcH}^2 + V_{caH}^2\right]}$$

$$I_{eH} = \sqrt{\frac{I_{aH}^2 + I_{bH}^2 + I_{cH}^2 + I_{nH}^2}{3}}$$

☞ Implementation straightforward with modern digital instrumentation

- **Arithmetic** apparent power S_A:

- The Budeanu power definition for single-phase power systems are applied per phase

$$S_a = \sqrt{P_a^2 + Q_{Ba}^2 + D_{Ba}^2}$$

$$S_b = \sqrt{P_b^2 + Q_{Bb}^2 + D_{Bb}^2}$$

$$S_c = \sqrt{P_c^2 + Q_{Bc}^2 + D_{Bc}^2}$$

$$S_A = S_a + S_b + S_c$$

- **Vector** apparent power S_V:

- Active, Budeanu's reactive and distortion power is summated over all three phases:

$$P_{\Sigma,3\phi} = P_a + P_b + P_c$$

$$Q_B = Q_{Ba} + Q_{Bb} + Q_{Bc}$$

$$D_B = D_{Ba} + D_{Bb} + D_{Bc}$$

$$S_V = \sqrt{P_{\Sigma,3\phi}^2 + Q_B^2 + D_B^2}$$

And the effective apparent power is.....

The *three-phase* or *system effective apparent power* S_e can be written in terms of the contribution of all harmonic components:

$$S_e^2 = (V_e I_e)^2 = (V_{e,1} I_{e,1})^2 + (V_{e,1} I_{eH})^2 + (V_{eH} I_{e,1})^2 + (V_{eH} I_{eH})^2$$

The components in the ***system effective apparent power*** S_e can be grouped in the **fundamental and nonfundamental** frequency voltage and current components:

$$S_e^2 = S_{e,1}^2 + S_{eN}^2$$

The ***non-fundamental frequency apparent power*** S_{eN} consist of 3 “distortion” components:

$$S_{eN}^2 = \left(V_{e,1} I_{eH}\right)^2 + \left(V_{eH} I_{e,1}\right)^2 + \left(V_{eH} I_{eH}\right)^2$$
$$= D_{eI}^2 + D_{eV}^2 + D_{eH}^2$$

And the "distortion" powers are…..

$$S_{eN}^2 = \left(V_{e,1} I_{eH}\right)^2 + \left(V_{eH} I_{e,1}\right)^2 + \left(V_{eH} I_{eH}\right)^2$$

$$= D_{eI}^2 + D_{eV}^2 + D_{eH}^2$$

$V_{e,1}I_{eH}$: The ***current distortion power***, D_{eI}

$V_{eH}I_{e,1}$: The ***voltage distortion power***, D_{eV}

$V_{eH}I_{eH}$: The ***harmonic distortion power***, D_{eH}

An ***effective harmonic apparent power*** S_{eH} is defined:

$$S_{eH}^2 = P_{H,3\phi}^2 + D_{eH}^2$$

The Total Three-Phase Active Power

The ***Joint*** **(*Total*)** ***Harmonic Active Power*** of three-phase power system:

$$P_{H,3\phi} = \mathrm{Re}\sum_{h\neq 1}^{N}\left(\boldsymbol{V}_{ah}\boldsymbol{I}_{ah}^{*} + \boldsymbol{V}_{bh}\boldsymbol{I}_{bh}^{*} + \boldsymbol{V}_{ch}\boldsymbol{I}_{ch}^{*}\right)$$

$$= \sum_{h\neq 1}^{N} P_{h,3\phi}$$

The ***Joint Active Power*** of three-phase power system:

$$P_{3\phi} = \left[\boldsymbol{v}(t)_{3\phi}, \boldsymbol{i}(t)_{3\phi}\right]$$

$$= \mathrm{Re}\sum_{h=1}^{N}\left(\boldsymbol{V}_{ah}\boldsymbol{I}_{ah}^{*} + \boldsymbol{V}_{bh}\boldsymbol{I}_{bh}^{*} + \boldsymbol{V}_{ch}\boldsymbol{I}_{ch}^{*}\right)$$

$$= \sum_{h=1}^{N} P_{h,3\phi}$$

Quantification on the level of distortion is done with ***three-phase effective values***:

