EE811PE POWER QUALITY AND FACTS (PE - V)

B.TECH. IV YEAR II SEM

L T P C

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- **Prerequisite:**
- Power Electronics, Power System Operation and Control, HVDC Transmission
- **Course Objectives:**
- Definition of power quality and different terms of power quality.
- Study of voltage power quality issue – short and long interruption.
- Detail study of characterization of voltage sag magnitude and three phase unbalanced voltage sag.
- Know the behaviour of power electronics loads; induction motors, synchronous motor etc by the power quality issues.
- Overview of mitigation of power quality issues by the VSI converters.
- To understand the fundamentals of FACTS Controllers,
- To know the importance of controllable parameters and types of FACTS controllers & their benefits
- To understand the objectives of Shunt and Series compensation
- To Control STATCOM and SVC and their comparison and the regulation of STATCOM,
- Functioning and control of GCSC, TSSC and TCSC

COURSE OUTCOMES:

- ✓ After completion of this course, the student will be able to:
- ✓ Know the severity of power quality problems in distribution system
- ✓ Understand the concept of voltage sag transformation from up-stream (higher voltages) to down-stream (lower voltage)
- ✓ Concept of improving the power quality to sensitive load by various mitigating custom power devices
- ✓ Choose proper controller for the specific application based on system requirements
- ✓ Understand various systems thoroughly and their requirements
- ✓ Understand the control circuits of Shunt Controllers SVC & STATCOM for various functions viz.
- ✓ Transient stability Enhancement, voltage instability prevention and power oscillation damping
- ✓ Understand the Power and control circuits of Series Controllers GCSC, TSSC and TCSC

UNIT - I
POWER QUALITY PROBLEMS IN DISTRIBUTION SYSTEMS

Power Quality problems in distribution systems:

Transient and Steady state variations in voltage and frequency. Unbalance, Sags, Swells, Interruptions,

Wave-form Distortions: harmonics, noise, notching, dc-offsets, fluctuations. Flicker and its

measurement.

UNIT- II
TRANSMISSION LINES AND SERIES/SHUNT REACTIVE POWER COMPENSATION:

- **Basics of AC Transmission. Analysis of uncompensated AC transmission lines. Passive Reactive Power Compensation. Shunt and series compensation at the mid-point of an AC line. Comparison of Series and Shunt Compensation.**

UNIT- III
STATIC SHUNT COMPENSATORS:

- Objectives of shunt compensation, Methods of controllable VAR generation, Static Var Compensator, its characteristics, TCR, TSC, FC-TCR configurations, STATCOM, basic operating principle, control approaches and characteristics

UNIT- IV
STATIC SERIES COMPENSATORS:

- Objectives of series compensator, variable impedance type of series compensators, TCSC, TSSC-operating principles and control schemes, SSSC, Power Angle characteristics, Control range and VAR rating, Capability to provide reactive power compensation, external control

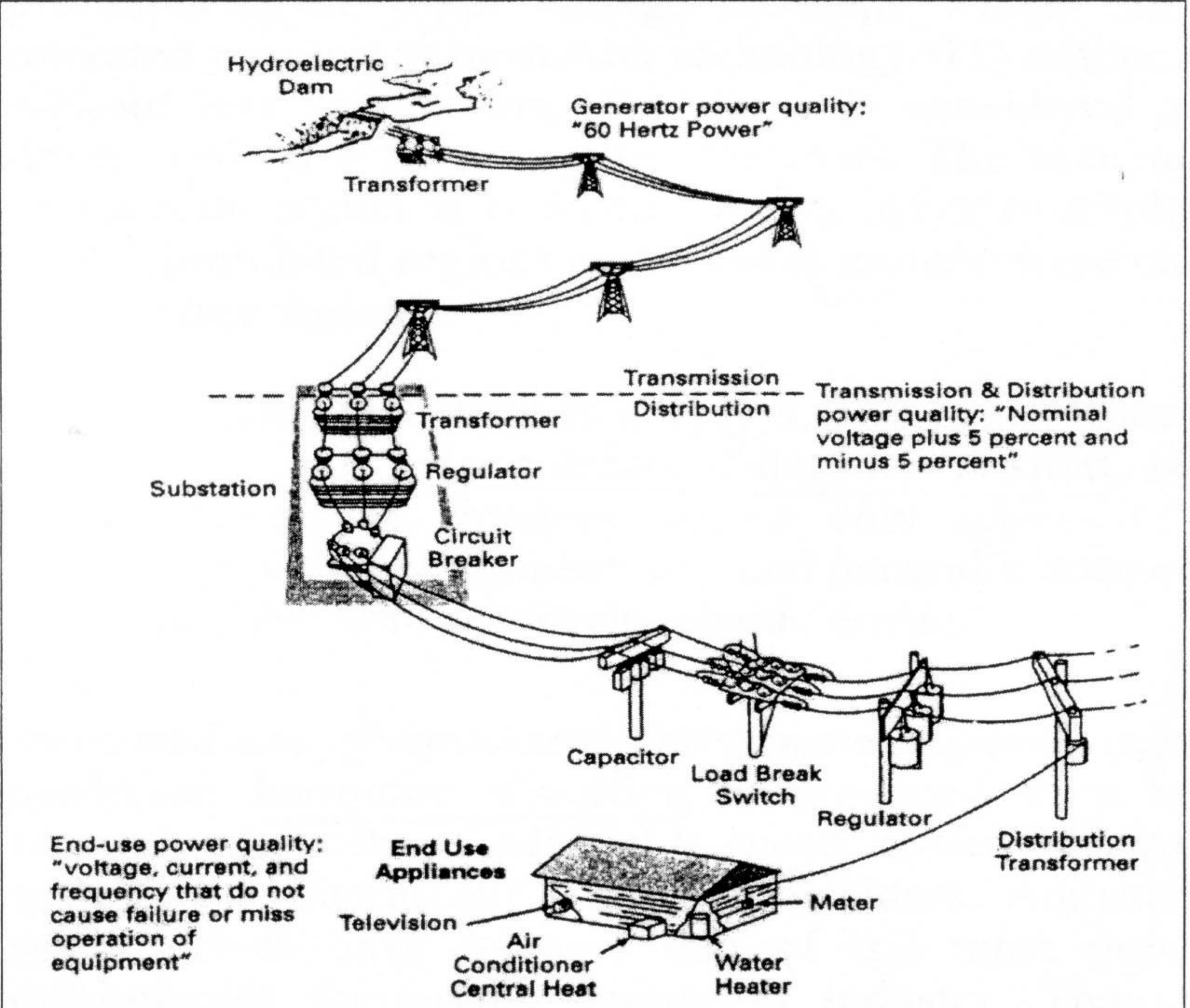
UNIT-V:
COMBINED COMPENSATORS:

- **Introduction to Unified Power Flow Controller, Basic operating principles, Conventional control capabilities, Independent control of real and reactive power.**

- **TEXT BOOKS:**
- 1. Electrical Power Systems Quality, Dugan Roger C, Santoso Surya, Mc Granaghan, Marks F.
- Beaty and H. Wayre, Mc Graw Hill
- 2. Power Systems Quality Assessment, J. Arillaga, N.R. Watson, S.Clon, John Wiley.
- **REFERENCE BOOKS:**
- 1. Power Quality, C.Sankaran, CRC Press 4. Understanding power quality problems, Math H.
- Bollen, IEEE press.
- 2. “Understanding FACTS –Concepts and Technology of Flexible AC Transmission Systems” Narain G.Honorani, Laszlo Gyugyi

AN INTRODUCTION..POWER QUALITY

- Aim of electric power system: to generate electrical energy and to deliver this energy to end-user equipment at an acceptable voltage.
- Power quality becoming important to electricity consumers at all levels of usage.
- The end-users are now more concerned to protect their sensitive loads from power quality disturbances by installing protection equipment.

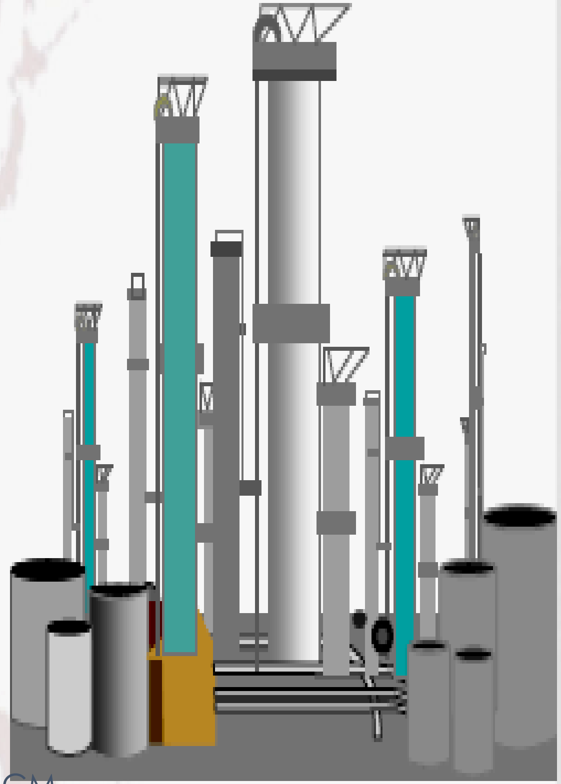


Hydroelectric Dam
Generator power quality: "60 Hertz Power"
Transformer
Transmission
Distribution
Transmission & Distribution power quality: "Nominal voltage plus 5 percent and minus 5 percent"
Transformer
Regulator
Substation
Circuit Breaker
Capacitor
Load Break Switch
Regulator
Distribution Transformer
End-use power quality: "voltage, current, and frequency that do not cause failure or miss operation of equipment"
End Use Appliances
Television
Air Conditioner Central Heat
Water Heater
Meter

Sources Of Power Problems

Referenced at the utility PCC (point of common coupling)

- **Utility**
  - lightning, PF correction caps, faults, switching
  - impact from other customers
- **Internal to the facility**
  - individual load characteristics, motors, ASDs
  - computers, microprocessors
  - wiring
  - changing loads



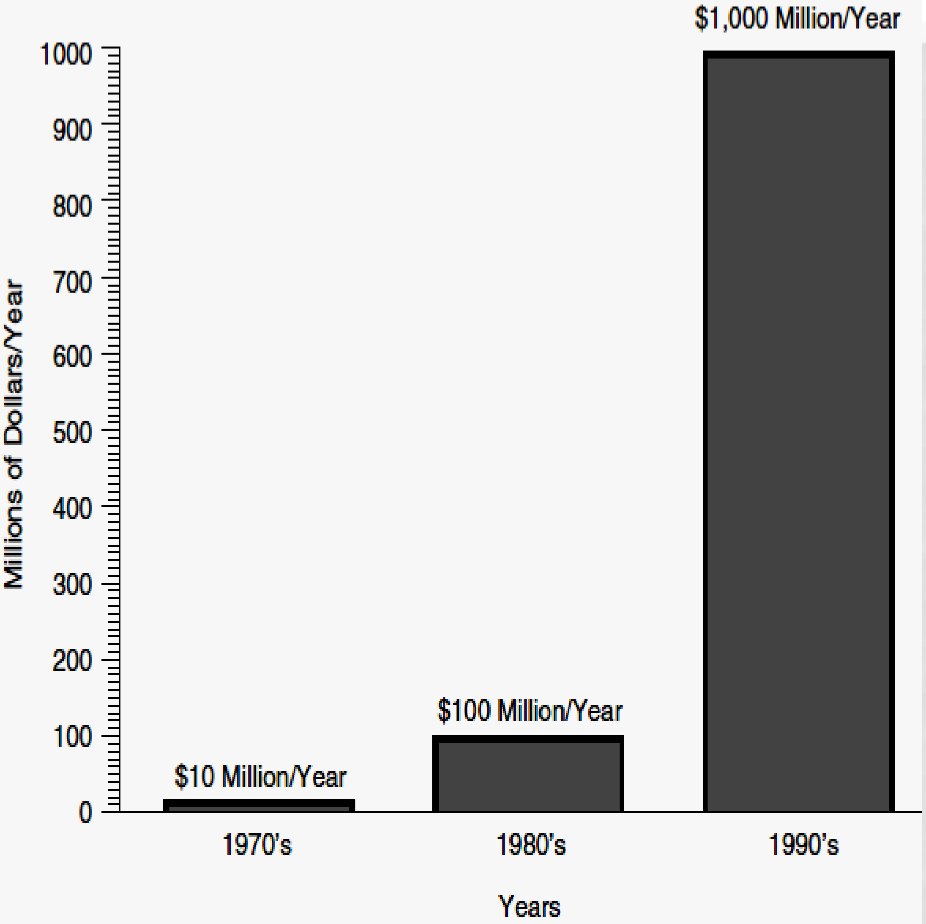
Typically, 70% of all PQ events are generated within the facility

THE COST OF POOR POWER QUALITY

Who cares?

- $100+ billion in losses per year
  - Just in the U.S.
- Financial impact
  - Scrap, equipment damage, etc.
- Operational impact
  - Downtime, critical shipments, etc.

Power Quality = Financial Problem



- *In a ten-month period 858 disturbances were logged with a financial loss totaling 600,000 European dollar.(measured voltage disturbances at 12 sites with demand between 5 and 30 MVA)*

Industry	Typical financial loss per event	
Semiconductor production	€3 800 000	
Financial trading	€6 000 000	per hour
Computer centre	€750 000	
Telecommunications	€30 000	per minute
Steel works	€350 000	
Glass industry	€250 000	

- For example, data processing equipment should tolerate an over-voltage of five times nominal supply for a duration of 100 μs **but only 20 % over-voltage for 10 ms.**
- On the under voltage side, a complete loss of supply should be tolerated for up to 20 ms (one mains cycle) but for 100 ms the minimum retained voltage must be 70 % of nominal.

What does "Quality" mean?

- Absence of malfunctions or failures
- Depends on point of view
  - Utility has one view
  - Customer may have another view

Quality = Proper Equipment Operation & Longevity

POWER QUALITY- DEFINITION

- **Definition of Power quality : any power problem manifested in voltage, current or frequency deviations that result in failure or mal-operation of customer equipment.**
- In most cases, ***power quality is the quality of the voltage that is being addressed***.
- WHY? This is because the supply system can only control the quality of voltage; it has no control over the currents that some particular loads might draw. Thus, the standards in power quality area are devoted to maintaining supply voltage within certain limits.

From IEEE, power quality is

- "a concept of powering and grounding sensitive electronic equipment in a manner suitable for the equipment."

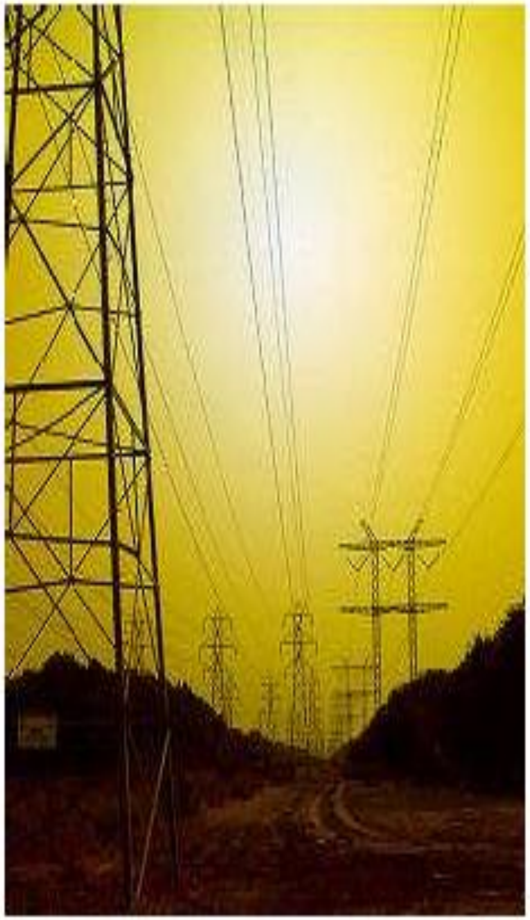
Another definition,

- "Power quality is a set of electrical boundaries that allows a piece of equipment to function in its intended manner **without significant loss of performance or life expectancy."**

