EE6508 - Power Quality
Concept of Power Quality

presented by

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Lecture Schedule

- **Week 1 – Week 6**
  Power System Harmonics by Prof So Ping Lam

- **Week 7 – Week 13**
  Concept of Power Quality by Prof Amer M. Y. M. Ghias
  Transient Overvoltages by Prof Amer M. Y. M. Ghias
  Voltage Fluctuations and Variations by Amer M. Y. M. Ghias

Assessment Scheme

- **Continuous Assessment (CA)** - 20% (Two CAs, 10% for each CA)
  - The first CA or Quiz will be conducted in Week 6 (19 February 2020)
  - The second CA or Quiz will be conducted in Week 13 (15 April 2020)

Final Examination - 80%

Lecture Outline

- Power Quality
  - Definitions
  - Typical Causes and Characteristics
  - Voltage Disturbance
    - ✓Types and Typical Causes
    - ✓CBEMA and ITI Curves
  - Power Quality Standards
  - System Overvoltage's
  - Effect of Load Behaviour on Voltages

References

Texts:

1. Dugan R C, McGranaghan M F, Santoso S, and Beaty H W, Electrical Power Systems Quality, Second Edition, McGraw-Hill, 2002. 2.
2. Kennedy B W, Power Quality Primer, First Edition, McGraw-Hill, 2000.

Reference:

3. Allan Greenwood, “Electrical Transients in Power Systems”, 2nd Edition, John Wiley & Sons Inc., 1991.

What is Quality?

- Depends on Circumstances
  - Functions
  - Environments
  - Preferences

Quality – Function Dependent

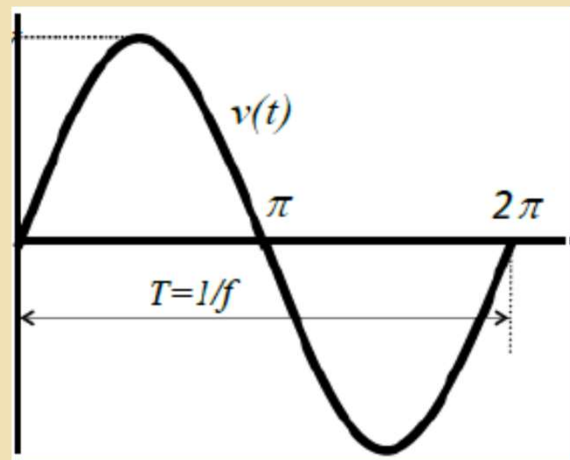
Quality – Depends on Environment

Quality – Depends on Preferences

What is Power Quality?

- What is Quality?
  - Depends on circumstances
    - ✓Functions
    - ✓Environment
    - ✓Preferences
- Standard Power Supply
  - Electrical equipment are designed to operate at rated conditions
    - ✓Waveform shape: Sinusoidal
    - ✓Magnitude: 220/110 V
    - ✓Frequency: 50/60 Hz

$V_m = \sqrt{2}V$



What is Power Quality?

- Major Power Quality issues:
  - Voltage variations/fluctuations
    - ✓Transients
    - ✓Long duration voltage variation
    - ✓Short duration voltage variation
  - Harmonics
  - Poor power factor
  - Power frequency variation
  - Earthing systems and leakage currents etc
- Issues impact on the efficiency of the equipment
  - Higher energy usage and costs
  - Higher maintenance costs
  - Equipment failure

Definition of Power Quality and its Causes

- Definition: Any power problem manifested in voltage, current or frequency deviations that results in failure or mis-operation of customer equipment
  - Any significant deviation from the ideal waveform, i.e., in terms of magnitude, frequency, phase, waveform impurity is a power quality problem.
- Power quality problems may arise because of two reasons:
  - Deficiencies and disturbances in the supply system, and/or
  - Nature and behavior of the load and installation.
- Although power delivered depends on the voltage and current, the supply industry does not have control over the current drawn by customers
- The effect of current should be addressed because even a perfect supply voltage can change due to system currents, such as:
  - Short circuit current can change the voltage drastically.
  - Currents from lightning can disrupt the system.
  - Distorted currents from some consumers can create distorted voltage at the point of common coupling (PCC) to other customers.

Table 2.2 Categories and Characteristics of Power System Electromagnetic Phenomena [1]