$$VTHD_e = \frac{V_{eH}}{V_{e,1}}$$

$$ITHD_e = \frac{I_{e,H}}{I_{e,1}}$$

☞ **Voltage total harmonic distortion factor:** $VTHD_e$

☞ **Current total harmonic distortion factor:** $ITHD_e$

☞ The IEEE 1459-2000 write these symbols as THD_{eV} and THD_{eI}

A shortcut to S_{eN}:

$$S_{eN} = S_{e1}\sqrt{VTHD_e + ITHD_e + \left(VTHD_e ITHD_e\right)^2}$$

And to D_{eI}; D_{eV}; D_{eH} (The “distortion” powers):

$$D_{eI} = S_{e1} ITHD_e$$

$$D_{eV} = S_{e1} VTHD_e$$

$$D_{eH} = S_{e1} ITHD_e VTHD_e$$

To do what with?

Harmonic pollution (S_{eN}/S_{e1})**:**

$$\left(\frac{S_{eN}}{S_{e1}}\right)^2 = \left(ITHD_e\right)^2 + \left(VTHD_e\right)^2 + \left(ITHD_e VTHD_e\right)^2$$

Unbalance pollution:

☝ The positive sequence voltage (V_1^+) and current (I_1^+) in the three-phase fundamental frequency components have to be found…..

$$S_1^+ = 3V_1^+ I_1^+$$

Then calculate:

$$S_{u1} = \sqrt{S_{e1}^2 - \left(S_1^+\right)^2}$$

The “unbalance pollution”:

$$UnbalancePollution(\%) = \frac{S_{u1}}{S_{e1}} * 100$$

☝ “Unbalance pollution” includes both the effect on loading unbalance and voltage asymmetry

☞ The positive sequence components in the three-phase fundamental frequency voltages and currents:

- ✓ The 50 Hz positive sequence active power: $P_1^+ = 3V_1^+ I_1^+ \cos\theta_1^+$
- ✓ The 50 Hz positive sequence reactive power: $Q_1^+ = 3V_1^+ I_1^+ \sin\theta_1^+$
- ✓ The 50 Hz positive sequence apparent power: $\left(S_1^+\right)^2 = \left(P_1^+\right)^2 + \left(Q_1^+\right)^2$

And power factor?

Various options exist….

Different answers to the same question!

Different apparent powers have been formulated:

- Arithmetic apparent power, S_A
- Vector apparent power, S_v
- Three-phase effective apparent power, S_e
- Positive sequence apparent power, S_1^+

Different apparent power factors have been formulated:

- Arithmetic apparent power factor $$PF_A = \frac{P}{S_A}$$
- Vector apparent power factor $$PF_V = \frac{P}{S_V}$$
- Three-phase effective apparent power factor $$PF_e = \frac{P_{\Sigma,3\phi}}{S_e} = \frac{P_{1,3\phi} + P_{H,3\phi}}{S_e}$$
- Positive sequence apparent power factor $$PF^+ = \frac{P_1^+}{S_1^+}$$

If the waveforms are sinusoidal, the loading in perfect balance and the supply voltages in perfect symmetry, then:

$$PF_A = PF_V = PF_e = PF^+$$

In a practical power system with distorted waveforms, unbalanced loading and asymmetrical supply voltages:

$$PF_e < PF_A < PF_V$$

• PF_e reflects the impact of harmonics and asymmetrical waveforms the best.

☞ The smallest numerical value – regulatory application

☝ What power factor formulation does your instrument use?