Power =

Current, Time & Voltage

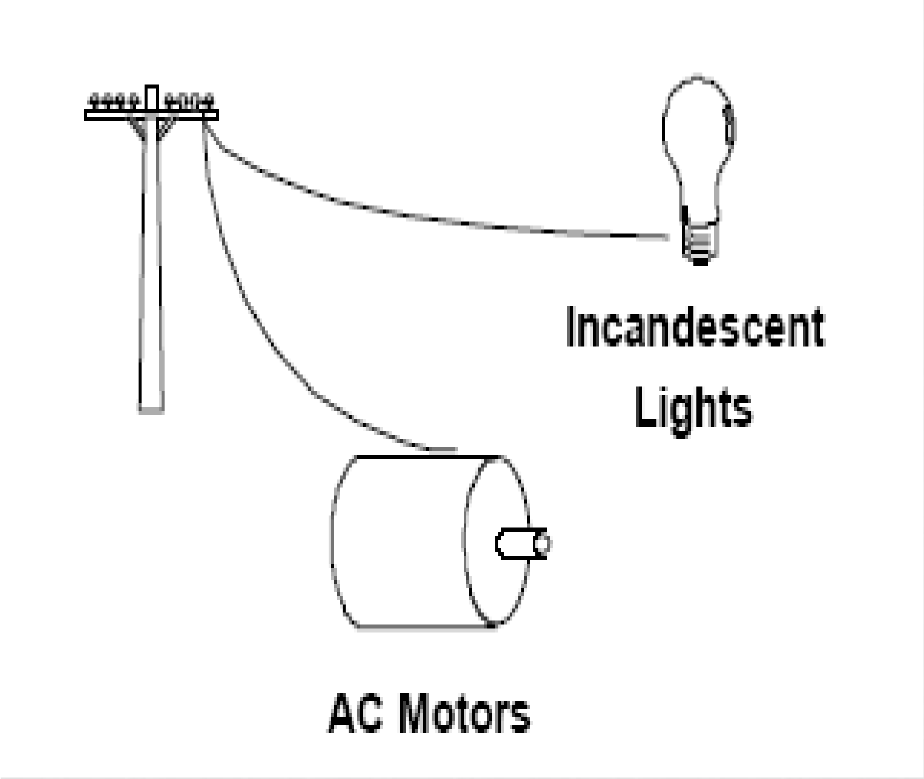
- Amps are governed by the load
- Time cannot be changed
- **Only voltage is controllable**



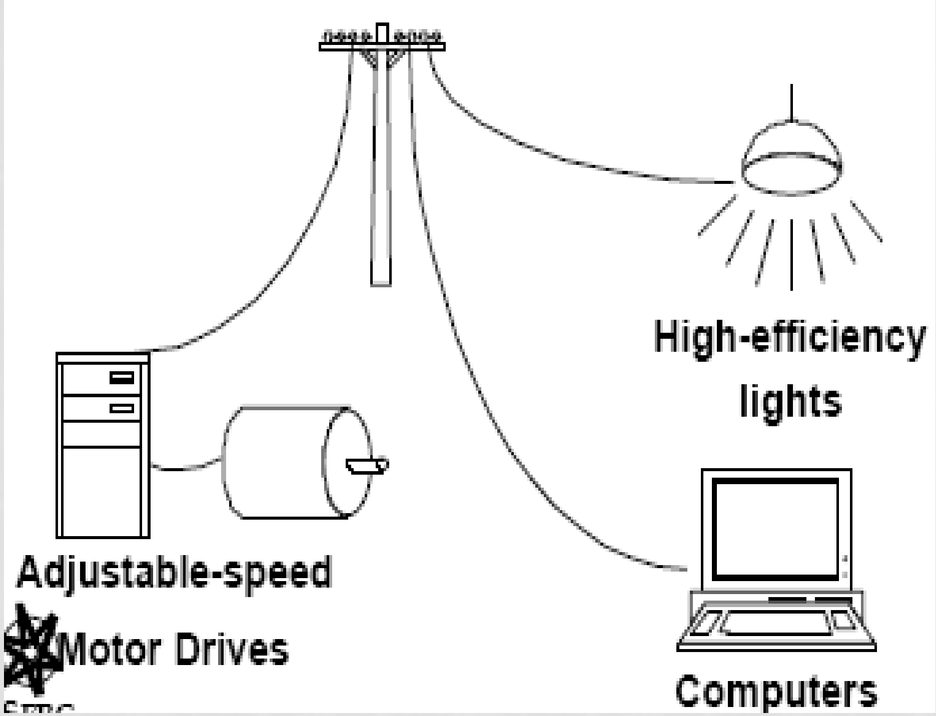
$$\boxed{\textbf{Power Quality = Voltage Quality}}$$

POWER QUALITY

Our Power Systems are designed for



Now the power system serves



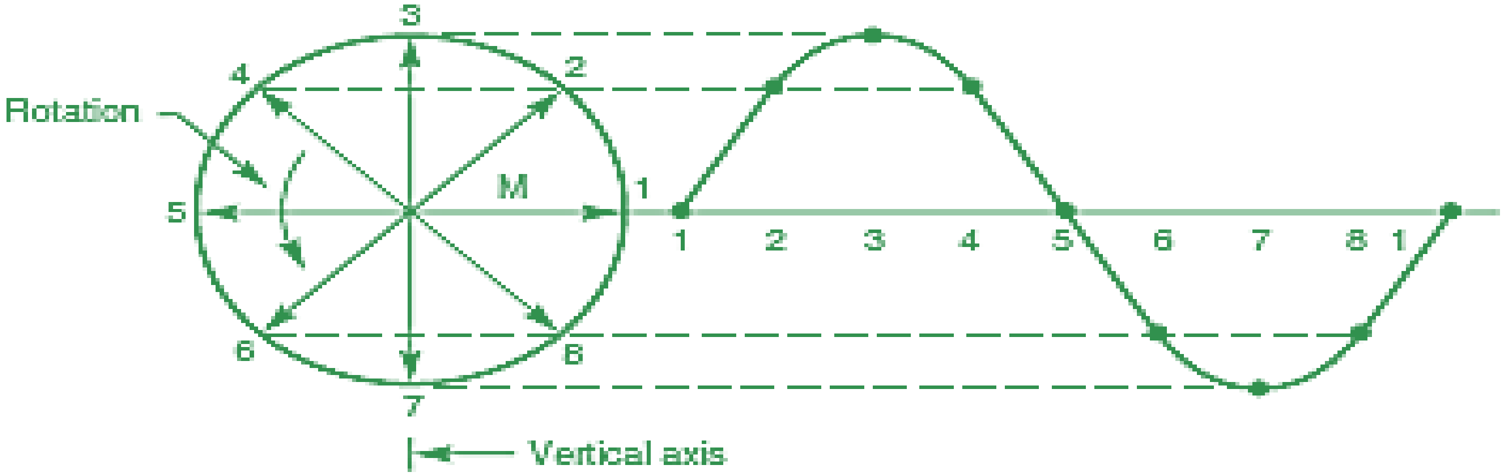
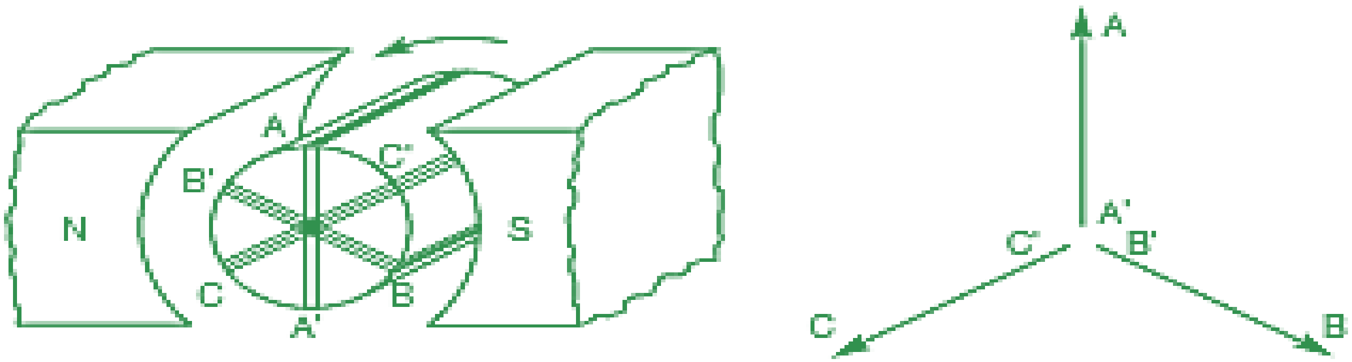
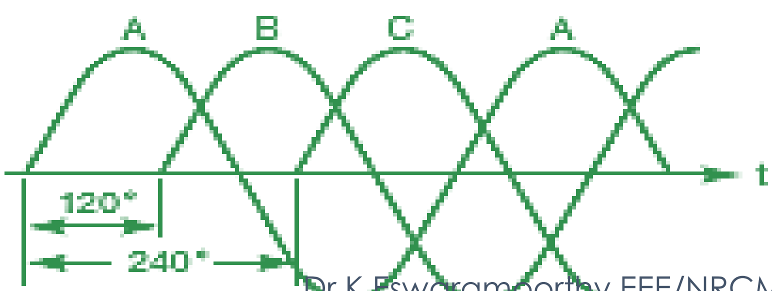


Figure 2.2 Sinusoidal wave derivation.

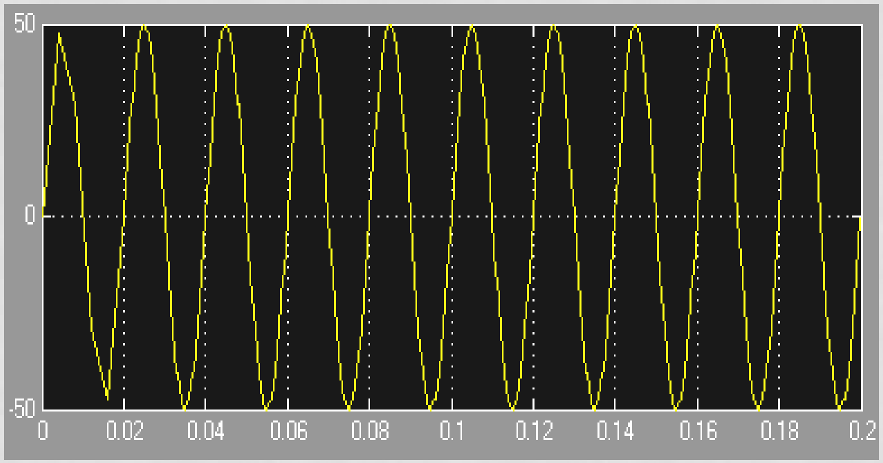


(a) (b)

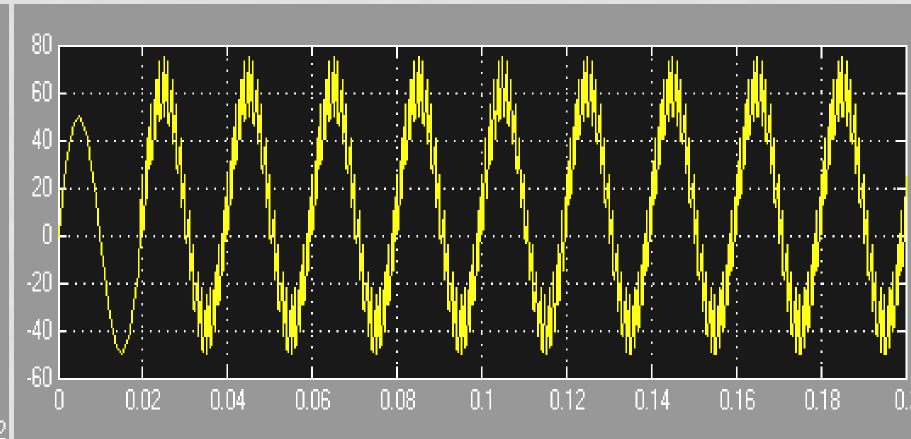


POWER QUALITY

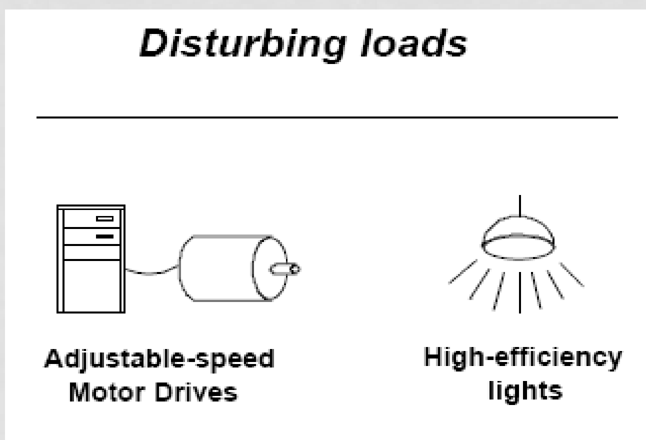
What do we need ?

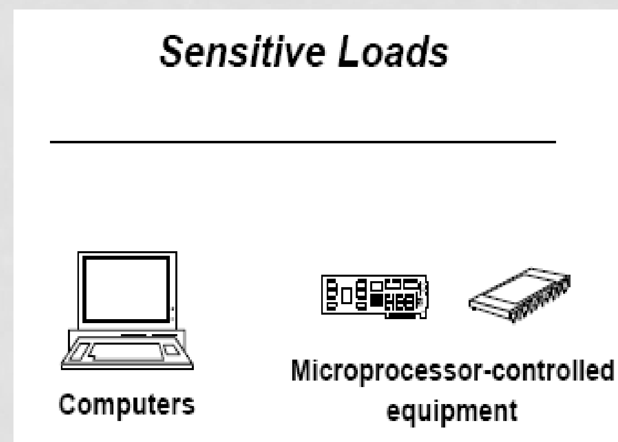


What do we have ?



Victims





GENERAL CLASSES OF POWER QUALITY PROBLEMS..

- 2 committees involved:
  - IEEE (Institute of Electrical and Electronic Engineers) www.ieee.org
  - IEC (International Electrotechnical Commission) www.iec.ch

CLASSIFICATION OF POWER QUALITY ISSUES

- The magnitude and duration of events can be used to classify power quality events.
- In the magnitude–duration plot, there are nine different parts.
- Various standards give different names to events in these parts. The voltage magnitude is split into three regions:
  - interruption: voltage magnitude is zero,
  - undervoltage: voltage magnitude is below its nominal value, and
  - overvoltage: voltage magnitude is above its nominal value.
- The duration of these events is split into four regions:
  - very short
  - Short
  - long
  - very long.

TYPES OF DISTURBANCES

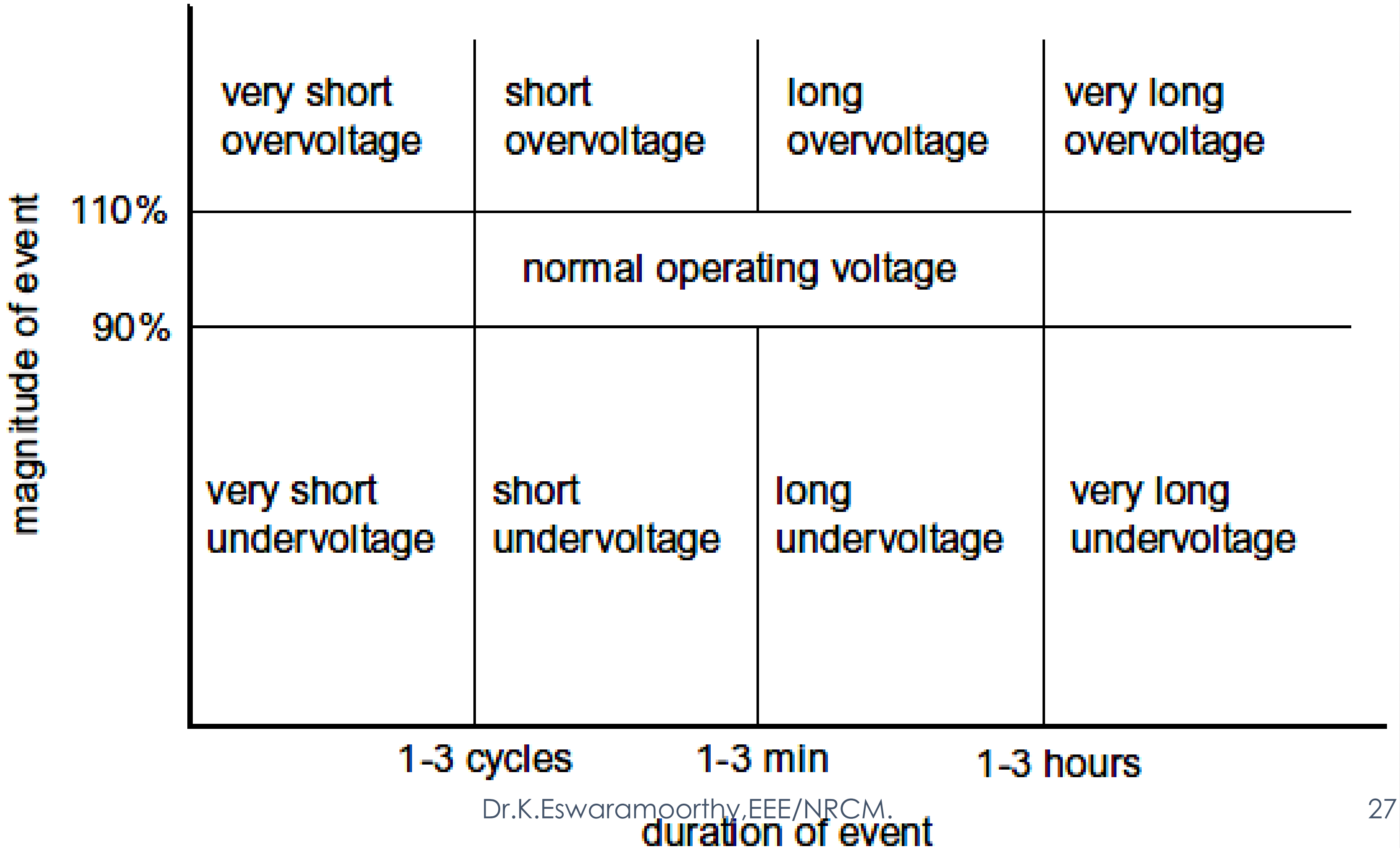
- There are two main classes of electric power quality disturbances:

1. steady-state disturbance - lasts for a long period of time (and is often periodic)
2. Transient - generally exists for a few milliseconds, and then decays to zero.