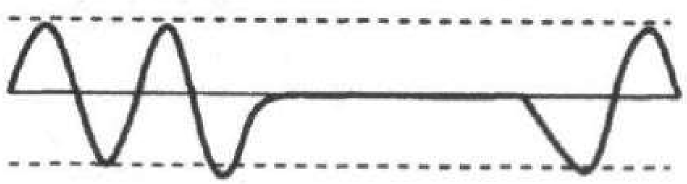
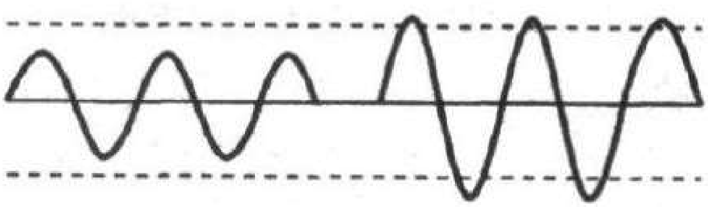
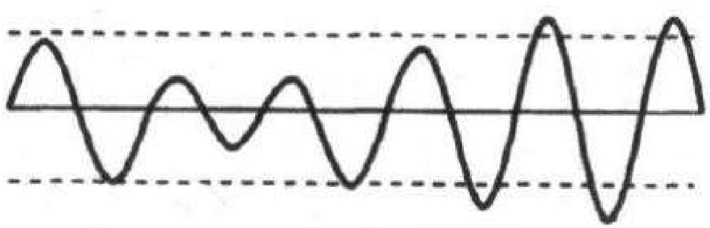
Categories	Typical spectral content	Typical duration	Typical voltage magnitude
1.0 Transients			
1.1 Impulsive			
1.1.1 Nanosecond	5-ns rise	<50 ns	
1.1.2 Microsecond	1-μs rise	50 ns–1 ms	
1.1.3 Millisecond	0.1-ms rise	>1 ms	
1.2 Oscillatory			
1.2.1 Low frequency	<5 kHz	0.3–50 ms	0–4 pu
1.2.2 Medium frequency	5–500 kHz	20 μs	0–8 pu
1.2.3 High frequency	0.5–5 MHz	5 μs	0–4 pu
2.0 Short-duration variations			
2.1 Instantaneous			
2.1.1 Interruption		0.5–30 cycles	<0.1 pu
2.1.2 Sag (dip)		0.5–30 cycles	0.1–0.9 pu
2.1.3 Swell		0.5–30 cycles	1.1–1.8 pu
2.2 Momentary			
2.2.1 Interruption		30 cycles–3 s	<0.1 pu
2.2.2 Sag (dip)		30 cycles–3 s	0.1–0.9 pu
2.2.3 Swell		30 cycles–3 s	1.1–1.4 pu
2.3 Temporary			
2.3.1 Interruption		3 s–1 min	<0.1 pu
2.3.2 Sag (dip)		3 s–1 min	0.1–0.9 pu
2.3.3 Swell		3 s–1 min	1.1–1.2 pu
3.0 Long-duration variations			
3.1 Interruption, sustained		>1 min	0.0 pu
3.2 Undervoltages		>1 min	0.8–0.9 pu
3.3 Overvoltages		>1 min	1.1–1.2 pu
4.0 Voltage unbalance		Steady state	0.5–2%
5.0 Waveform distortion			
5.1 DC offset		Steady state	0–0.1%
5.2 Harmonics	0–100th harmonic	Steady state	0–20%
5.3 Interharmonics	0–6 kHz	Steady state	0–2%
5.4 Notching		Steady state	
5.5 Noise	Broadband	Steady state	0–1%
6.0 Voltage fluctuations	<25 Hz	Intermittent	0.1–7% 0.2–2 Pst
7.0 Power frequency variations		<10 s	

NOTE: s = second, ns = nanosecond, μs = microsecond, ms = millisecond, kHz = kilohertz, MHz = megahertz, min = minute, pu = per unit.

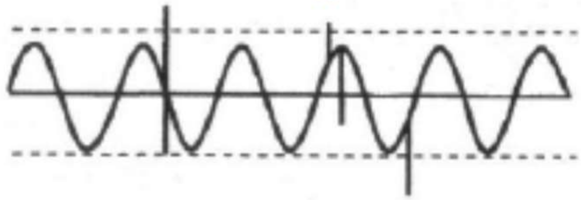
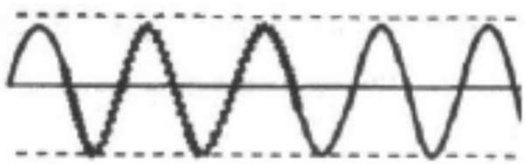
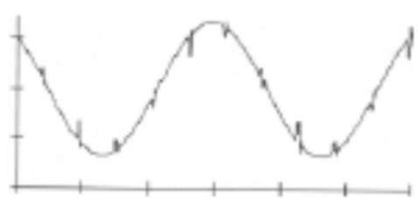
Voltage Disturbance

- Voltage variations may be:
  - Long term disturbances, or
  - Short term disturbances
- The common voltage quality problems are:
  - Interruption or outages
  - Over voltages or under voltages
  - Voltage swells and sags
  - Transients/Surges
  - Flickers
  - Harmonic distortions
  - Notches
  - Noise
- Brief descriptions and the common causes are given in next few slides

Types of Voltage Disturbances & Typical Causes

Type	Possible Causes
Outage or Interruption 	▪ Severe weather ▪ Accidents in lines ▪ Equipment failure
Under voltage, Over voltage 	▪ Heavy or light load ▪ Level of reactive power ▪ Equipment setting
Voltage Sags/Swells 	▪ Disturbances, eg lightning ▪ Sudden increase/decrease of load ▪ Incorrect tap settings, etc

Types of Voltage Disturbances & Typical Causes

Type	Causes
Transients / Surges 	▪ Lightning ▪ Switching (lines, capacitor) ▪ System faults, etc
Harmonic Distortion 	▪ Converters & Inverters ▪ Rectifier Loads ▪ Switching power supplies
Noise 	▪ External signals, ▪ Arcing, switching, ▪ Converters and Inverters
Notches 	▪ Converters and Inverters ▪ Reclosing, switching

CBEMA & ITI Curves

- Developed originally to specify the voltage tolerance of computers.
- It has become defacto standard to design sensitive equipment.
- The curves show, durations of the over voltages that produce malfunction, and durations of under voltages when the equipment drop out due to lack of energy.