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3. Case Study

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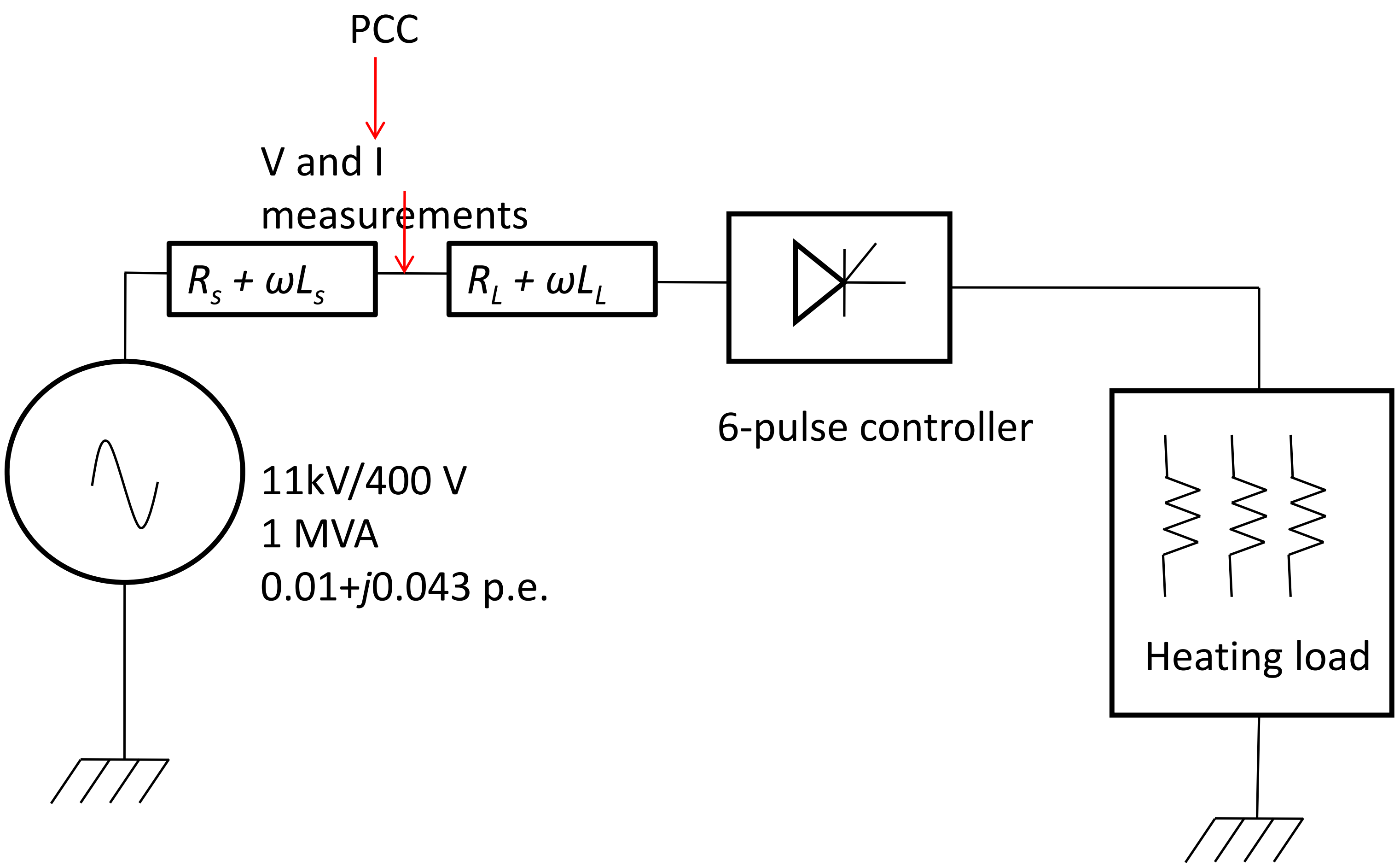
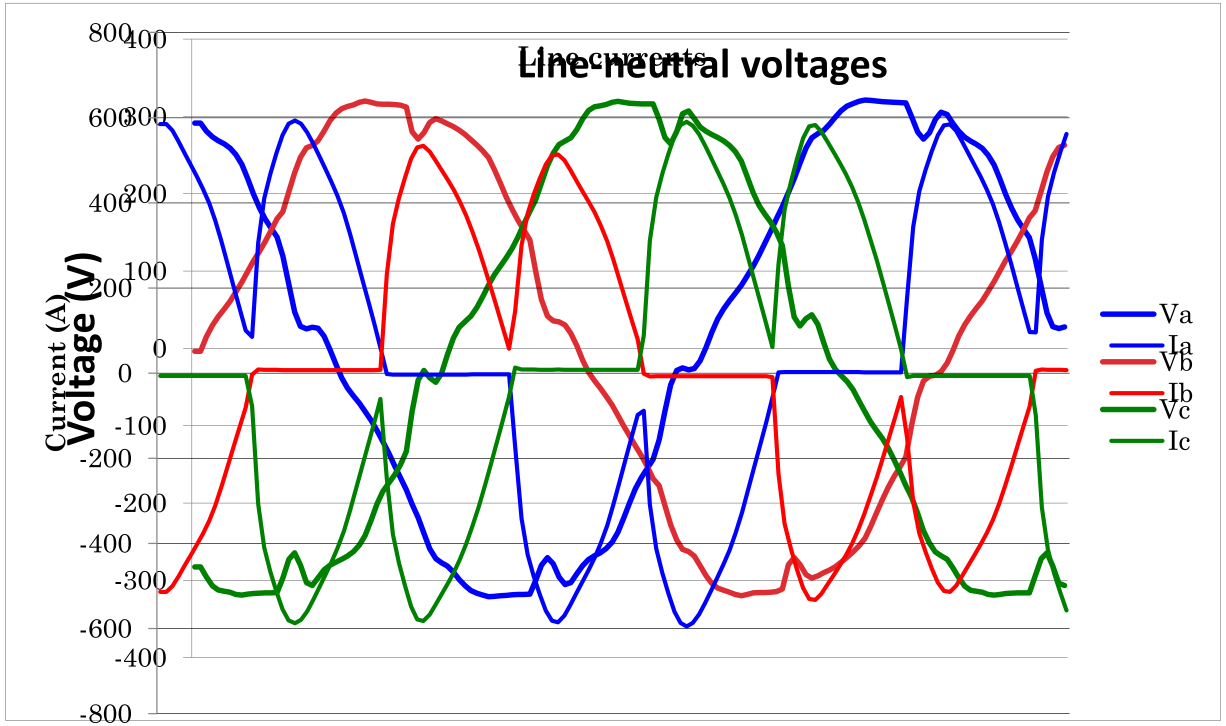
Application of IEEE 1459-2000 - practical power system