- Controversy surrounds which is more important, and a case could be made for either type of disturbance being more problematic as far as cost.
- The steady-state type of disturbance is generally less evident in its appearance, often at lower voltage and current levels, and less harmful to the operation of the system.
- Because steady-state phenomena last for a long period of time, the integrated effects of active power losses (low or high voltage) and inaccurate timing signals may be quite costly.
- Transient effects tend to be higher level in amplitude and are often quite apparent in harmful effects as well as occasionally spectacular in cost (e.g., causing loss of a manufactured product or
- causing long-term outages). The cost of transient power quality problems has been estimated in the 100 million to 3 billion dollar range annually in the United States. Table 10.2 lists some types of steady-state and transient power quality problems. The transient problems are often termed events.

Type	Problem	Appearance	Causes
Transient system problems	Impulses (surges, pulses)	High-voltage impulse for a short time, typically in the microsecond to 1 ms range	• Lightning • Switching surges • Rejection of inductive loads
	Momentary outages	Collapse of ac supply voltage for up to a few (e.g., 20) cycles	Circuit breaker operations
	Phase shift	Sinusoidal supply voltage proportional to a sine function whose phase angle suddenly shifts by an angle φ	Faults
	Sags (low voltage)	Momentary low voltage caused by faults in the supply	Faults
	Ringing	Damped sinusoidal voltages impressed on the ac wave	Capacitor switching
Steady-state system problems	Harmonics	Integer multiples of the ac supply frequency (e.g., 60 Hz) of (usually) lower amplitude signals impressed on the power frequency wave	• Nonlinear loads • Adjustable speed drives • Rectifiers • Inverters • Fluorescent lamps
	Voltage notches	Momentary low voltages of duration much shorter than one cycle caused by commutated loads	Adjustable speed drives
	Noise	Noise impressed on the power frequency	• Static discharge and corona • Arc furnaces
	Radio frequency	High-frequency (e.g., $f > 500$ kHz) sinusoidal signals of typically low amplitude impressed on the power frequency	Radio transmitters
	Interharmonics and fractional harmonics	Components of noninteger multiples of the power frequency	• Cycloconverters • Kramer drives • Certain types of adjustable speed drives

MAGNITUDE-DURATION PLOT FOR CLASSIFICATION OF POWER QUALITY EVENTS



MAIN PHENOMENA CAUSING ELECTROMAGNETIC AND POWER QUALITY DISTURBANCES

- The IEC classifies electromagnetic phenomena into the groups as given below.
- Conducted low-frequency phenomena
  - Harmonics, interharmonics
  - Signal systems (power line carrier)
  - Voltage fluctuations (flicker)
  - Voltage dips and interruptions
  - Voltage imbalance (unbalance)
  - Power frequency variations
  - Induced low-frequency voltages

- Radiated low-frequency phenomena
  - Magnetic fields
  - Electric fields
- Conducted high-frequency phenomena
  - Induced continuous wave (CW) voltages or currents
  - Unidirectional transients
  - Oscillatory transients
- Radiated high-frequency phenomena
  - Magnetic fields
  - Electric fields
  - Electromagnetic field
  - Steady-state waves
  - Transients
- Electrostatic discharge phenomena (ESD)
  - Nuclear electromagnetic pulse (NEMP)

TRANSIENTS

- Power system transients are undesirable, fast- and short-duration events that produce distortions.
- Their characteristics and waveforms depend on the mechanism of generation and the network parameters(e.g., resistance, inductance, and capacitance) at the point of interest.
- "Surge" is often considered synonymous with transient.
- Transients can be classified with their many characteristic components such as
  - **Amplitude,**
  - **duration,**
  - **rise time,**
  - **frequency of ringing polarity,**
  - **energy delivery capability,**
  - **amplitude spectral density,**
  - **and frequency of occurrence.**
- Transients are usually classified into two categories:
  - **impulsive**
  - **oscillatory**

- All the power quality issues are comprised into following categories
- **Transients**
- **Long-Duration Voltage Variations**
- **Short-Duration Voltage Variations**
- **Voltage Imbalance**
- **Waveform Distortion**
- **Voltage Fluctuation**
- **Power Frequency Variations**

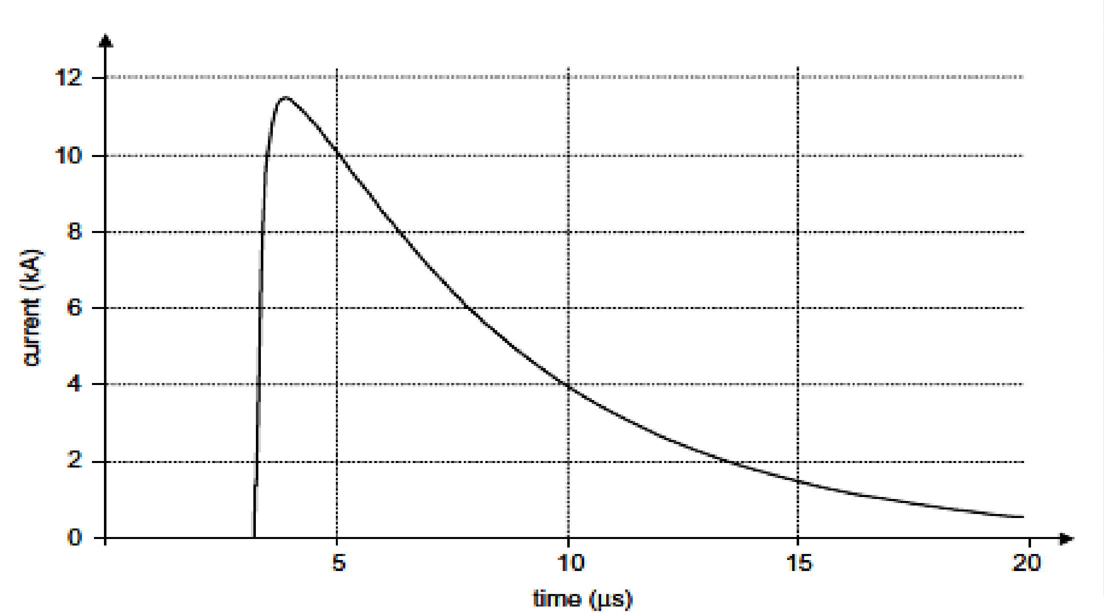
CATEGORIES AND CHARACTERISTICS OF ELECTROMAGNETIC PHENOMENA IN POWER SYSTEMS AS DEFINED BY IEEE-1159

Categories		Typical spectral content	Typical duration	Typical voltage magnitude
1. Transient				
	1.1. Impulsive			
	• nanosecond	5 ns rise	<50 ns	
	• microsecond	1 μs rise	50 ns–1 ms	
	• millisecond	0.1 ms rise	>1 ms	
	1.2. Oscillatory			
	• low frequency	<5 kHz	0.3–50 ms	0–4 pu
	• medium frequency	5–500 kHz	20 μs	0–8 pu
	• high frequency	0.5–5 MHz	5 μs	0–4 pu
2. Short-duration variation	2.1. Instantaneous			
	• interruption		0.5–30 cycles	<0.1 pu
	• sag		0.5–30 cycles	0.1–0.9 pu
	• swell		0.5–30 cycles	1.1–1.8 pu
	2.2. Momentary			
	• interruption		30 cycle–2 s	<0.1 pu
	• sag		30 cycles–3 s	0.1–0.9 pu
	• swell		30 cycles–3 s	1.1–1.4 pu
	2.3. Temporary			
	• interruption		2 s–2 min	<0.1 pu
	• sag		3 s–1 min	0.1–0.9 pu
	• swell		3 s–1 min	1.1–1.2 pu
3. Long-duration variation	3.1. Sustained interruption		>1 min	0.0 pu
	3.2. Undervoltage		>1 min	0.8–0.9 pu
	3.3. Overvoltage		>1 min	1.1–1.2 pu
4. Voltage imbalance			steady state	0.5–2%

Categories		Typical spectral content	Typical duration	Typical voltage magnitude
5. Waveform distortion	5.1. DC offset		steady state	0–0.1%
	5.2. Harmonics	0–100th	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. Voltage fluctuation		<25 Hz	intermittent	0.1–7%
7. Power frequency variations			<10 s	

IMPULSIVE TRANSIENT

- An impulsive transient is a sudden frequency change in the steady-state condition of voltage, current, or both that is unidirectional in polarity.
- The most common cause of impulsive transients is a lightning current surge.
- Impulsive transients can excite the natural frequency of the system.



OSCILLATORY TRANSIENT

- An oscillatory transient is a sudden frequency change in the steady-state condition of voltage, current, or both that includes both positive and negative polarity values.
- Oscillatory transients occur for different reasons in power systems such as appliance switching, capacitor bank switching, fast-acting overcurrent protective devices, and ferroresonance.
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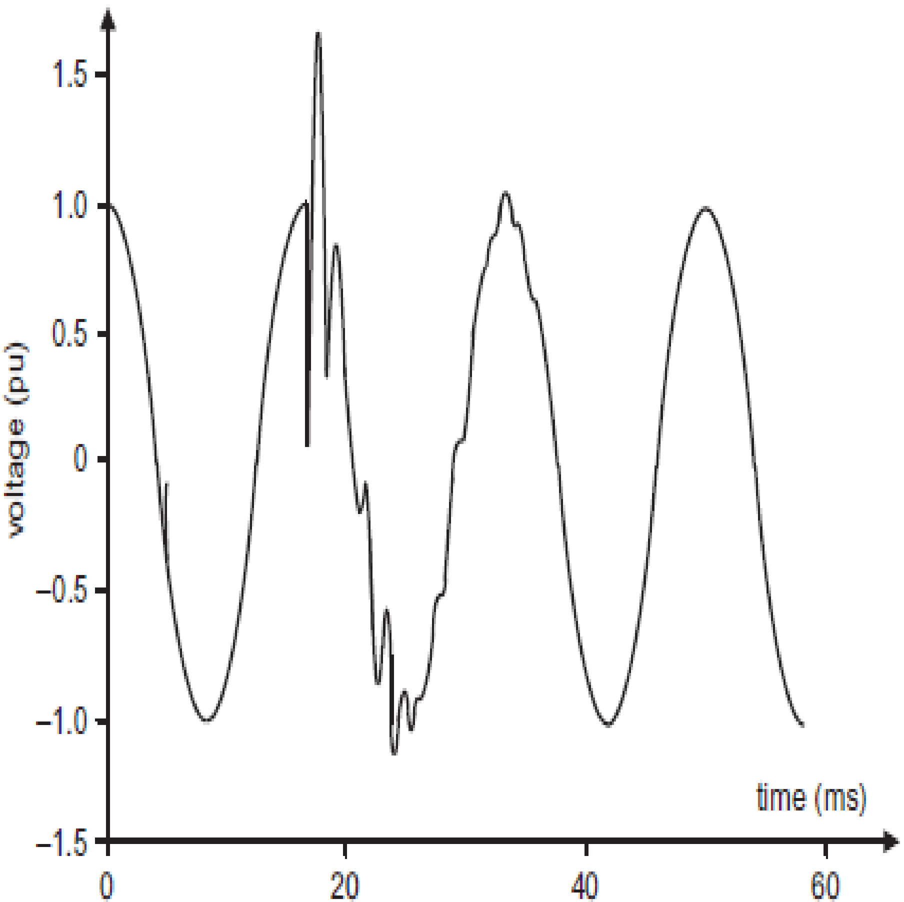
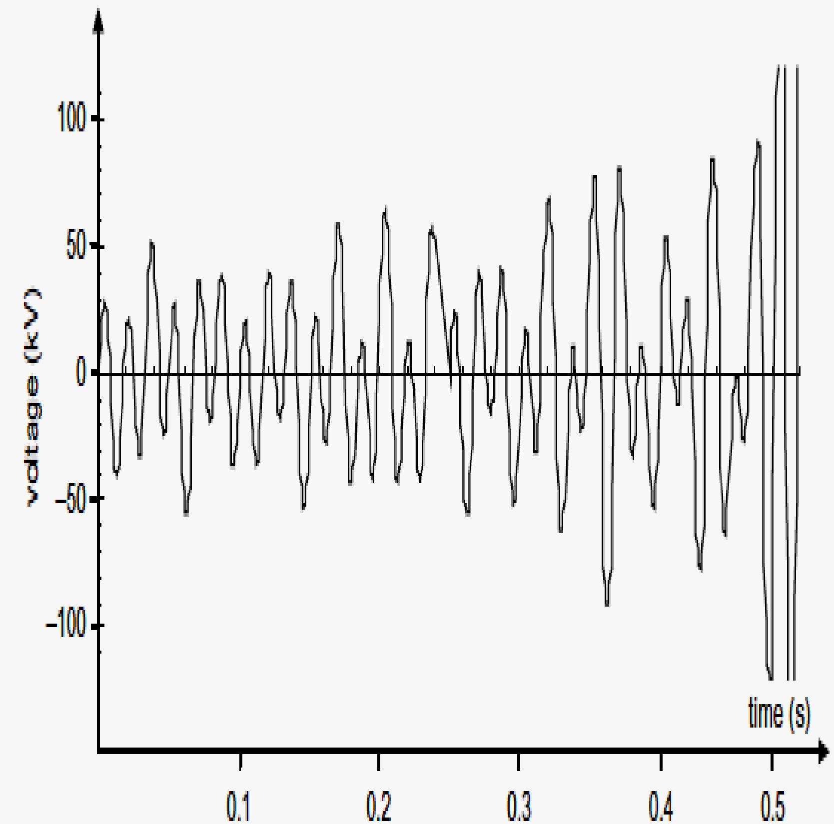
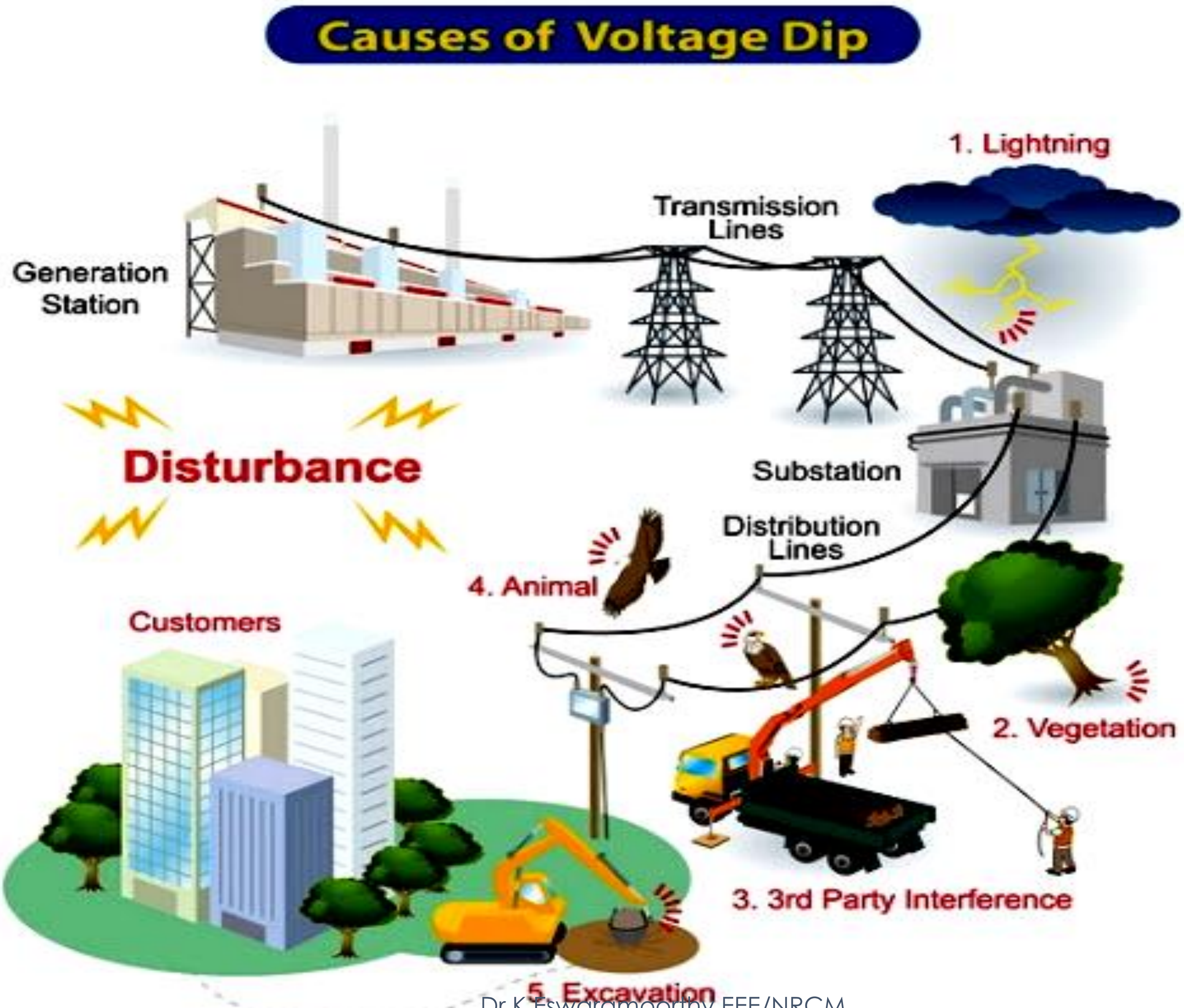
Low-frequency oscillatory transient caused by capacitor bank energization