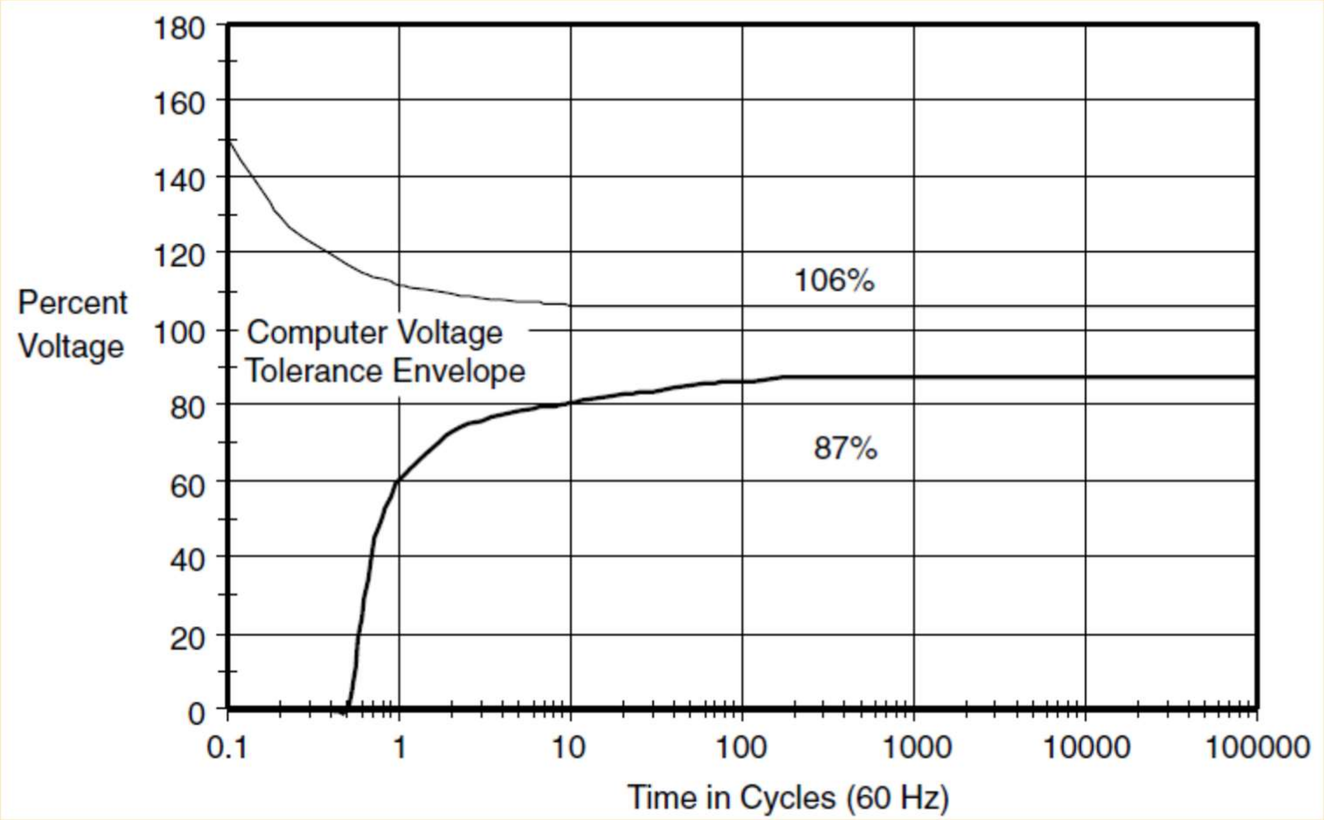


Figure 2.15: A portion of the CBEMA curve commonly used as a design target for equipment and a format for reporting power quality variation data [1].

CBEMA & ITI Curves

- Modified CBEMA curve
- Originally meant for 120V computer equipment
- Widely used for general power quality evaluation