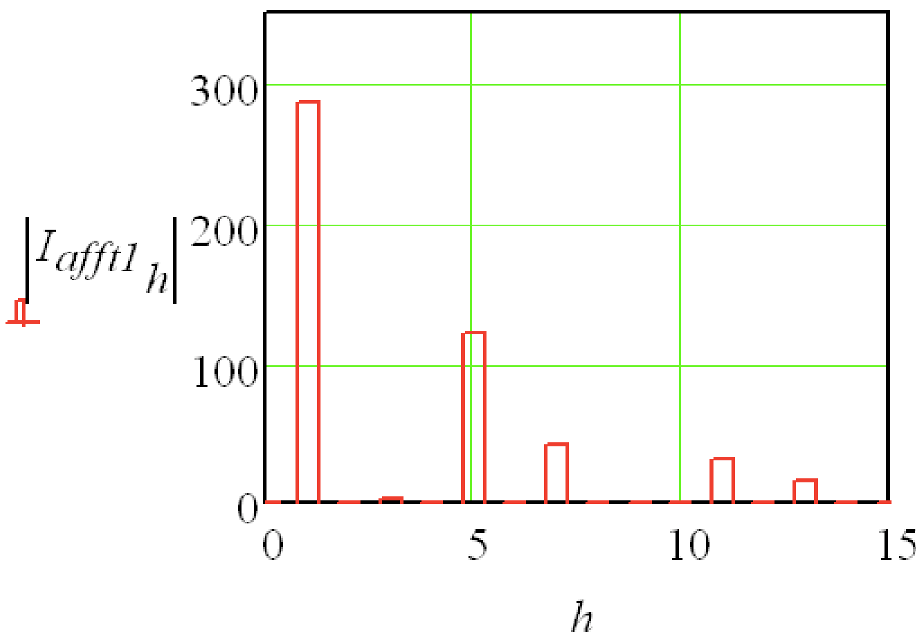


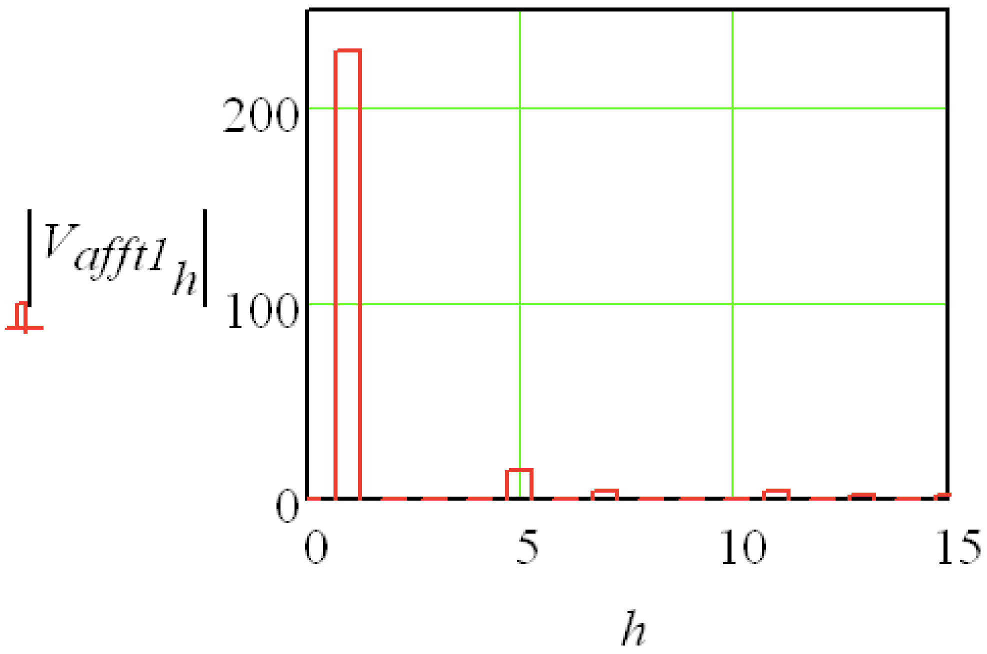
Voltage and Current waveforms



- Line-neutral voltages
- Line Currents

The IEEE 1459 power definitions require translating time-domain waveforms to the frequency domain by means of the Fourier transform:





The level of distortion requires quantification:

- $ITHD_e$= 48.3%
- $VTHD_e$= 7.5%

- The **non-fundamental** frequency components of the *effective voltage* and *current*:

$$V_{eH} = \sqrt{\frac{1}{18}\left[3\left(V_{aH}^2 + V_{bH}^2 + V_{cH}^2\right) + V_{abH}^2 + V_{bcH}^2 + V_{caH}^2\right]}$$

$$= 17.2 \text{ V}$$

$$I_{eH} = \sqrt{\frac{I_{aH}^2 + I_{bH}^2 + I_{cH}^2 + I_{nH}^2}{3}}$$

$$= 145.8 \text{ A}$$

- The **fundamental frequency** components of the *effective voltage* and *current*:

$$V_{e,1} = \sqrt{\frac{1}{18}\left[3\left(V_{a,1}^2 + V_{b,1}^2 + V_{c,1}^2\right) + V_{ab,1}^2 + V_{bc,1}^2 + V_{ca,1}^2\right]}$$

$$= 227.6 \text{ V}$$

$$I_{e,1} = \sqrt{\frac{I_{a,1}^2 + I_{b,1}^2 + I_{c,1}^2 + I_{n,1}^2}{3}}$$

$$= 301.5 \text{ A}$$

The *effective voltage* and *current* :

$$V_e = \sqrt{V_{e1}^2 + V_{eH}^2}$$

$$= 228.3 \text{ V}$$

$$I_e^2 = \sqrt{I_{e1}^2 + I_{eH}^2}$$

$$= 335 \text{ A}$$

The RMS line-neutral voltages per phase:

$$V_a = \sqrt{\sum_{h=1}^{\infty} V_{a,h}^2} = 229.2 \text{ V}$$

$$V_b = 227.7 \text{ V}$$

$$V_c = 227.8 \text{ V}$$

The RMS line currents per phase:

$$I_a = \sqrt{\sum_{h=1}^{\infty} I_{a,h}^2} = 315.4 \text{ A}$$

$$I_b = 342.9 \text{ A}$$

$$I_c = 345.8 \text{ A}$$

The RMS neutral current:

$$I_n = 8.1 \text{ A}$$

The powers

Effective apparent power: $S_{e1} = 229.4 \text{ KVA}$

Arithmetic apparent power: $S_A = 199.7 \text{ KVA}$

Vector apparent power: $S_V = 199.7 \text{ KVA}$

Joint harmonic active power:

$$P_{H,3\phi} = \text{Re}\sum_{h\neq 1}^{N}\left(\boldsymbol{V}_{ah}\boldsymbol{I}_{ah}^{*} + \boldsymbol{V}_{bh}\boldsymbol{I}_{bh}^{*} + \boldsymbol{V}_{ch}\boldsymbol{I}_{ch}^{*}\right) = \sum_{h\neq 1}^{N} P_{h,3\phi} = -387 \text{ W}$$

Joint (three-phase) active power:

$$P_{3\phi} = \left[\boldsymbol{v}(t)_{3\phi}, \boldsymbol{i}(t)_{3\phi}\right] = \text{Re}\sum_{h=1}^{N}\left(\boldsymbol{V}_{ah}\boldsymbol{I}_{ah}^{*} + \boldsymbol{V}_{bh}\boldsymbol{I}_{bh}^{*} + \boldsymbol{V}_{ch}\boldsymbol{I}_{ch}^{*}\right) = \sum_{h=1}^{N} P_{h,3\phi} = 92.9 \text{ kW}$$

Current distortion power: $D_{eI} = S_{e1} ITHD_e = 99.9 \text{ kVar}$

Voltage distortion power: $D_{eV} = S_{e1} VTHD_e = 15.5 \text{ kVar}$

Harmonic distortion power: $D_{eH} = S_{e1} ITHD_e VTHD_e = 7.5 \text{ kVar}$

And the power factors….

The arithmetic power factor: 0.465 p.u.

The vector power factor: 0.465 p.u.

The effective power factor: 0.405 p.u

And the "pollution" factors….

Harmonic pollution:

$$\frac{S_{eN}}{S_{e1}}(\%) = \sqrt{(ITHD_e)^2 + (VTHD_e)^2 + (ITHD_e VTHD_e)^2} * 100$$

$$= 3.6\%$$

Unbalance pollution:

$$S_{u1} = \sqrt{S_{e1}^2 - (S_1^+)^2} = 9.1\,\mathrm{KVA}$$

$$\therefore UnbalancePollution(\%) = \frac{S_{u1}}{S_{e1}} * 100 = 4.4\%$$

Unbalance factors:

$$V_{UB} = \frac{V_2}{V_1} = 0.4\%$$

$$I_{UB} = \frac{I_2}{I_1} = 3\%$$

☞ The three-phase effective power factor is numerically the smallest if unbalance and/or waveform distortion exist.

☞ It is a helpful reflection on the impact of nonsinusoidal waveforms, unbalanced loading and asymmetrical supply voltages from the point of view from operating such power system.

☞ It is possible to isolate the contribution of harmonics to useles power by means of voltage distortion power (D_V), current distortion power (D_I) and harmonic distortion power (D_H).

☞ The three-phase effective distortion index for voltage ($VTHD_e$) and current ($ITHD_e$) furthers straightforward calculation of distortion powers.

☞ The contribution to apparent power by both voltage asymmetry and unbalance in loading, was shown to be significant even with “low” values in V_{UB} and I_{UB}.

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Conclusion on Power Theory

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- The classical power theory explains phenomena in a power system with a sound physical explanation but is inadequate when waveforms are non-sinusoidal, loading is unbalanced and voltage waveforms are asymmetrical.
- Numerous approaches to power theory exists which are formulated in either the time- or frequency domain.
- New contributions are forthcoming as inadequacies are better understood.
- In general, a power theory has to:
  - ✓ Conform to Electrical Network Laws
  - ✓ Explain Physical Phenomena
  - ✓ Be Measurable
  - ✓ Enables Compensation

☞ The IEEE 1459-2000 is a practical approach to the operation of a power system