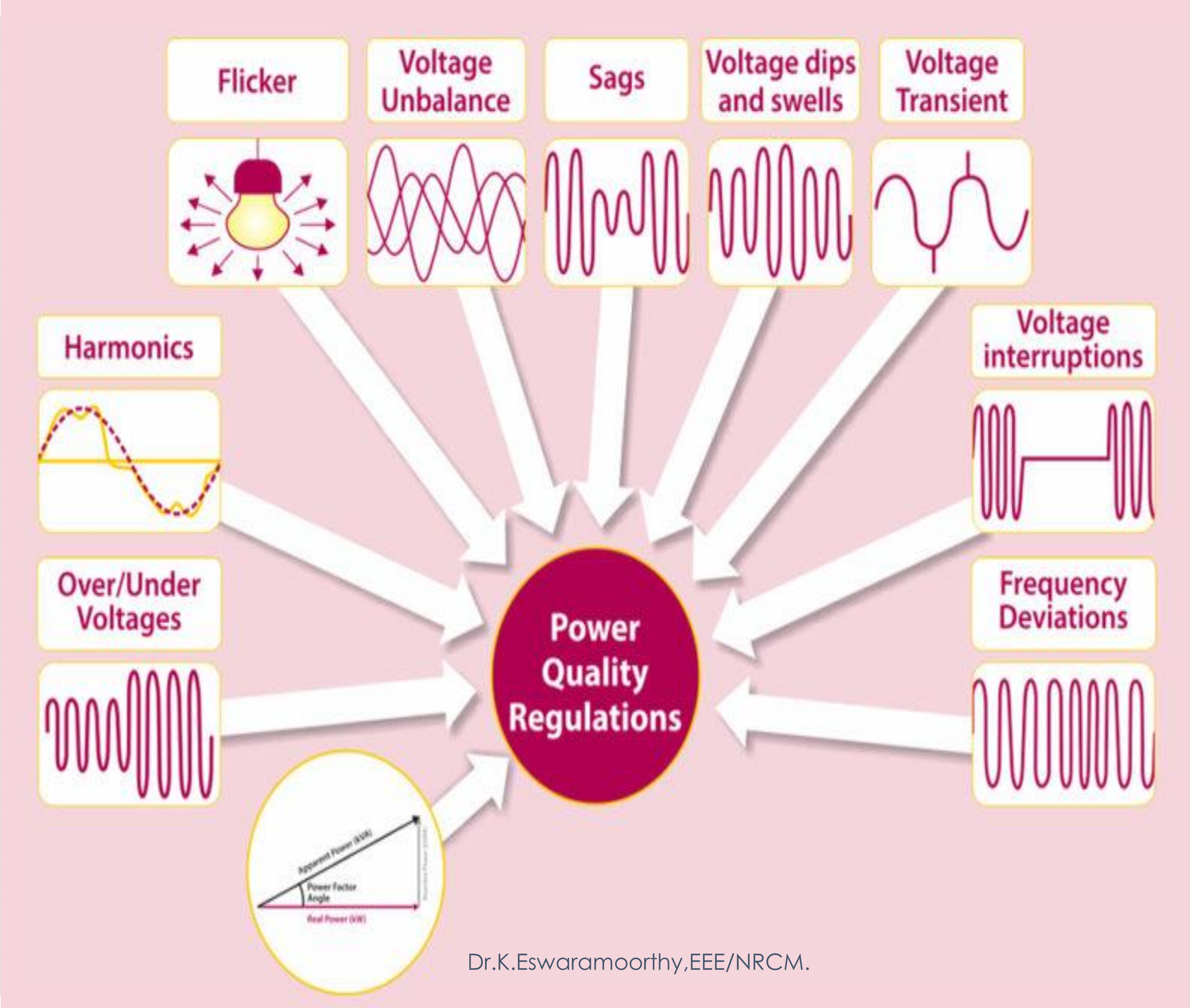
Low-frequency oscillatory transient caused by ferroresonance of a transformer at no load, result of Mathematica simulation



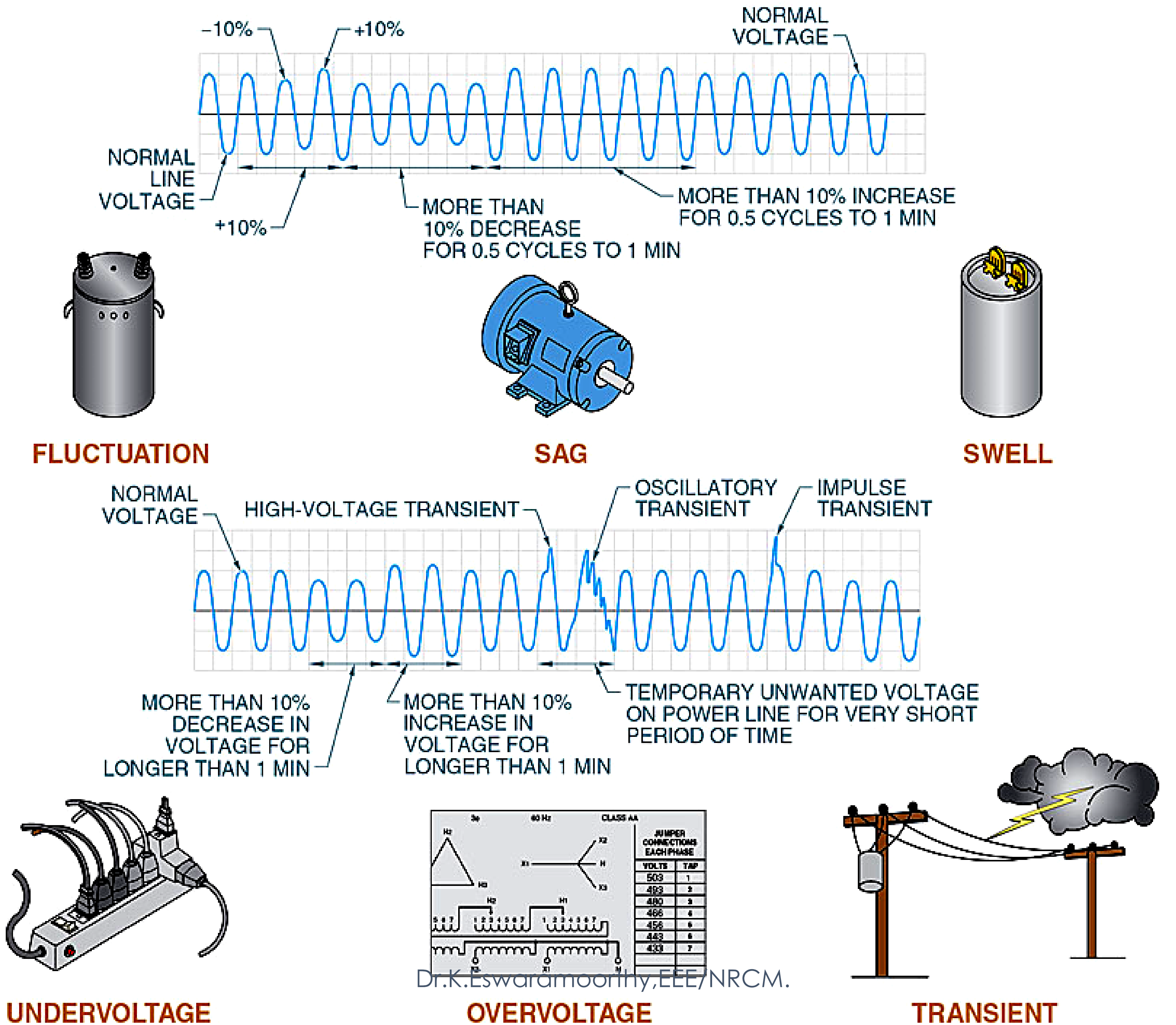

Causes of Voltage Dip
1. Lightning
Transmission Lines
Generation Station
Disturbance
Substation
Distribution Lines
4. Animal
Customers
2. Vegetation
3. 3rd Party Interference
5. Excavation

VOLTAGE POWER QUALITY PROBLEMS

- Voltage Sag
- Voltage Swell
- Voltage Interruption
- Under/ Over Voltage
- Voltage Flicker
- Harmonic Distortion
- Voltage Notching
- Transient Disturbance
- Outage and frequency variation

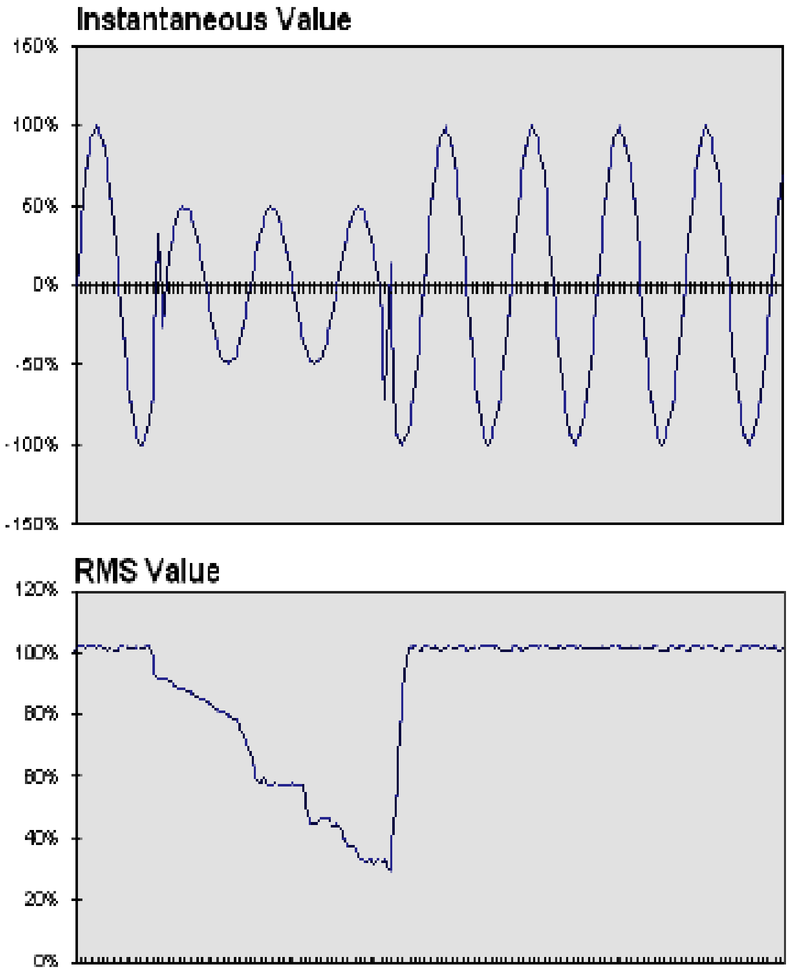

Flicker
Voltage Unbalance
Sags
Voltage dips and swells
Voltage Transient
Harmonics
Voltage interruptions
Over/Under Voltages
Frequency Deviations
Power Quality Regulations
Apparent Power (kVA)
Power Factor Angle
Real Power (kW)

VOLTAGE CHANGES



VOLTAGE SAG

A decrease of the normal voltage level between 10 and 90% of the nominal rms voltage at the power frequency, for durations of 0,5 cycle to 1 minute.



Causes:

- Faults on the transmission or distribution network.
- Faults in consumer's installation.
- Connection of heavy loads and start-up of large motors.

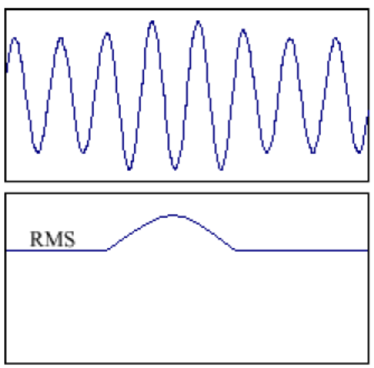
Consequences:

- Malfunction of microprocessor-based control systems (PCs, PLCs, ASDs, etc) that may lead to a process stoppage.
- Tripping of contactors and electromechanical relays.
- Disconnection and loss of efficiency in electric rotating machines.

VOLTAGE SWELLS

- An **increase in rms voltage in the range of 1.1 to 1.8 p.u.** for duration **from 0.5 cycles to 1 minute**. Also called *momentary overvoltage*. Caused by system faults, load switching and capacitor switching.

Momentary increase of the voltage, at the power frequency, outside the normal tolerances, with duration of more than one cycle and typically less than a few seconds.



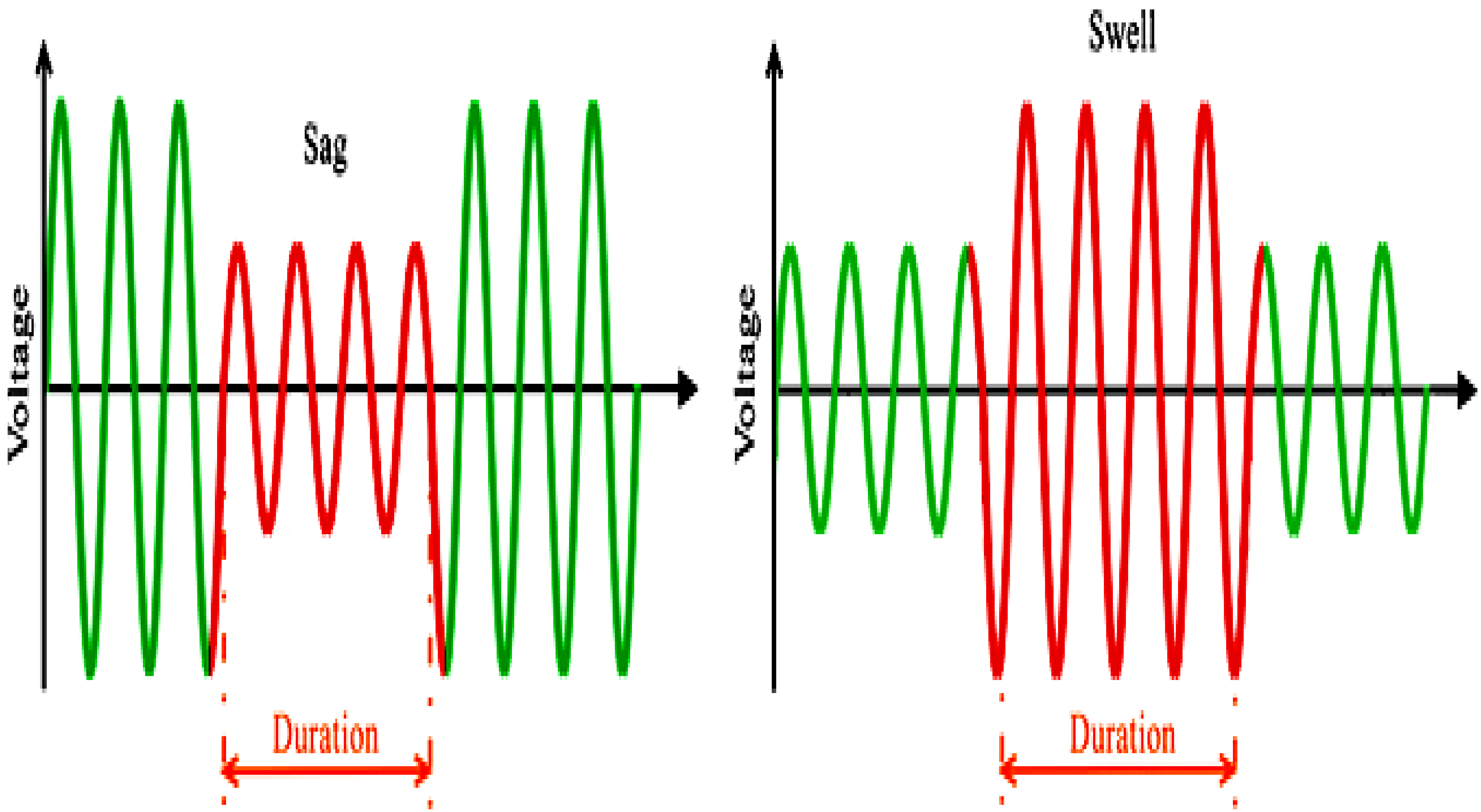
Causes:

- Start/stop of heavy loads.
- Poorly dimensioned power sources.
- Poorly regulated transformers.