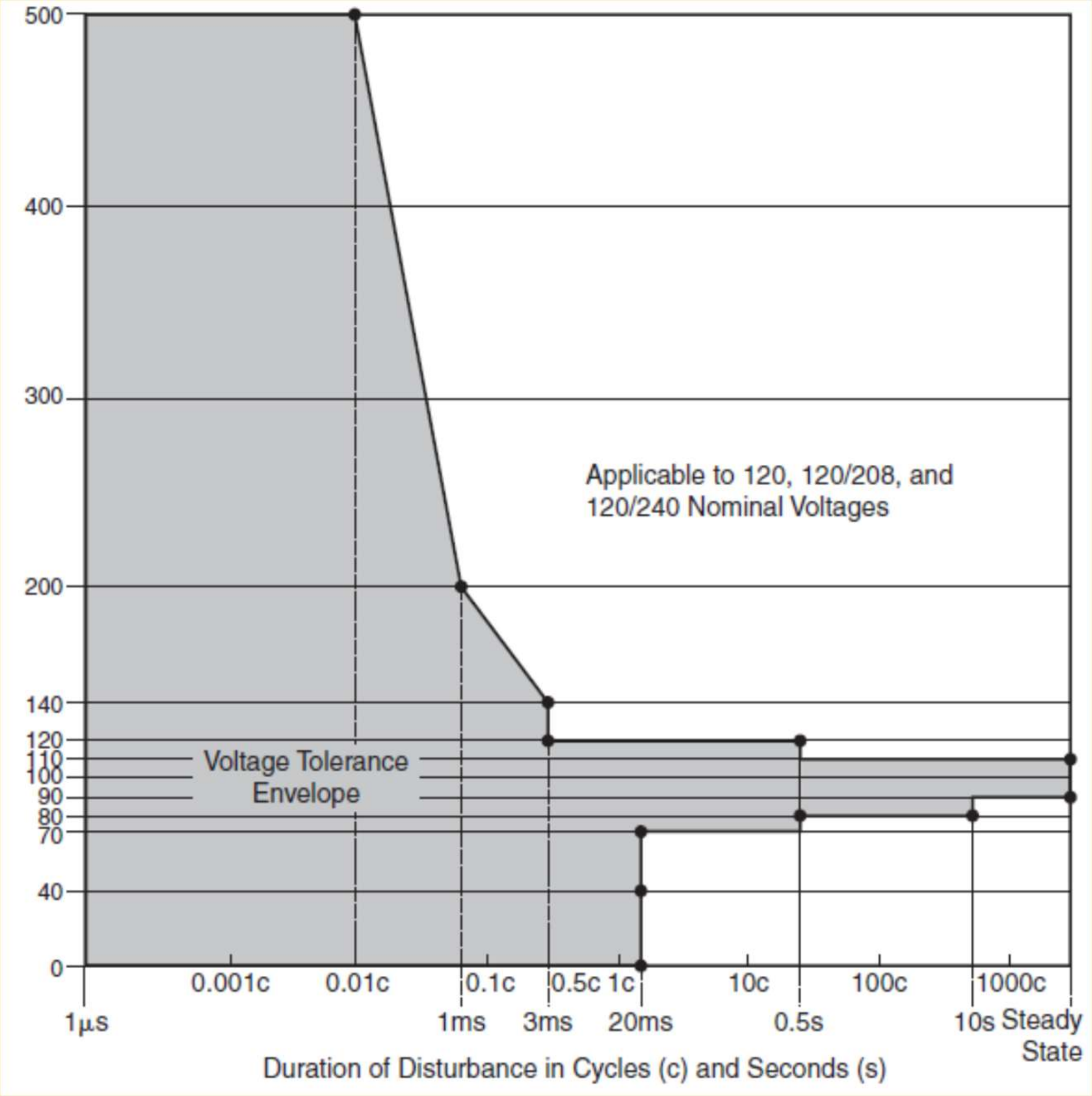


Figure 2.16: ITI curve for susceptibility of 120-V computer equipment [1].

Power Quality Standards

- Many 'Standards' publishing organizations, international, national, industries, etc. Two Major standards are IEC, and IEEE standards.
- IEC standards:
  – National experts from different participating countries
  – Standards are written by the experts in working groups
  – Adopted by two thirds majority vote
  – The standards are binding on members
  – A sample of standards is shown in the Table

Table 3.3 IEC Power Quality Standards by Topic [2].

Topic	Description	IEC number
General	-Fundamental principles -Definitions -Terminology	IEC Pub. 1000-1
Environment	-Description -Classification -Compatibility limits	IEC Pub. 1000-2
Limits	-Emission and immunity limits -Generic standards	EIC Limits 1000-3
Testing and measurement	Techniques for conducting tests	IEC Pub. 1000-4
Installation and mitigation	-Installation guidelines -Mitigation methods -Mitigation devices	IEC Guide 1000-5

Power Quality Standards

- IEEE standards
  - IEEE is largest professional voluntary organization
  - Standards are written by volunteers
  - Standards are adopted by consensus
  - Standards are more like <u>'information'</u> and <u>'Education'</u>
  - Tables shows the comparison of IEEE standards with IEC standards
  - Different standards may differ in terminology or in concept

Table 3.4 Comparison of IEEE and IEC Power Quality Standards [2].

Disturbance	IEEE standard	IEC standard
Harmonic environment	None	IEC 1000-2-1/2
Compatibility limits	IEEE 519	IEC 1000-3-2/4 (555)
Harmonic measurement	None	IEC 1000-4-7/13/15
Harmonic practices	IEEE 519A	IEC 1000-5-5
Component heating	ANSI/IEEE C57.110	IEC 1000-3-6
Under-Sag-environment	IEEE 1250	IEC 38, 1000-2-4
Compatibility limits	IEEE P1346	IEC 1000-3-3/5 (555)
Sag measurement	None	IEC 1000-4-1/11
Sag mitigation	IEEE 446, 1100, 1159	IEC 1000-5-X
Fuse blowing/upsets	ANSI C84.1	IEC 1000-2-5
Oversurge environment	ANSI/IEEE C62.41	IEC-1000-3-7
Compatibility levels	None	IEC 3000-3-X
Surge measurement	ANSI/IEEE C62.45	IEC 1000-4-1/2/4/5/12
Surge protection	C62 series, 1100	IEC 1000-5-X
Insulation breakdown	By product	IEC 664

SOURCE: EPRI's PEAC Corp. (*Courtesy of EPRI's "Signature."*)

System Overvoltages

- System generated:
  i. Transient
  ii. Sustained

  This is caused by direct or indirect (intentional or unintentional) switching operations and faults, and the magnitude is related to the system voltages in most instances
- Atmospheric (lightning):

  The magnitude is substantially independent of the system voltage.
- Major topics covered:
  - Background and fundamental concepts
  - Capacitor switching transients
  - Traveling waves: Switching surges and lightning
  - Protection against transient over-voltages

Electrical Circuit Component Models

- Electrical Circuit Components
  - Representation and characteristics of the Electrical components:

Component	Voltage-Current relationship			Energy
	RMS	t-domain	s-domain	
Resistance: 	$V = I\,R$	$v(t) = i(t)\,R$	$v(s) = i(s)\,R$	dissipates $\int i^2 R\,dt$ or $\int \frac{v^2}{R}\,dt$
Inductance: 	$V = I(j\omega L)$	$v(t) = L\frac{di(t)}{dt}$	$v(s) = i(s)\,sL$	stores: $\frac{1}{2} L\, i^2$
Capacitance: 	$V = I\frac{1}{j\omega C}$	$i(t) = C\frac{dv(t)}{dt}$	$v(s) = i(s)\frac{1}{sC}$	stores: $\frac{1}{2} C V^2$

- These parameters may be lumped in many situations, but they might be required to be treated as distributed parameters in many other situations.