Consequences:

- Flickering of lighting and screens.
- Damage or stoppage or damage of sensitive equipment.

Sags and Swells

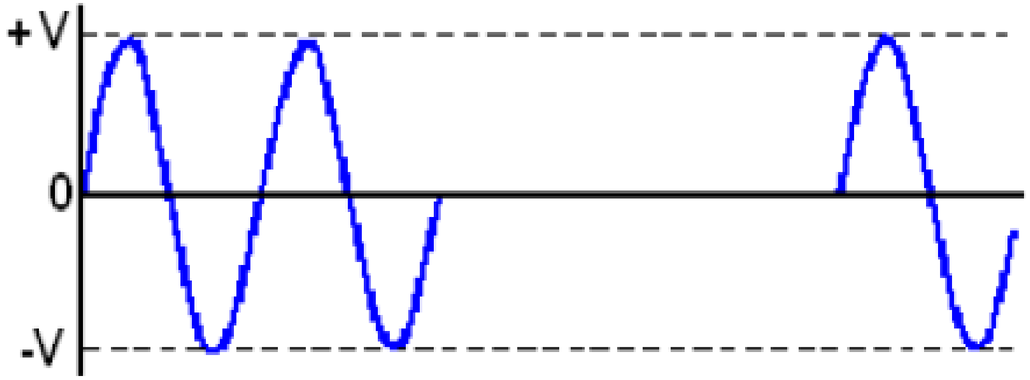


Occurs when the rms voltage decreases between 10% and 90% for a duration of a half-cycle to one minute.

Occurs when the rms voltage increases to over 110% for a duration of a half-cycle to one minute.

MICRO INTERRUPTIONS

Total interruption of electrical supply for duration from few milliseconds to one or two seconds.



Causes:

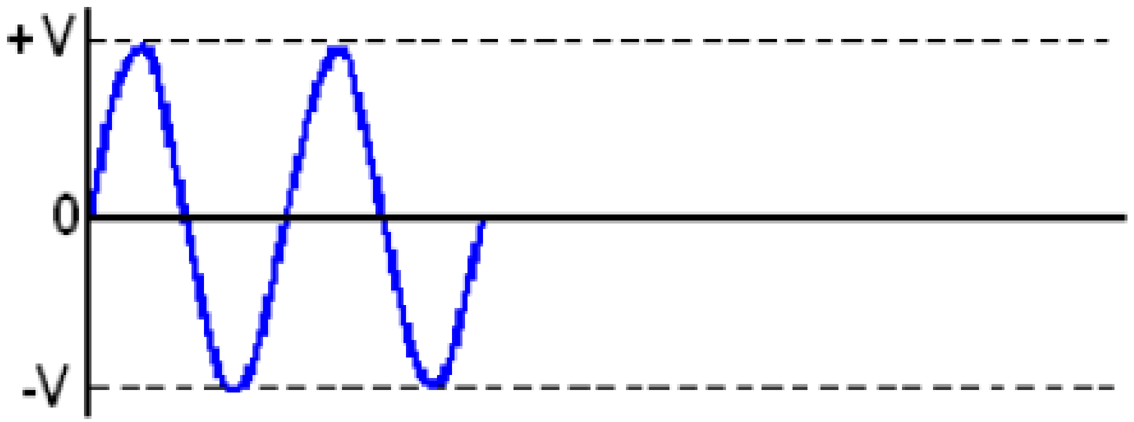
- Opening and automatic reclosure of protection devices.
- Insulation failure, lightning and insulator flashover.

Consequences:

- Tripping of protection devices.
- Loss of information and malfunction of data processing equipment.
- Stoppage of sensitive equipment (such as ASDs, PCs, PLCs).

LONG INTERRUPTIONS

Total interruption of electrical supply for duration greater than 1 to 2 seconds.



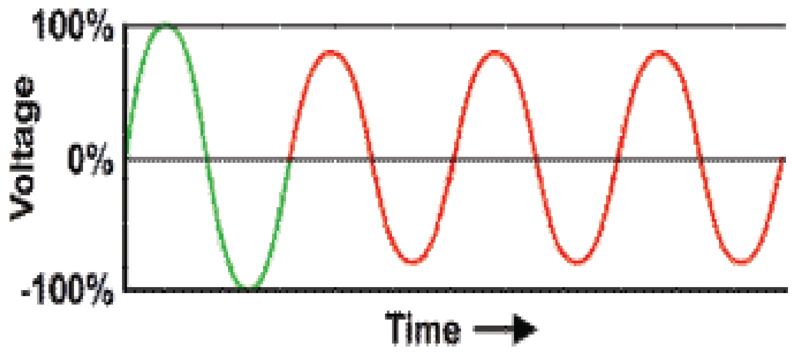
Causes:

- Equipment failure in the power system network.
- Storms and objects (trees, cars, etc) striking lines or poles, fire.
- Human error, bad coordination or failure of protection devices.

Consequences:

- Stoppage of all equipment.

UNDER VOLTAGE



Voltage 90% of nominal or less

Source: Utility or facility

Duration: > 1 minute

Incidence: Medium - high

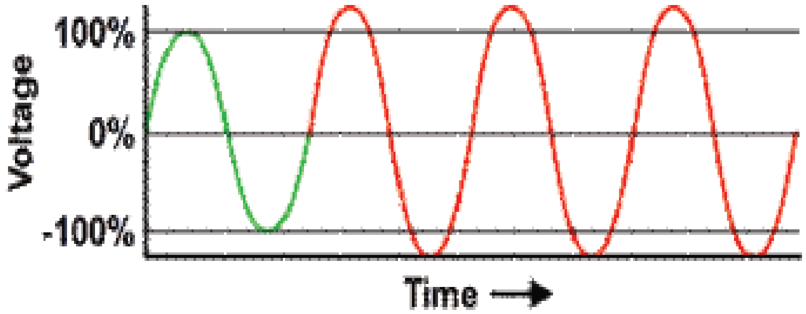
Symptoms: Malfunction or premature equipment failure

Protection: Voltage regulation

Undervoltage can result from low distribution voltage, high voltage drop, heavy loads, etc. Symptoms include premature failure and overheating of motors. May also increase sensitivity to voltage sags.

Causes Equipment Shut Down or Malfunction

OVER VOLTAGE



Voltage >110% above nominal

Source: Utility

Duration: > 1 minute

Incidence : Medium - high

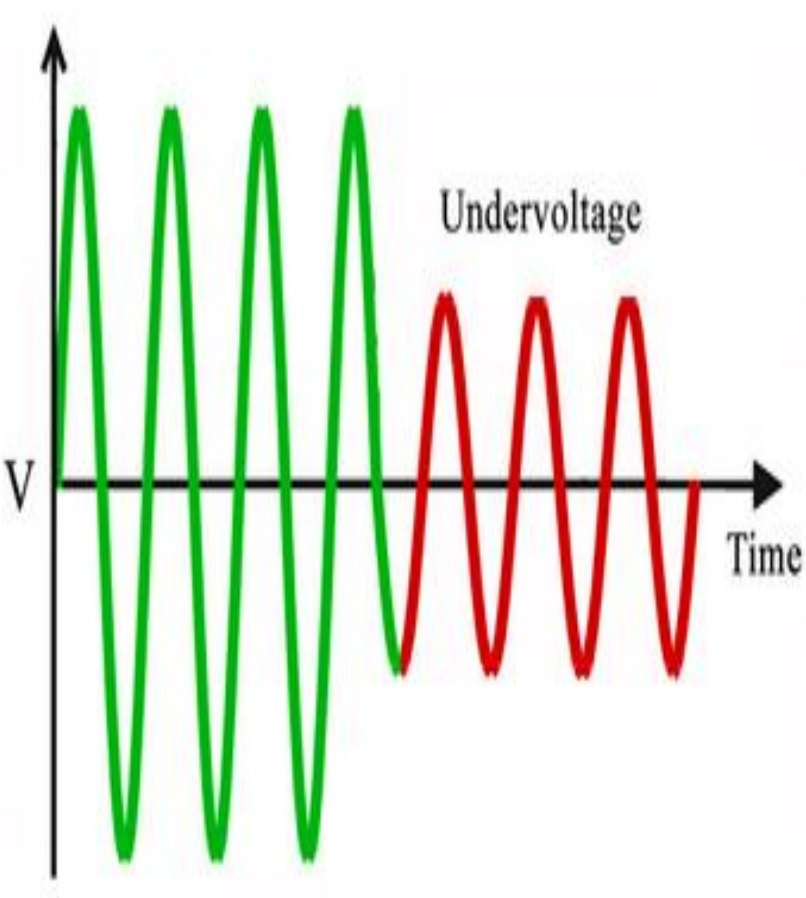
Symptom: Malfunction or premature equipment failure

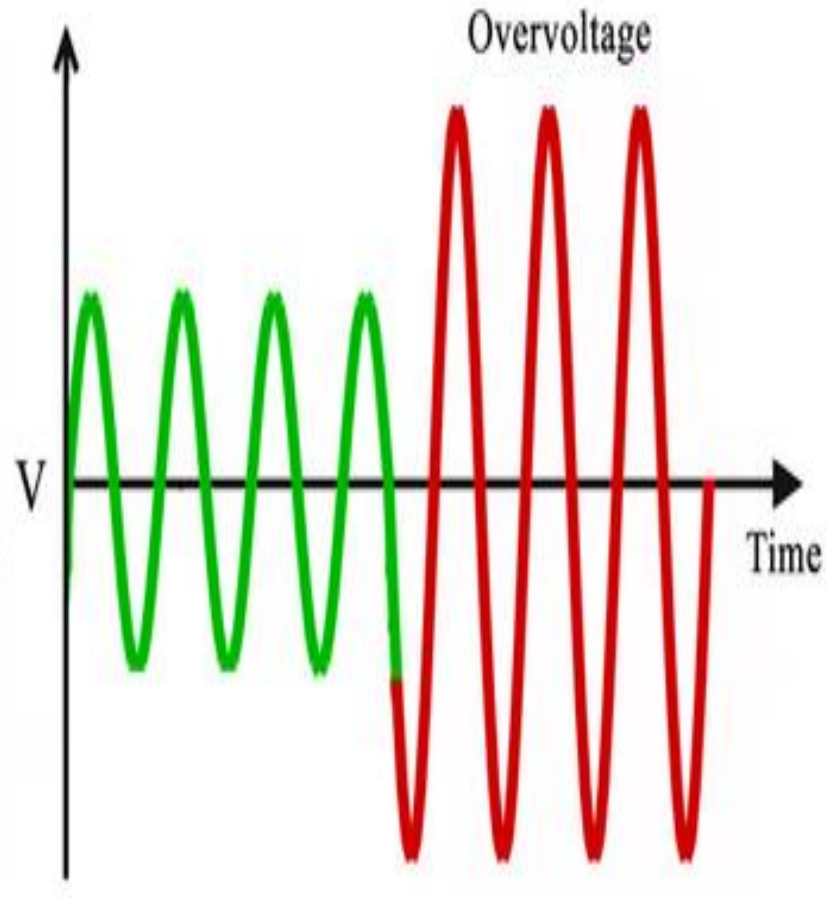
Protection: Voltage regulation

Overvoltage usually results from high distribution voltage. Often a problem nights, evening and weekends. Premature failure of electronics and printed circuit boards is a common symptom.

Causes Premature Circuit Board Failure

Undervoltage and Overvoltage





Undervoltage occurs when the rms voltage drops below 90% of the nominal rms voltage and stays at that level for more than one minute.

Overvoltage is an event where the rms voltage rises above 110% of the nominal rms voltage and stays at that level for more than one minute.

WAVEFORM DISTORTIONS

- Harmonics
- Interharmonics
- DC offset
- Notching
- Noise

WHAT ARE HARMONICS?

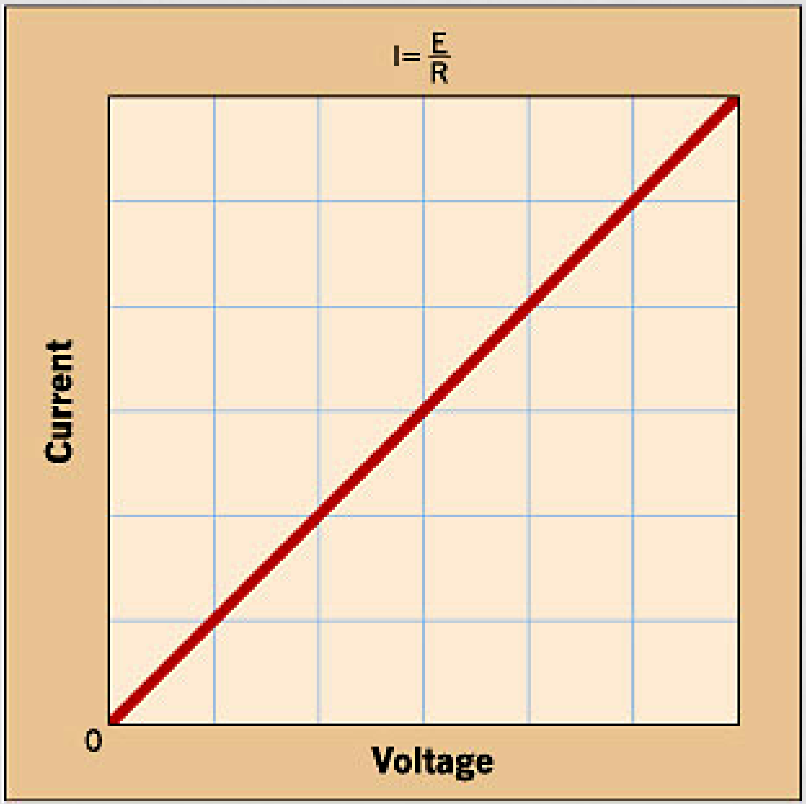
- "A component frequency of a harmonic motion of an electromagnetic wave that is an integral multiple of the fundamental frequency"
- Periodic distortion of the sine wave.
- fundamental frequency is 50 Hertz
  - 3rd Harmonic is 3 x 50Hz or *150Hz*
  - 5th Harmonic is 5 x 50Hz or *250Hz*, etc.

WHAT CAUSES HARMONICS?

<u>Non-Linear Loads</u>

Current is <u>not</u> proportional to the applied voltage

LINEAR VS. NON-LINEAR LOADS AND CURRENT WAVEFORMS



Linear loads and current waveforms.

Pure resistance, inductance, and capacitance are all linear.

What that means:

If a sine wave voltage of a certain magnitude is placed across a circuit containing pure resistance, the current in the circuit follows Ohm's Law:

I = E ÷ R.

So, for a specific value of ohms, the relationship of volts and amperes is a straight line. The current will always be a sine wave of the same frequency.

Linear Loads include Incandescent lighting, heating loads, and motors

LINEAR VS. NON-LINEAR LOADS AND CURRENT WAVEFORMS

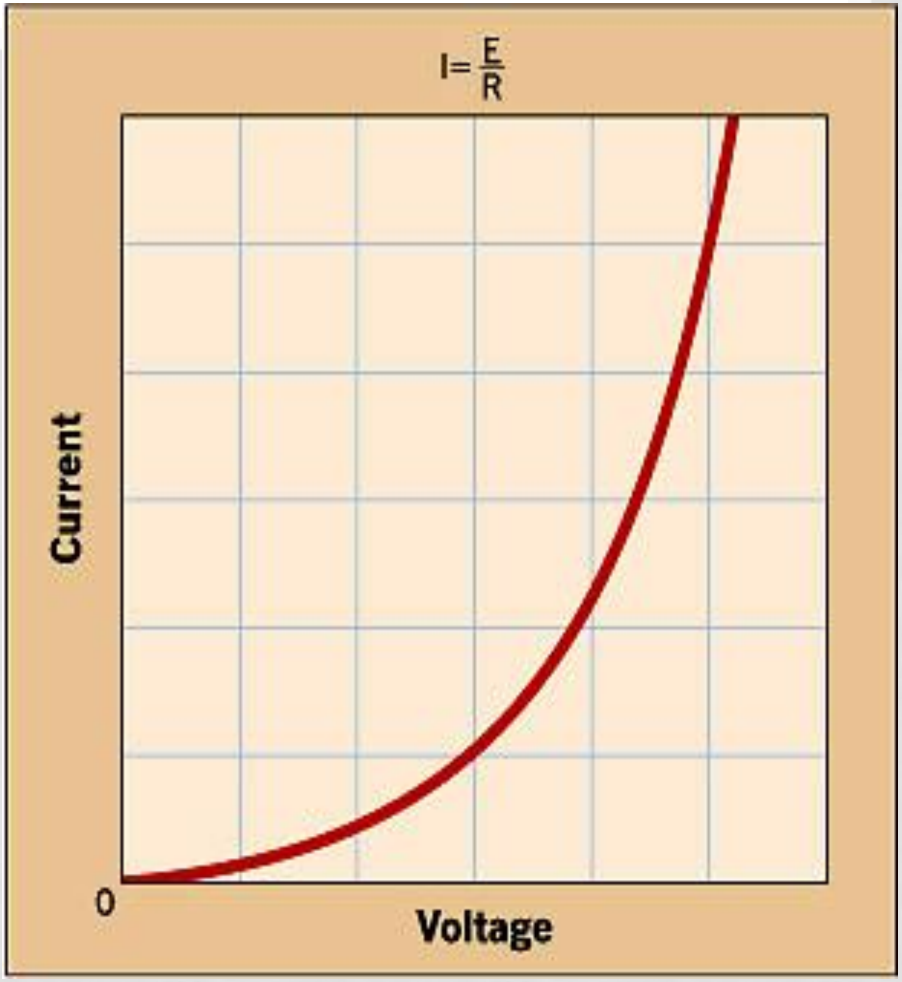
Nonlinear loads and current waveforms.

Solid state electronics is based on the use of semiconductors. These materials are totally different in that their response to voltage is not a straight line.

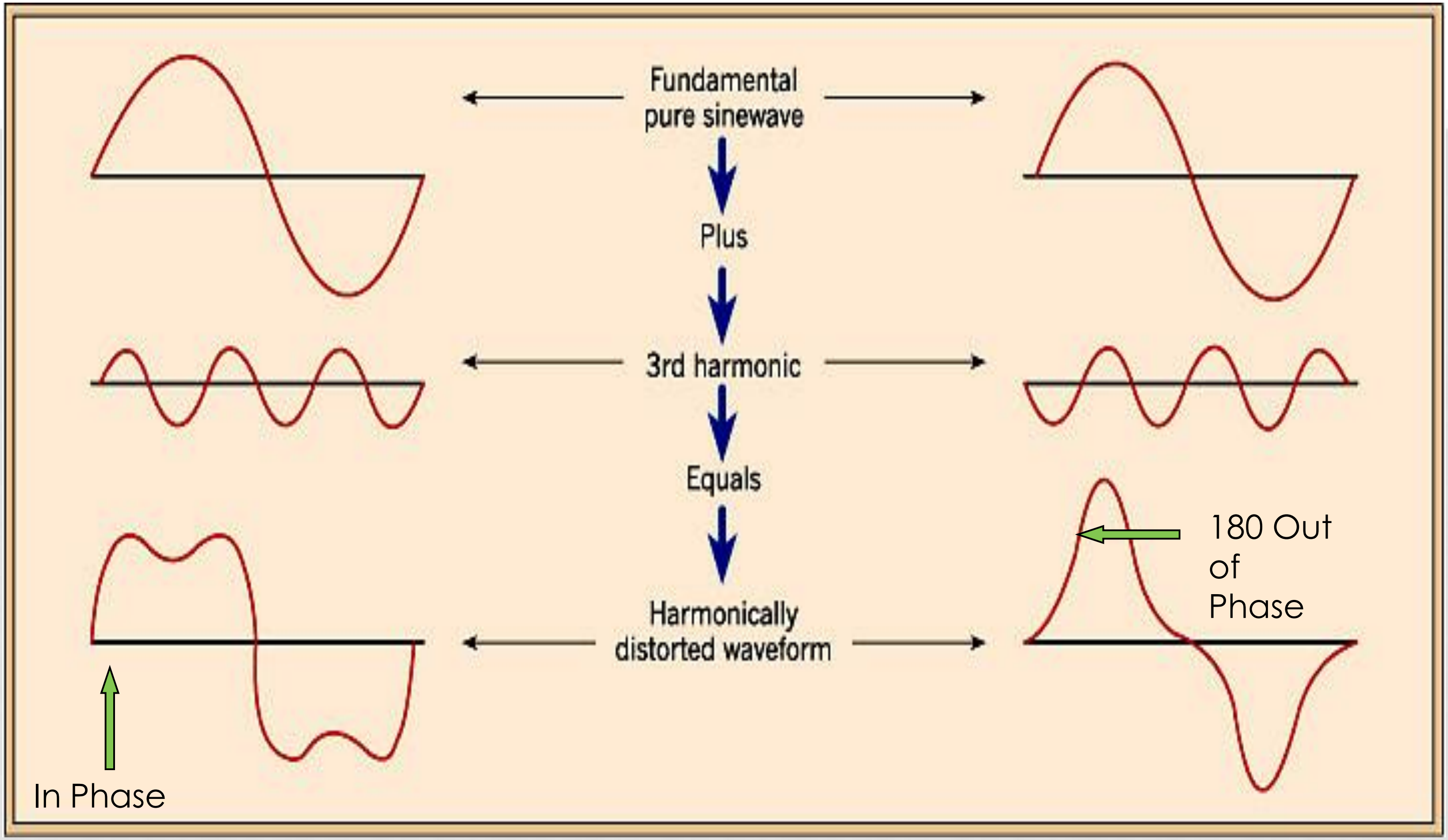
What this means:

With a nonlinear load, you cannot easily predict the relationship between voltage and current — unless you have an exact curve for each device. With equipment containing many solid-state devices, such an approach is impossible.

Nonlinear loads are switched on for only part of the cycle, as in a thyristor-controlled circuit, or pulsed, as in a controlled-rectifier circuit.



EFFECT OF HARMONICS ON WAVEFORM



When a waveform is identical from one waveform to the next, it can be represented as a sum of pure sine waves in which the frequency of each sinusoid is an integer multiple of the fundamental frequency of the distorted wave.

The sum of the sinusoids created by harmonics can be analyzed using the Fourier series concept.

WHAT DO HARMONICS DO?

- Harmonics are carried through the system from the source and can nearly **double** the amount of current on the neutral conductor in three phase four wire distribution systems.

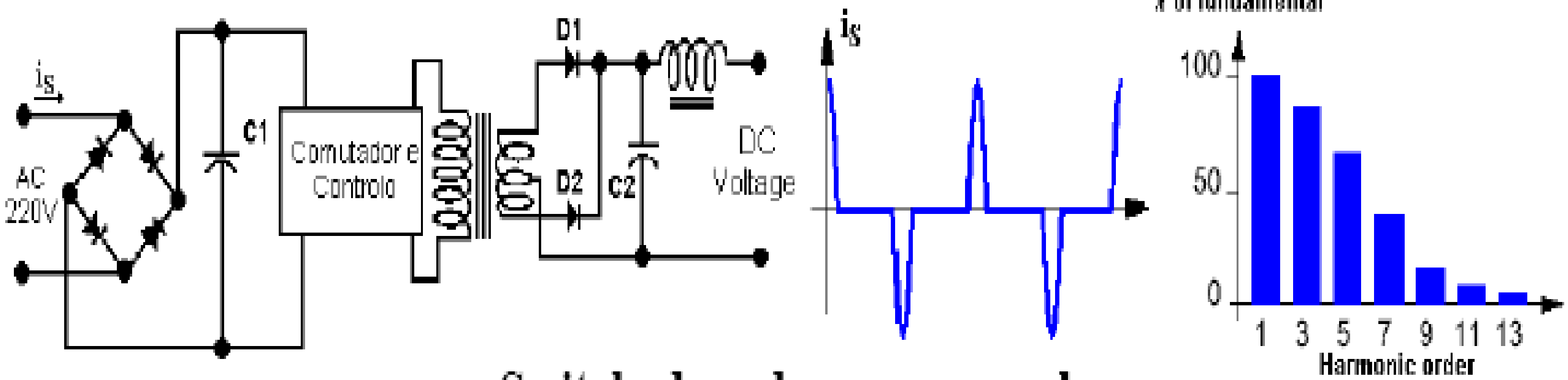
- Distorted currents from harmonic-producing loads also distort the voltage as they pass through the system impedance. Therefore, a distorted voltage can be presented to other end users on the system.

- Overall electrical system and power quality is affected by the introduction of harmonics.

SOURCES OF HARMONICS

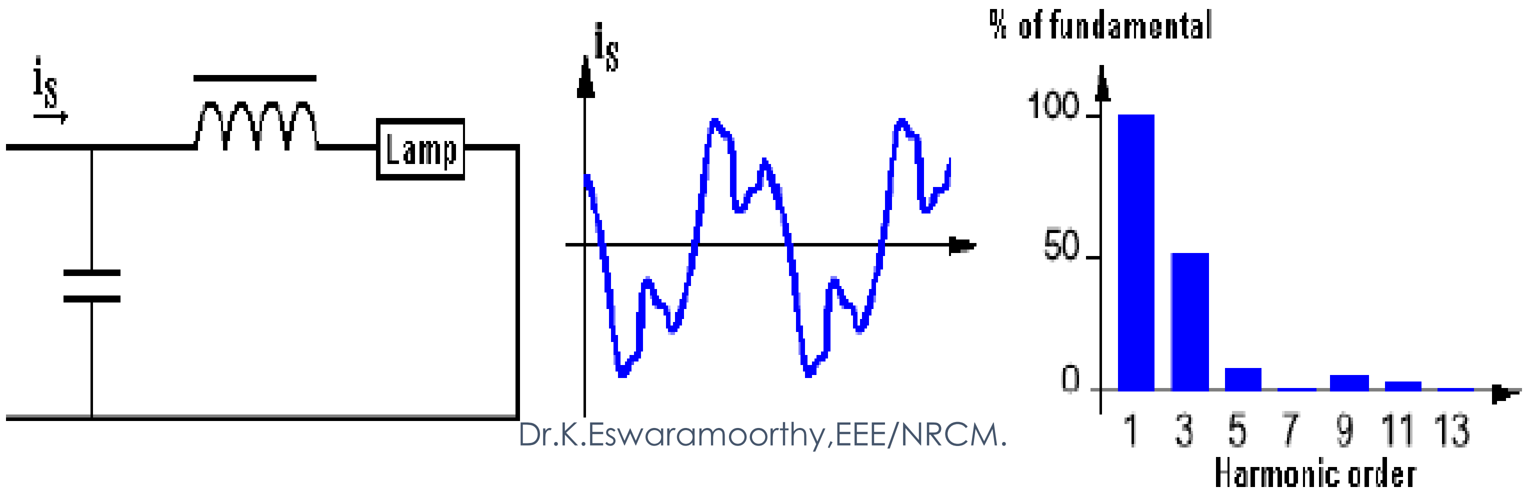
- Solid State Electronic Devices which contain a poor power supply
  - Computers (PCs/CPUs) – Video display terminals
  - Laser Printers – File Servers
  - Copy Machines – Battery Chargers
- *Solid State UPS Units
- Solid State Devices (Fluorescent lighting ballasts)
- **Rectifiers (AC-DC Converters → VFDs)
- Welding Units
- Arc Furnaces

Sources of harmonic distortion (1)

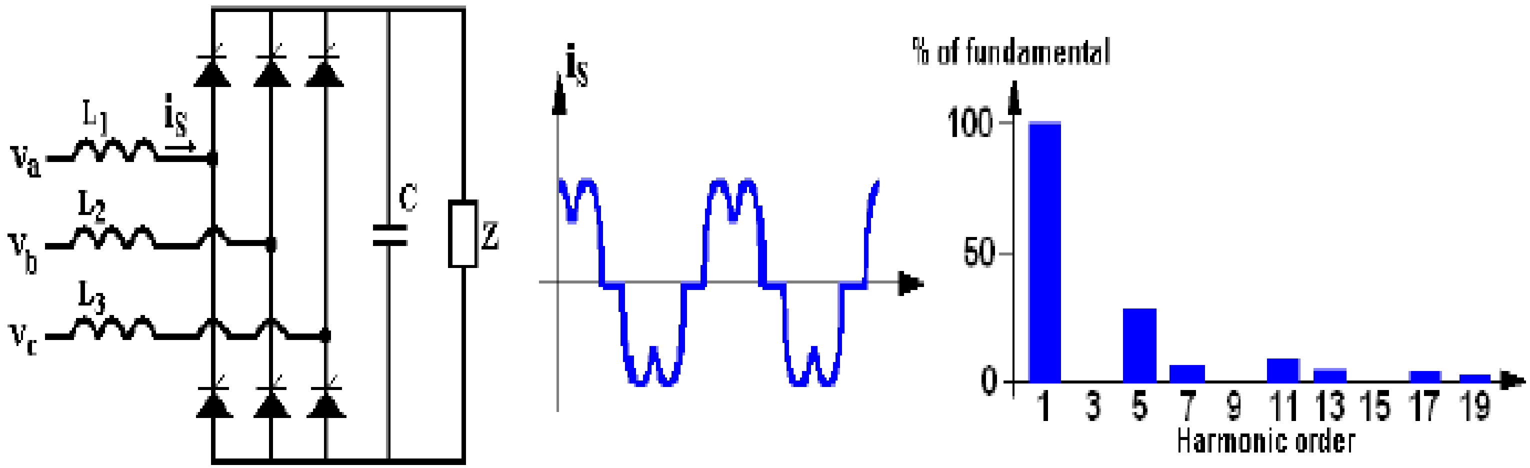


Switched mode power supply

Fluorescent lighting

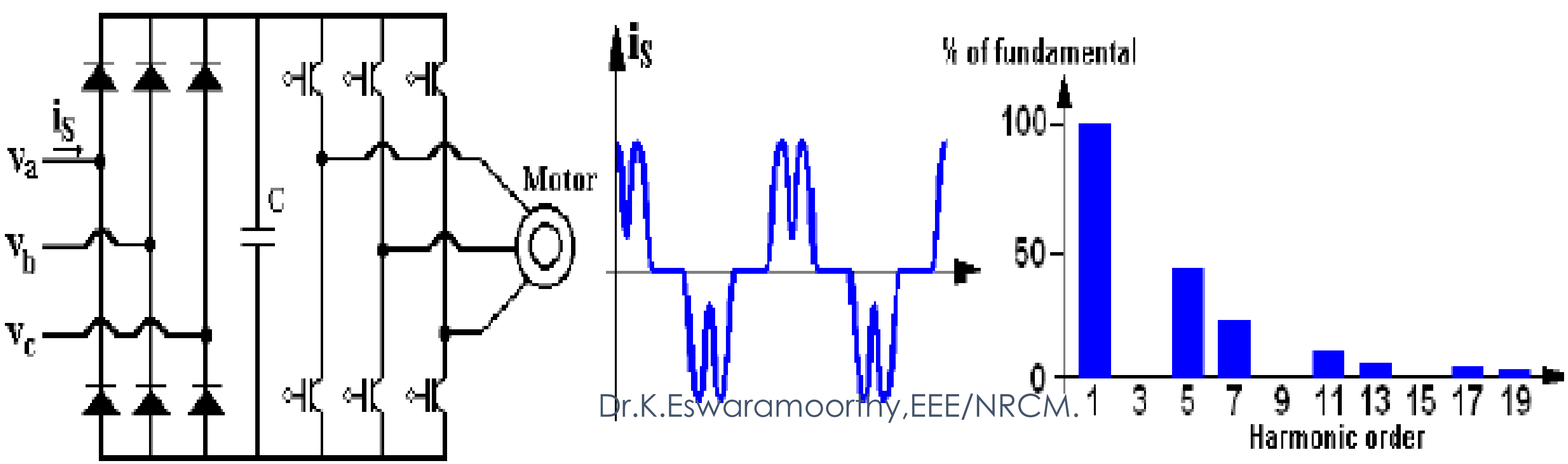


Sources of harmonic distortion (2)



3-phase rectifier

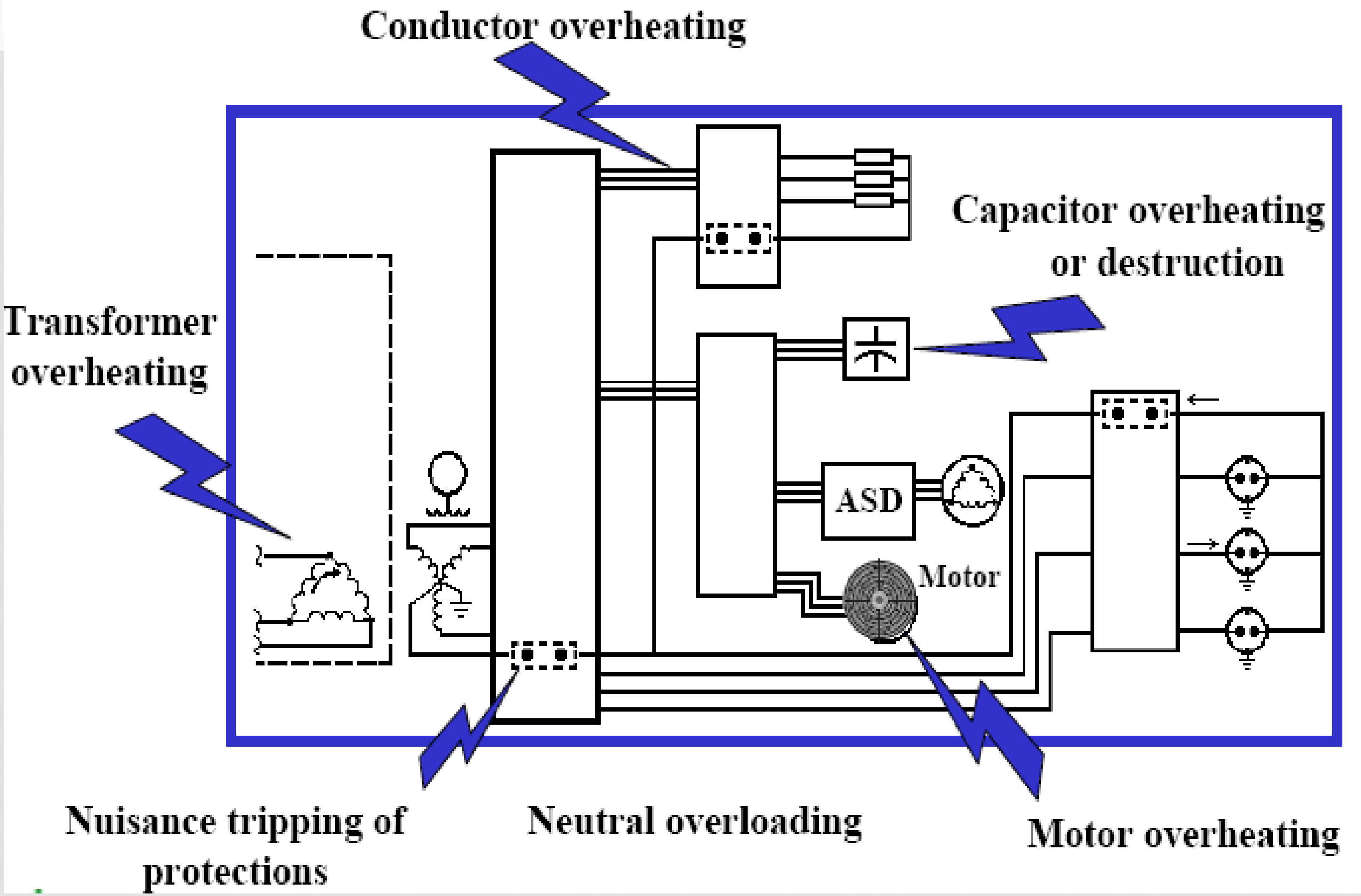
Adjustable speed drive



WHAT ARE THE ORDER OF TYPICAL HARMONICS GENERATED BY NON-LINEAR LOADS?