Key Useful Rules

- The current through the inductor cannot change suddenly.

$$v = L\frac{di}{dt} \qquad \Rightarrow \qquad \frac{di}{dt} = \frac{v}{L}$$

Therefore, sudden changes in *i* implies *v* must be <u>infinity</u> and this is not possible. Also, since Energy = ½ Li^2, sudden change in requires instantaneous change in energy (*is this possible?*).

- The voltage across a capacitor cannot change suddenly.

$$Q = Cv \quad \Rightarrow \quad \frac{dQ}{dt} = i = C\frac{dv}{dt} \quad \Rightarrow \quad \frac{dv}{dt} = \frac{i}{C}$$

Therefore, sudden changes in *v* implies *i* must be <u>infinity</u> and this is not possible. Also, since Energy = ½ Cv^2, sudden change in *v* requires instantaneous change in energy (*is this possible?*).

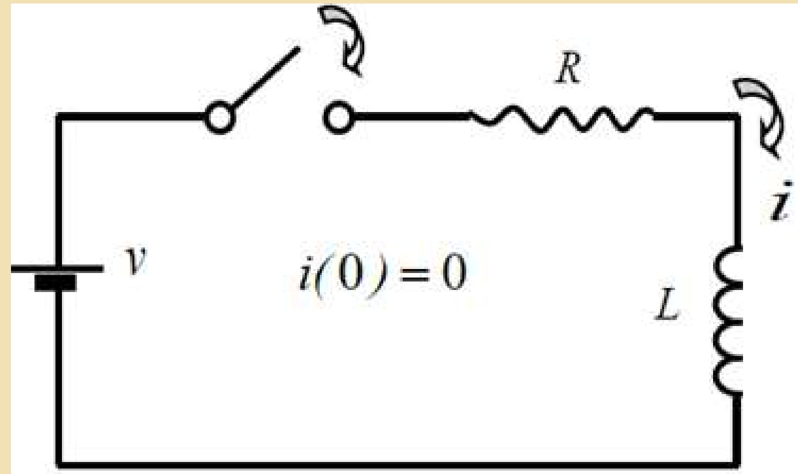
- *The Energy cannot change suddenly/instantaneously because redistribution of Energy following a <u>change</u> or <u>transient</u> in the system takes time and is governed by conservation of energy relationship.*

R-L Circuit: Energizing the field of a machine

- Using KVL rule, the voltage equation can be written as:

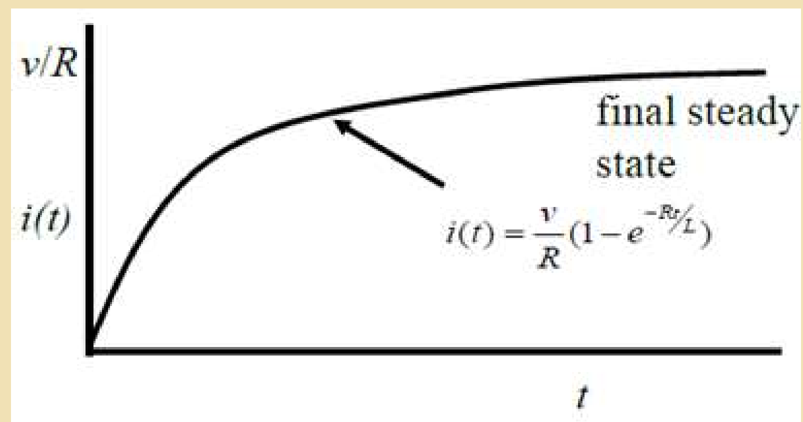
$$v = Ri + L\frac{di}{dt} \Rightarrow \frac{v}{s} = Ri(s) + sLi(s)$$

$$\Rightarrow i(s) = \frac{v}{s\left(s+\frac{R}{L}\right)L} = \frac{v}{R}\left[\frac{1}{s} - \frac{1}{s+\frac{R}{L}}\right]$$



- The current in time-doman can be obtained by taking inverse laplace:

$$i(t) = \frac{v}{R}\left[1 - e^{-\frac{R}{L}t}\right]$$



- Time Constant:
  - All RL circuits are associated with $e^{-\frac{t}{\tau}}. In\ this\ example\ e^{-\frac{t}{\tau}t} = e^{-\frac{R}{L}t}$.
  - $\tau = L/R$ is the time constant and it has the dimension of time
  - τ provides the rate of response of the system.

R-L Circuit: Voltage build-up

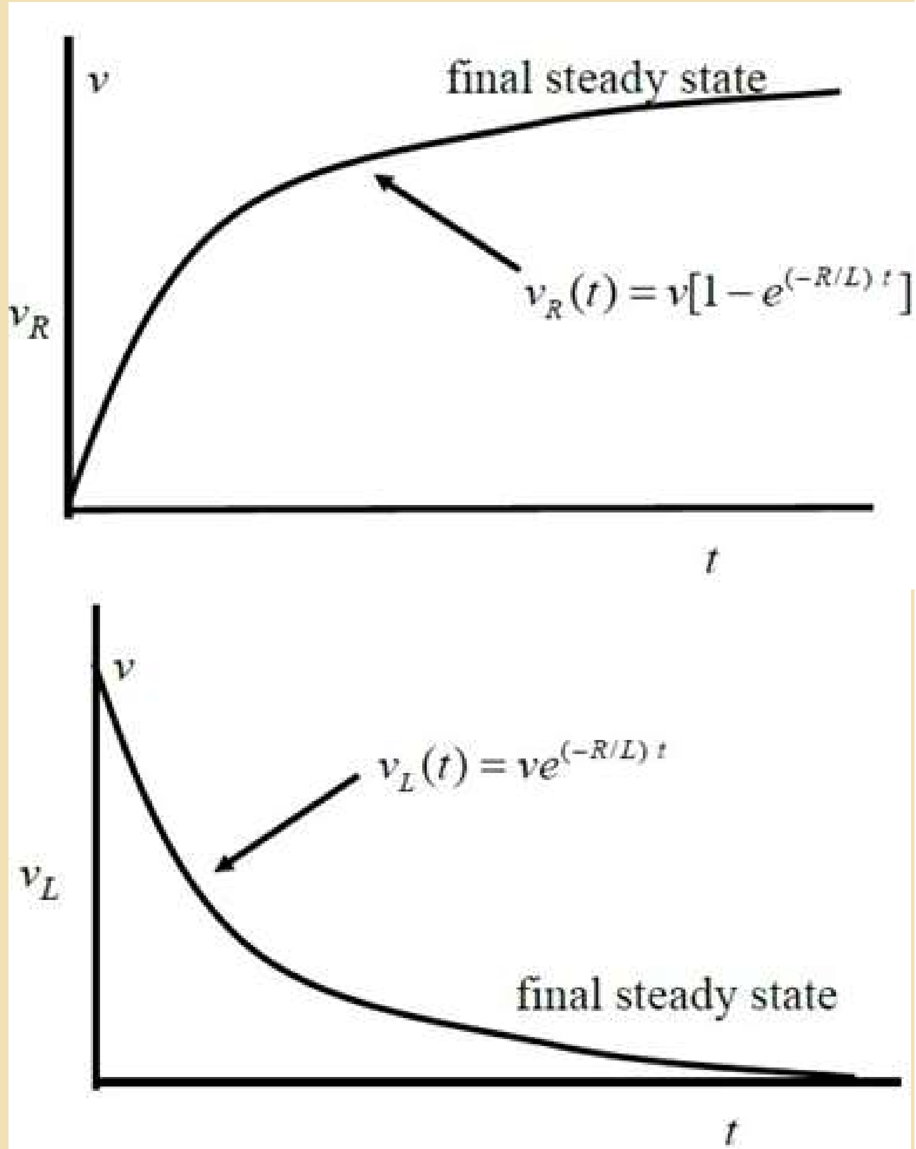
- Voltage across the resistor:

$$v_R(t) = iR = v\left[1 - e^{-\frac{R}{L}t}\right]$$

- Voltage across the inductor:

$$v_L(t) = v - v_R = ve^{-\frac{R}{L}t}$$

- No overvoltage is created in the system.



Example

- If the field of the generator has an impedance of:

  R+jωL and R=1.5Ω   and L = 400mH

  $\tau = \frac{L}{R} = \frac{04}{1.5} = 0.267s$

- If the exciter input voltage is 300V, the steady state value of the field current is: 300/1.5=200A

- Exercise:
  a) Determine how long does it take for the current to reach 99.5% of the final steady state value.
  b) Analyse a series RC circuit and investigate the behaviour of transient voltage created in RC circuit switching.
  c) Get familiar with application of differential equations and application of Laplace Transforms to circuit analysis.

Effects of Load Behavior on Voltage Magnitude

- Behaviour of the Load is very important.

  For example, starting of a motor draws very high current which can have significant impact on the load terminal voltages.