Load description	Harmonic Order							
	1	3	5	7	9	11	13	15
Six-pulse rectifier	100	—	17	11	—	5	3	—
Twelve-pulse rectifier	100	—	3	2	—	5	3	—
Eighteen-pulse rectifier	100	—	3	2	—	1	0.5	—
Twenty-four pulse rectifier	100	—	3	2	—	1	0.5	—
Electronic/computer	100	56	33	11	5	4	2	1
Lighting/electronic	100	18	15	8	3	2	1	0.5
Office with PCs	100	51	28	9	6	4	2	2
VFD's (range)	100	1 to 9	40 to 65	17 to 41	1 to 9	4 to 8	3 to 8	0 to 2

HARMONIC DISTORTION - CONSEQUENCES



EFFECTS OF HARMONICS

- Distorted Voltage
- Overheated Transformers and Motors
  - Increases Hysteresis (magnetization) losses in steel and iron cores of transformers, motor and magnetic trip units of circuit breakers (Equipment inefficiencies and overheating)
- Heating of Neutral Conductors
  - Skin Effect → Increased amount of current flowing on the outside of conductors (overheating)
- Low Voltage at End Loads
- High Neutral to Ground Voltages at End Loads

EFFECTS OF HARMONICS (CONT)

- Operation Problems of Relays and Circuit Breakers
  - Thermal/Magnetic Trip Circuit Breakers
    - Fuses & bimetal strips respond to True RMS
    - Harmonic currents increase eddy current losses in the core steel of the metallic strip.
    - This causes an OVER protection situation… Increased losses generate additional heat, this effect the thermal trip of the unit.
  - Electronic Trip Circuit Breakers
    - Magnitude and phase angle(s) of harmonic current(s) in relationship to the fundamental current can cause:
      - Over protection when: Peak current sensing > True RMS
      - Under protection when: Peak current sensing < True RMS
    - Changing power system loads will vary the magnitude and phase angle, resulting in inaccurate and unpredictable sensing units and overload protection

EFFECTS OF HARMONICS (CONT)

- Communication Problems
  - If sharing common parallel path, potential for harmonics to have inductive coupling effect on unshielded cabling
- Current Measurement Problems (distorted waveform)
- Unreliable Operation of Electronic Equipment
  - Mis-operation of electronic equipment that measures frequency or uses the zero crossing point of a sine wave.
- Control of Speed and Voltage Problems on Emergency Generators (supplying power)
- Capacitor Bank Application Problems (heating)
- Computer (PC/CPU) data errors / data loss
  - Affects power supplies and sensitive electronics

HARMONICS VS OTHER DISTURBANCES

- Voltage transients, surges and sags are all generally of short duration. typically fraction of a microsecond to a few milliseconds.
- Voltage sags surges are periods of under or over voltage lasting from a large portion of cycle of the power system waveform to perhaps a few seconds.
- Transients are associated with changes in the system such as switching a capacitor bank.

IMPORTANT DEFINITIONS

- Harmonic Distortion:
- Voltage Harmonic Distortion (VHD):
- Total Harmonic Distortion (THD):
- Distortion Factor, or %DF:

TOTAL HARMONICS DISTORTION(THD)

- Ratio of rms voltage or current harmonic content of a periodic wave to the rms of fundamental content of the wave, expressed as a percent. Also known as total harmonic distortion (THD).
- % THD =

$$\frac{\sqrt{I_{rms}^2 - I_{1,rms}^2}}{I_{1,rms}} x100$$

- *where : $I_{1,rms}$ is the fundamental sinusoidal input current and I_{rms} is the input utility rms current (may not be sinusoidal, depends on load)*

$$V_{\mathrm{THD}} = \frac{\sqrt{\sum_{h=2}^{50}}}{V_1} = \sqrt{\left(\frac{V_2}{V_1}\right)^2 + \left(\frac{V_3}{V_1}\right)^2 + \cdots \left(\frac{V_n}{V_1}\right)^2}$$

where V_1 = fundamental voltage value and $V_n = V_2, V_3, V_4$, etc. = harmonic voltage value.

IEEE DEFINED HARMONIC CURRENT LIMITS

TABLE 6.2 Harmonic Current Distortion Limits (I_h) in Percent of I_L

I_{SC}/I_L	$h < 11$	$11 \leq h < 17$	$17 \leq h < 23$	$23 \leq h < 35$	$35 \leq h$	TDD
			$V_n \leq 69$ kV			
<20	4.0	2.0	1.5	0.6	0.3	5.0
20–50	7.0	3.5	2.5	1.0	0.5	8.0
50–100	10.0	4.5	4.0	1.5	0.7	12.0
100–1000	12.0	5.5	5.0	2.0	1.0	15.0
>1000	15.0	7.0	6.0	2.5	1.4	20.0
			69 kV $< V_n \leq$ 161 kV			
<20*	2.0	1.0	0.75	0.3	0.15	2.5
20–50	3.5	1.75	1.25	0.5	0.25	4.0
50–100	5.0	2.25	2.0	0.75	0.35	6.0
100–1000	6.0	2.75	2.5	1.0	0.5	7.5
>1000	7.5	3.5	3.0	1.25	0.7	10.0
			$V_n >$ 161 kV			
<50	2.0	1.0	0.75	0.3	0.15	2.5
≥50	3.0	1.50	1.15	0.45	0.22	3.75

*All power generation equipment applications are limited to these values of current distortion regard less of the actual short-circuit current ratio I_{SC}/I_L.

SOURCE: IEEE Standard 519-1992, tables 10.3, 10.4, 10.5.

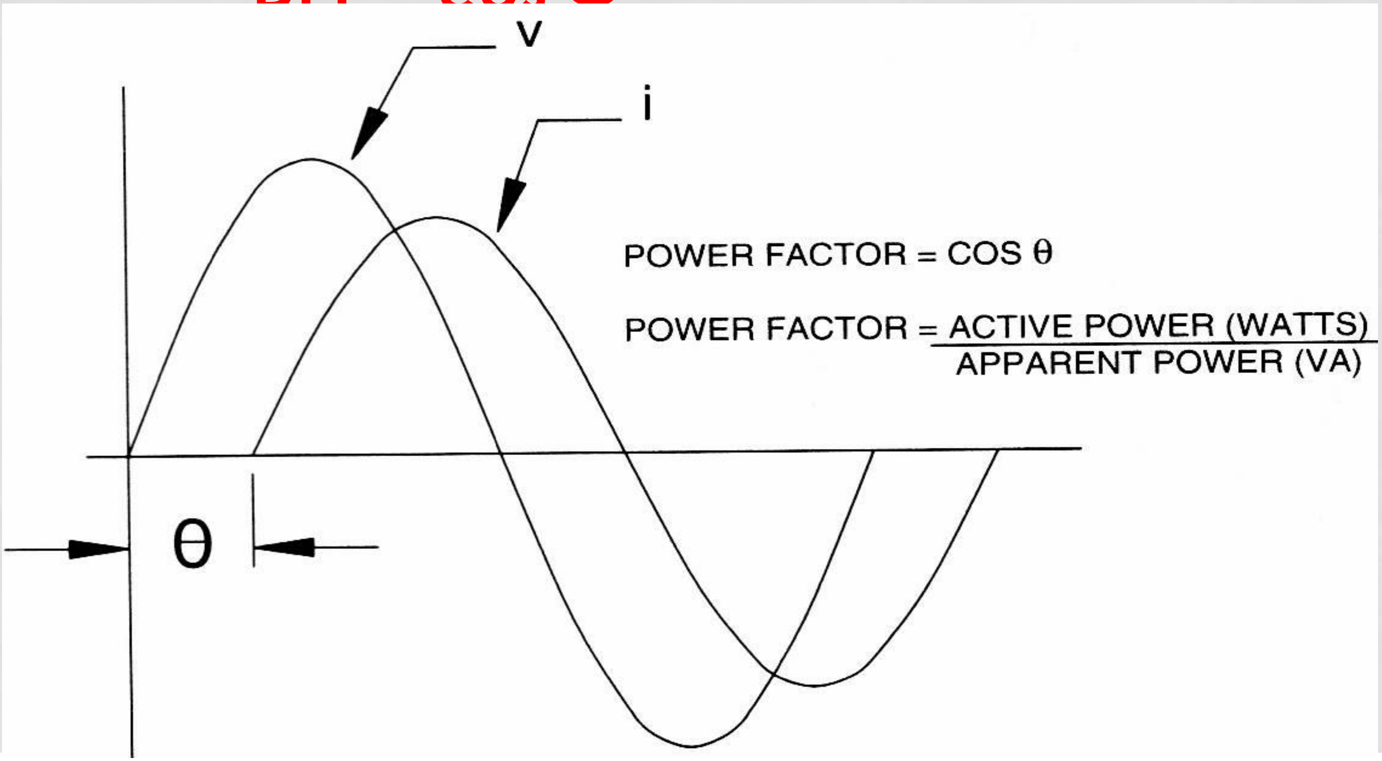
- I_h is the magnitude of individual harmonic components (rms amps).
- I_{SC} is the short-circuit current at the PCC.
- I_L is the fundamental component of the maximum demand load current at the PCC. It can be calculated as the average of the maximum monthly demand currents for the previous 12 months or it may have to be estimated.

- The total demand distortion (TDD) is expressed in terms of the maximum demand load current, i.e.,

$$\mathrm{TDD} = \frac{\sqrt{\sum_{2} I_h^2}}{I_L} \times 100\% \tag{6.1}$$

DISPLACEMENT POWER FACTOR (DPF)

- Ratio between active power (W) to apparent power (VA) of the fundamental wave. DPF is same as PF in linear circuit with sinusoidal V and I. DPF is cosine of displacement angle between V and I waveform.
    - **DPF = cos Φ**



POWER FACTOR (PF)

- Ratio of total active power to total apparent power of composite wave including all harmonic components.

$$PF = \frac{I_{s1}}{I_s} DPF$$

$$= \frac{1}{\sqrt{1 + THD^2}} DPF$$

INTERHARMONICS

- Voltages or currents having frequency components that are not integer multiples of the frequency at which the supply system is designed to operate (e.g., 50 or 60 Hz) are called interharmonics.
- Sources: Static frequency converter, cycloconverters, induction furnaces, and arcing devices.
- Power line carrier signals can also be considered as interharmonics.

CAUSE

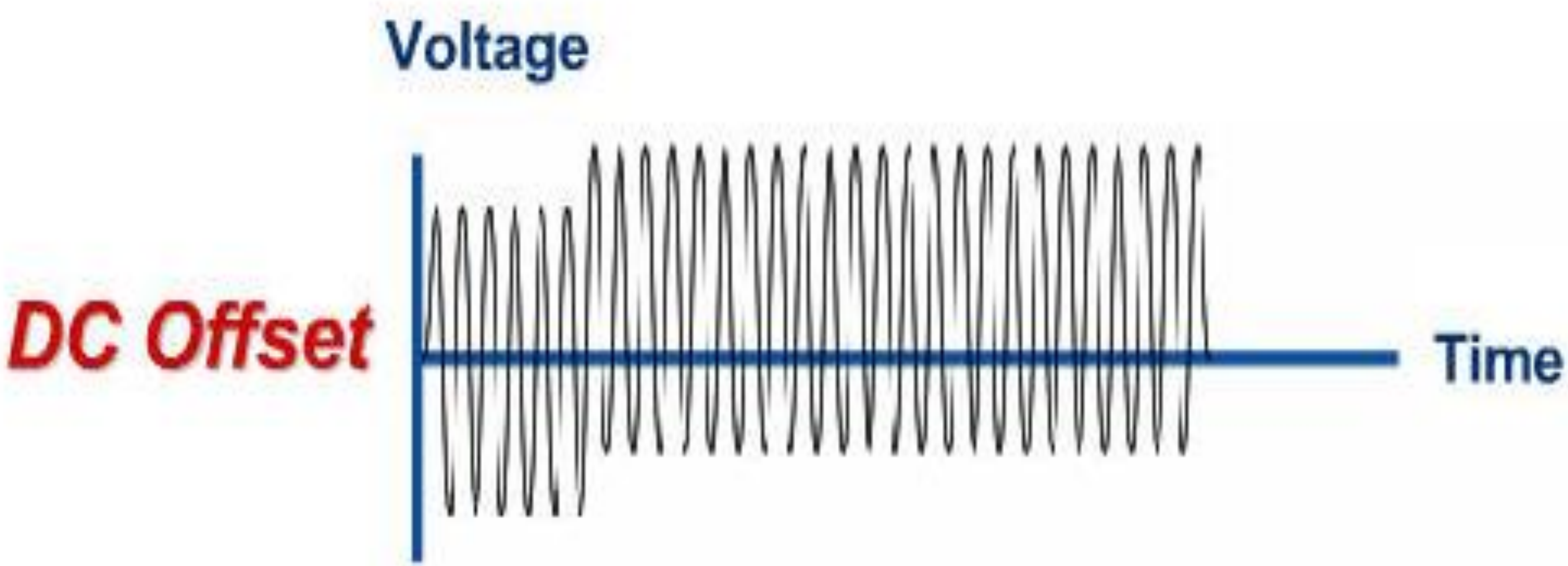
- Non-linear loads.
- SMPS used by personal computers.
- VFD.
- Electronics devices.