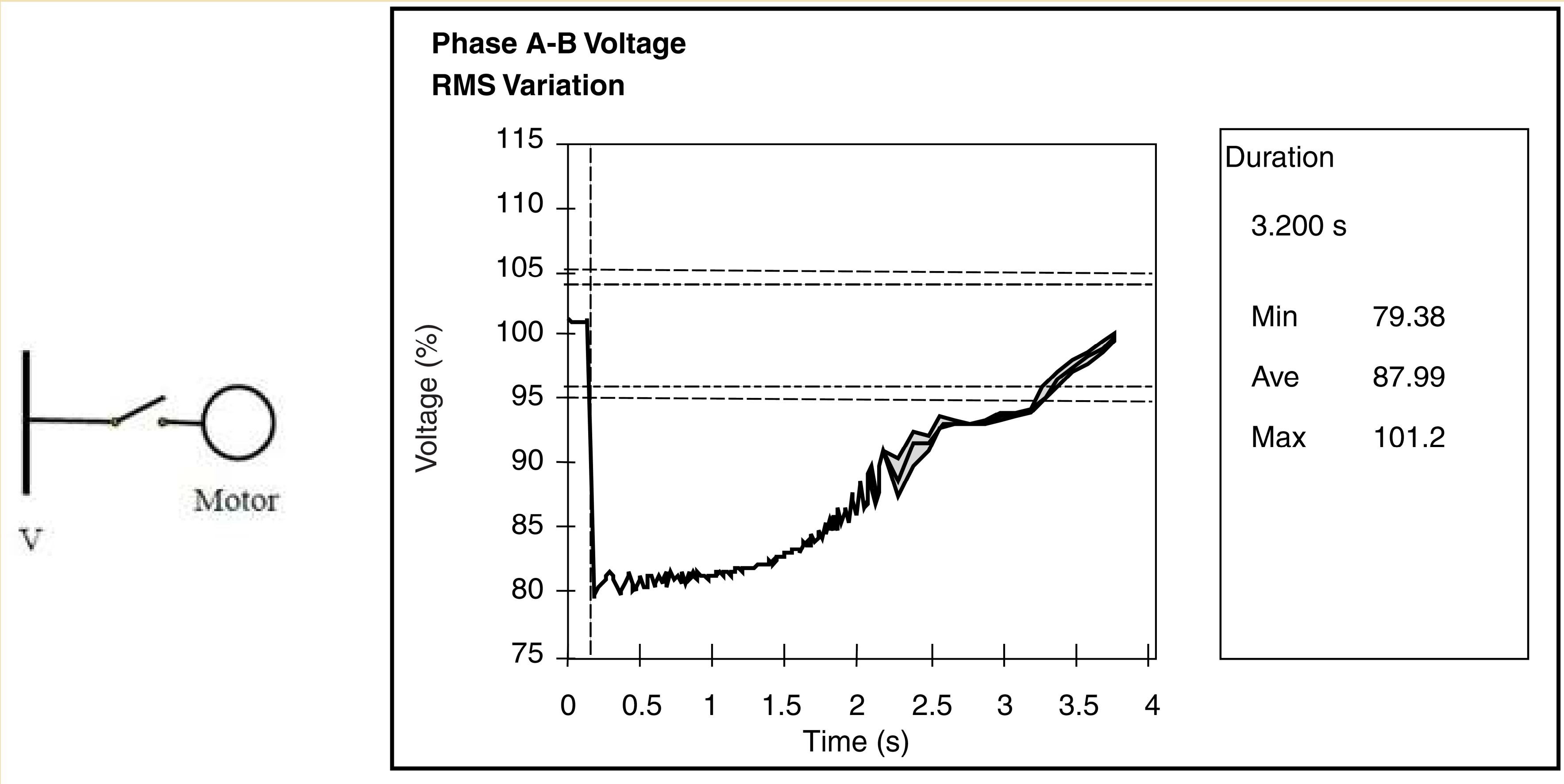
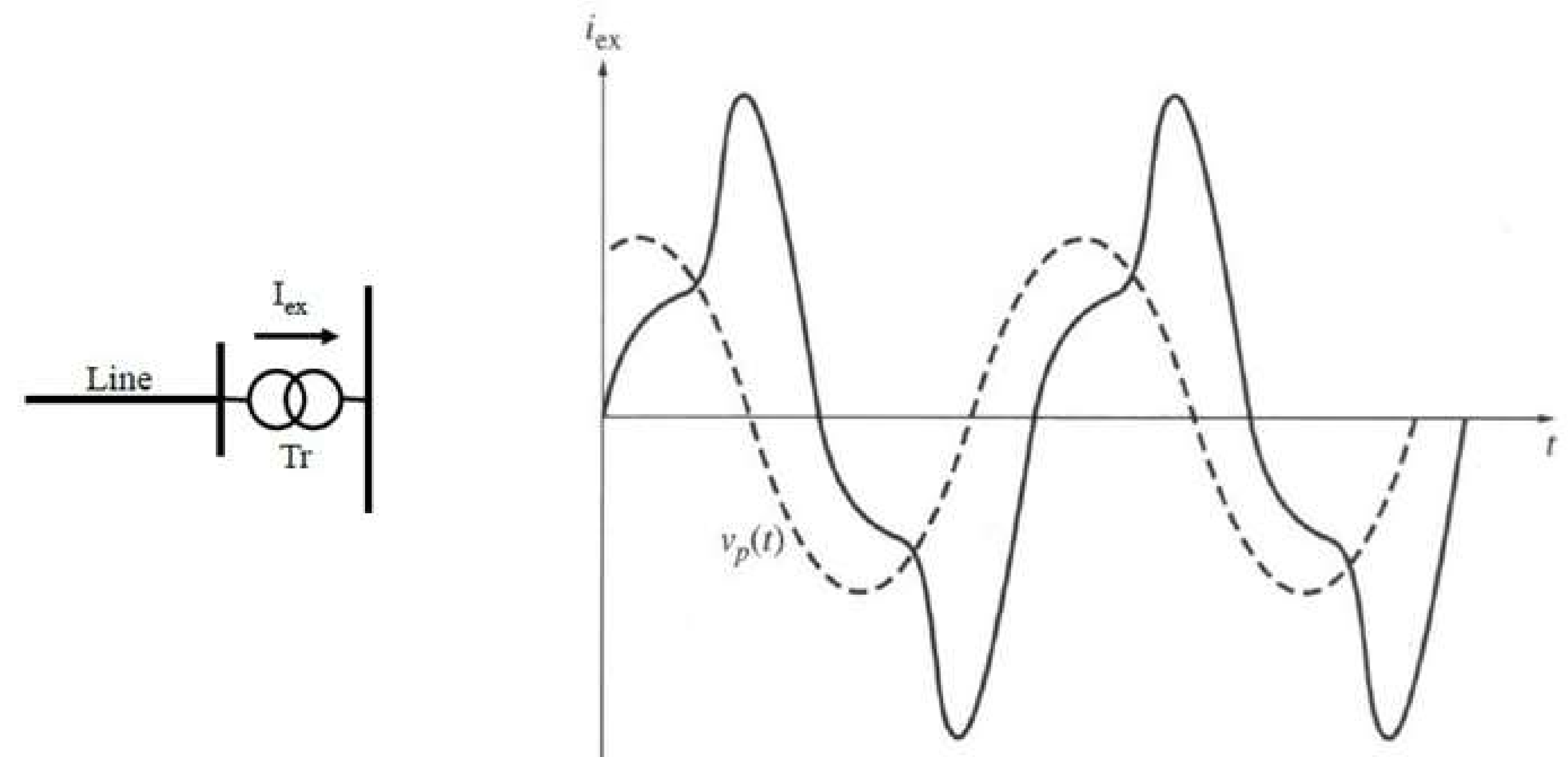


Figure 2.7: Temporary voltage sag caused by motor starting [1].

Effects of Load Behavior on Voltage Waveshapes

- Transformers draw magnetizing current, which is non sinusoidal in nature.
- Although the magnitude is relatively small, it will affect the whole region covered by the transformer.



The total excitation current in a transformer.

Effects of Load Behavior - Voltage Notching

- Many new generation power supplies commonly draw currents only during a small fraction of the cycle.
- This introduces voltage distortion called Notching.

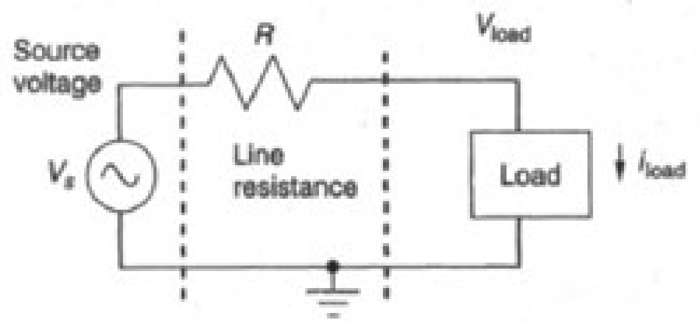


Figure 2.36 A simple circuit to illustrate voltage notching.

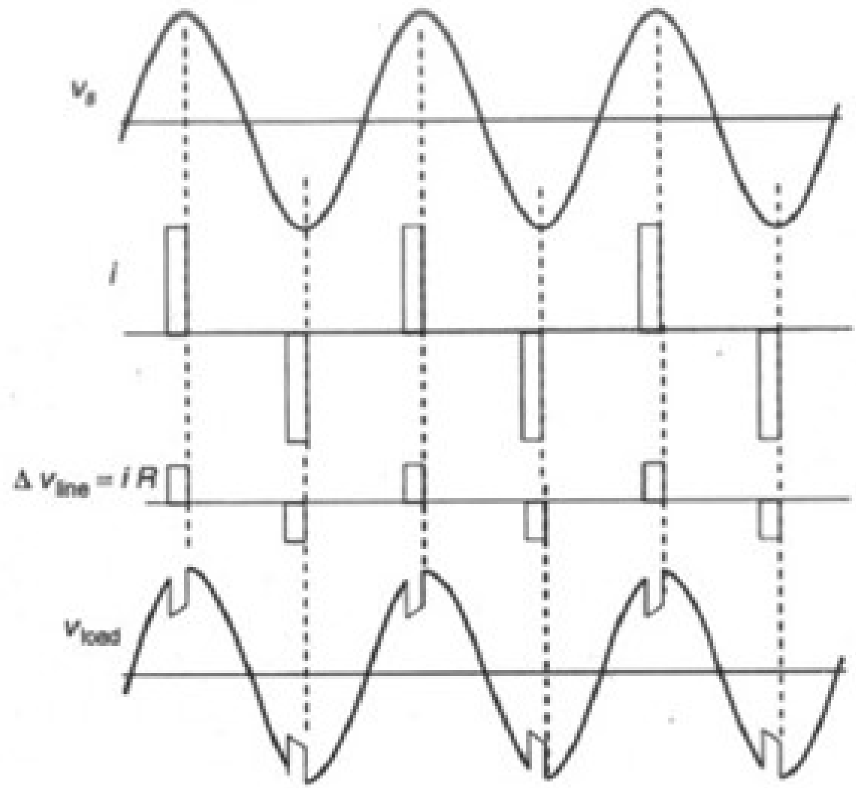


Figure 2.37 Source voltage, line current, voltage drop across the line, and resulting notched voltage to the load.

Basic Important Laplace Transforms

$f(t)$	F(s)
$u(t)$	$\frac{1}{s}$
t^n	$\frac{n!}{s^{n+1}}$
e^{-at}	$\frac{1}{s+a}$
$Sin\ \omega t$	$\frac{\omega}{s^2+\omega^2}$
$Cos\ \ \omega t$	$\frac{s}{s^2+\omega^2}$
$\frac{df}{dt}$ or $f\,'(t)$	$s\,F(s) - f(0)$
$\frac{d^2 f}{dt^2}$ or $f\,''(t)$	$s^2\,F(s) - s\,f(0) - f'(0)$
$\frac{d^n f}{dt^n}$ or $f^n(t)$	$s^n\,F(s) - s^{n-1}\,f(0) - \ldots - f^{(n-1)}(0)$
$\int_0^t f(\tau)\,d\tau$	$\frac{F(s)}{s}$