EFFECTS

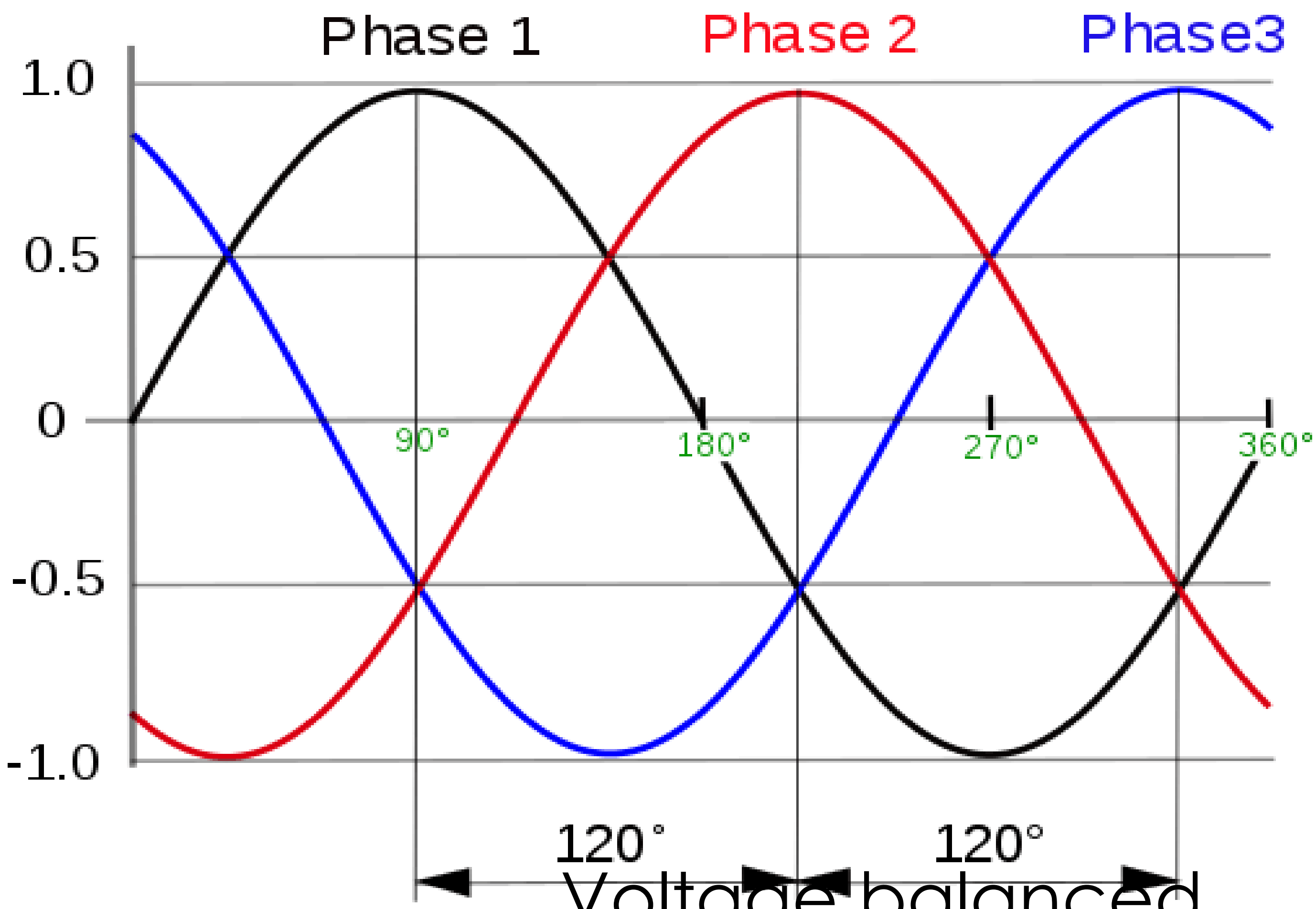
- Overheating conductors and transformers.
- Decreased efficiency.
- Increases losses

DC OFFSET

"The presence of a dc voltage or current in an ac power system is termed dc offset"



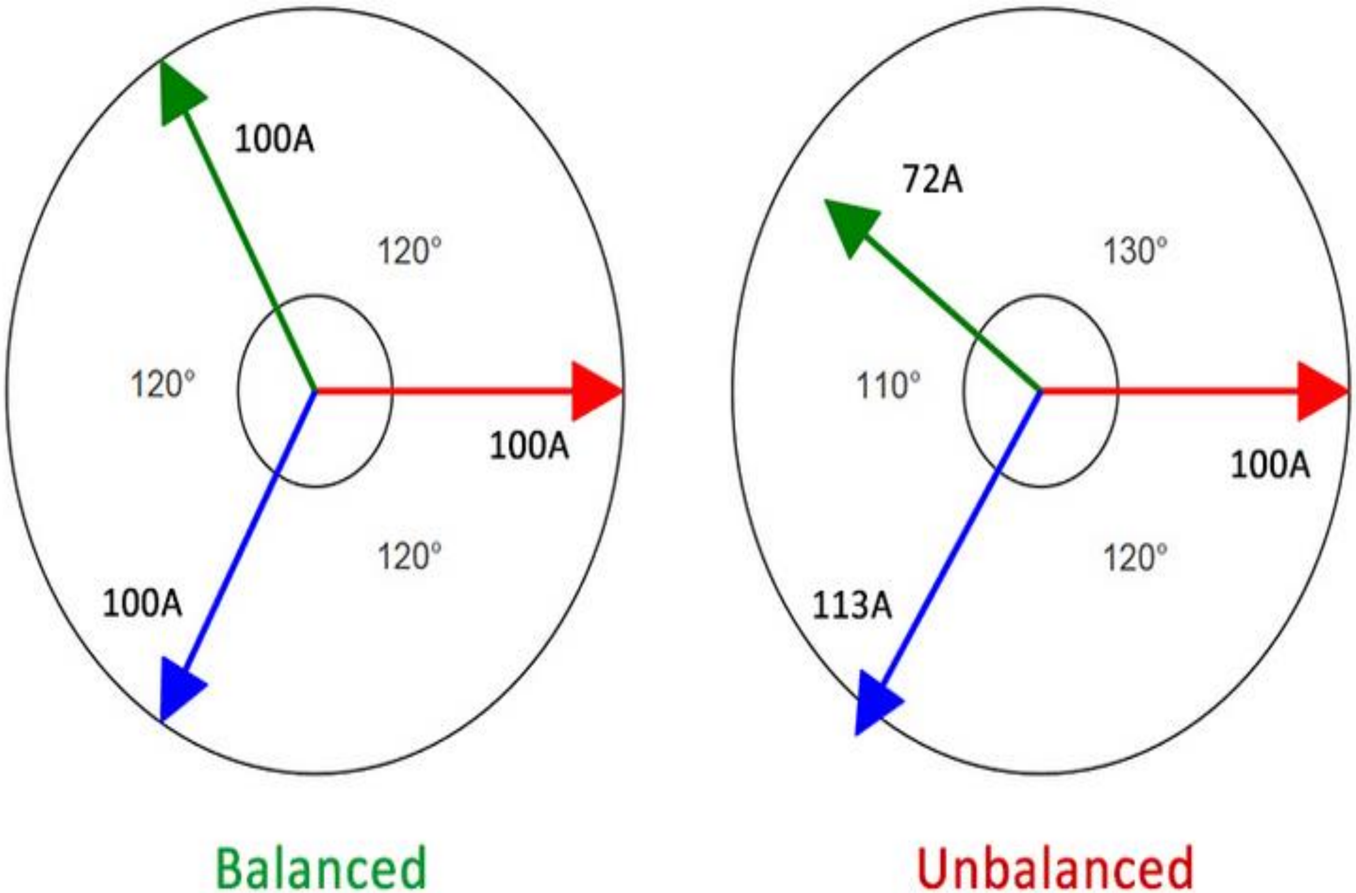
VOLTAGE UNBALANCE



Voltage balanced

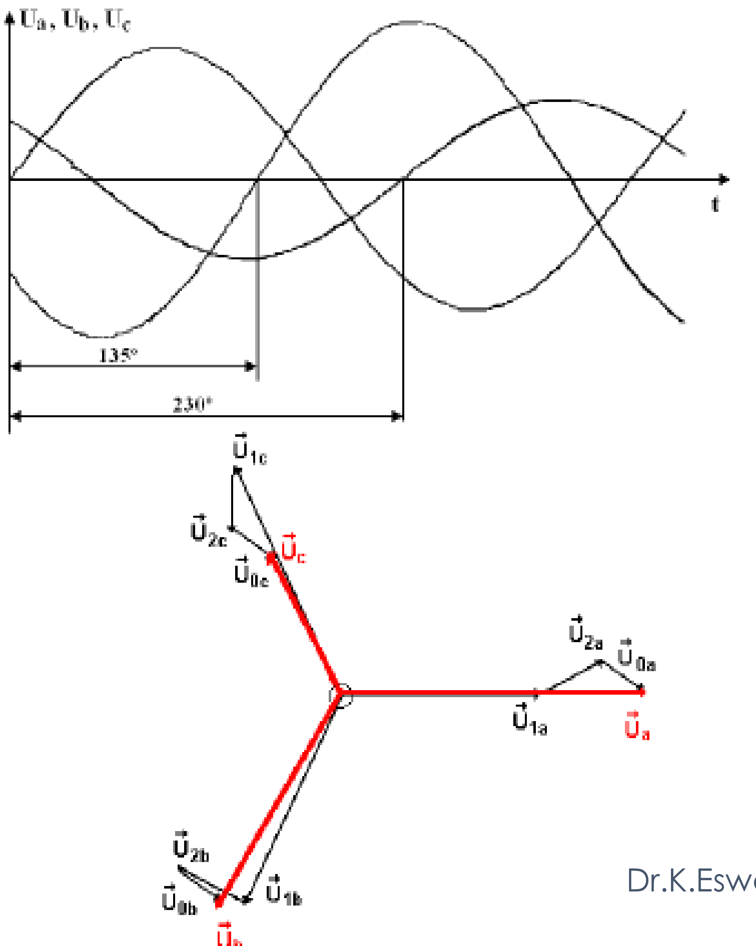
Unbalance

Occurs in three-phase power systems when single phase loads do not draw the same amount of current on each phase.



VOLTAGE UNBALANCE

A voltage variation in a three-phase system in which the three voltage magnitudes or the phase-angle differences between them are not equal.



Causes:

•Large single-phase loads (induction furnaces, traction loads).

• Incorrect distribution of loads by the three phases of the system.

Consequences:

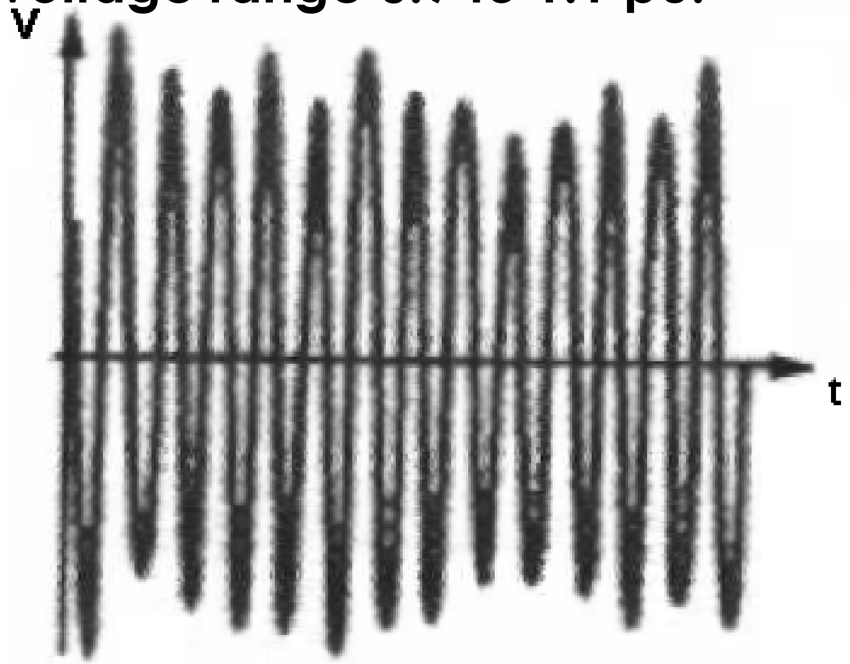
• The most affected loads are three-phase induction machines.

• Increase in the losses.

VOLTAGE FLUCTUATIONS

Oscillation of voltage value, amplitude modulated by a signal with low frequency.

the magnitude of which does not normally exceed the voltage range 0.9 to 1.1 pu.



Causes:

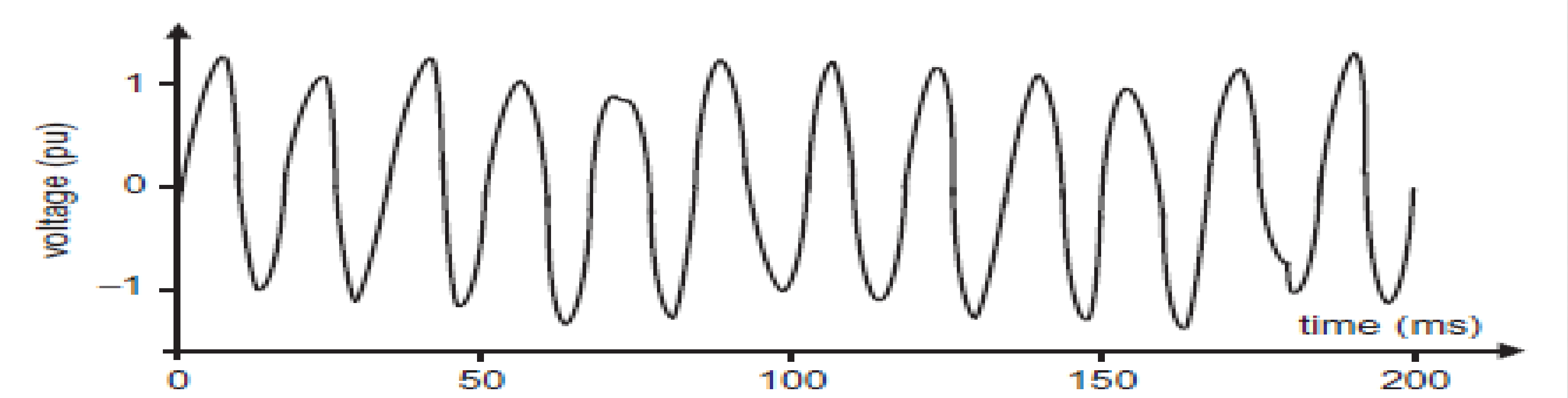
- Arc furnaces.
- Frequent start/stop of electric motors (for instance elevators).
- Oscillating loads.

Consequences:

- Most consequences are common to undervoltages.
- Flickering of lighting and screens.

FLICKER

- Fast changes in load cause changes in voltage drop
- Voltage "flicker" is caused by a varying load which tends to be repetitive in nature.
- This causes a repetitive voltage dip pattern.
- It is this repetitive voltage dip which causes a visible flicker in the output of incandescent bulbs.
- The worst flicker frequency is at about 1 Hz, which causes an irritating "strobe" effect on humans.
- This may be caused by an arc furnace, one of the most common causes
- of the voltage fluctuations in utility transmission and distribution systems



SOURCES OF FLICKER

- Repeated motor starting
- Cyclic loads such as welders, rolling mills, etc
- Stochastic sources, eg wind generators

NOISE

Superimposing of high frequency signals on the waveform of the power-system frequency.

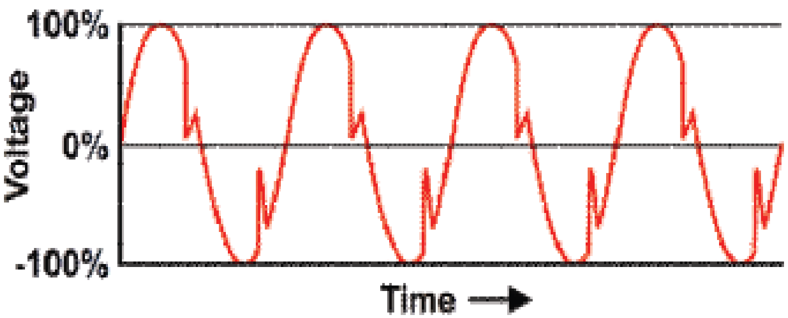
Causes:

- Electromagnetic interferences.
- Improper grounding may also be a cause.

Consequences:

- Disturbances on sensitive electronic equipment.
- May cause data loss and data processing errors.

NOTCHING



Deformed voltage waveform

Source: Electronic devices

Duration: Steady state

Incidence : Very low

Symptom: Malfunction

Protection: None

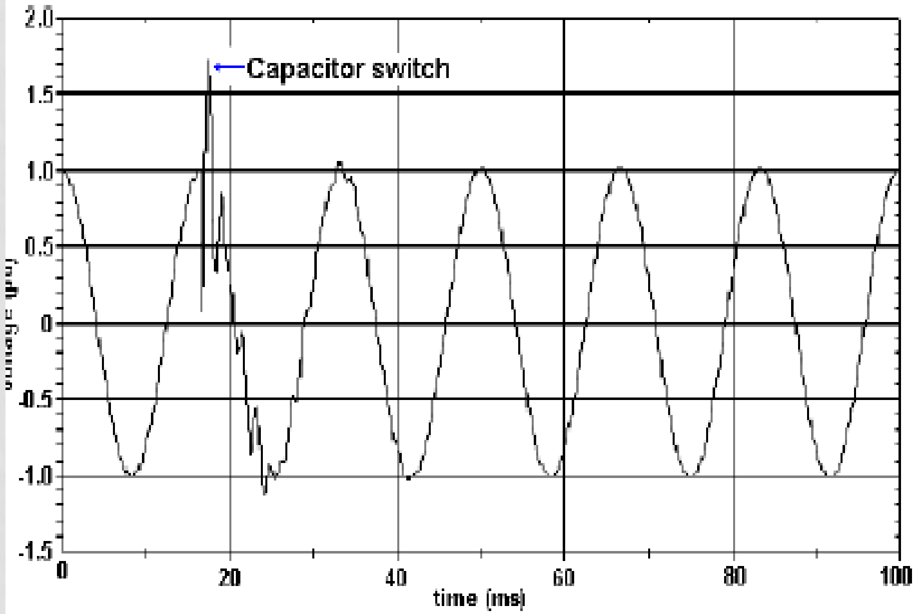
Notching can be caused by certain electronic devices. While it is rarely a problem, the solution usually involves isolation of sensitive equipment from the offending device.

Causes Operation Problems

- Notching is a periodic voltage disturbance caused by the normal operation of power electronic devices when current is commutated from one phase to another.
- The previous slide figure shows an example of voltage notching from a three-phase converter that produces continuous dc current.
- The notches occur when the current commutates from one phase to another.
- During this period, there is a momentary short circuit between two phases, pulling the voltage as close to zero as permitted by system impedances.

VOLTAGE SPIKES

Very fast variation of the voltage value for durations from a several microseconds to few milliseconds.



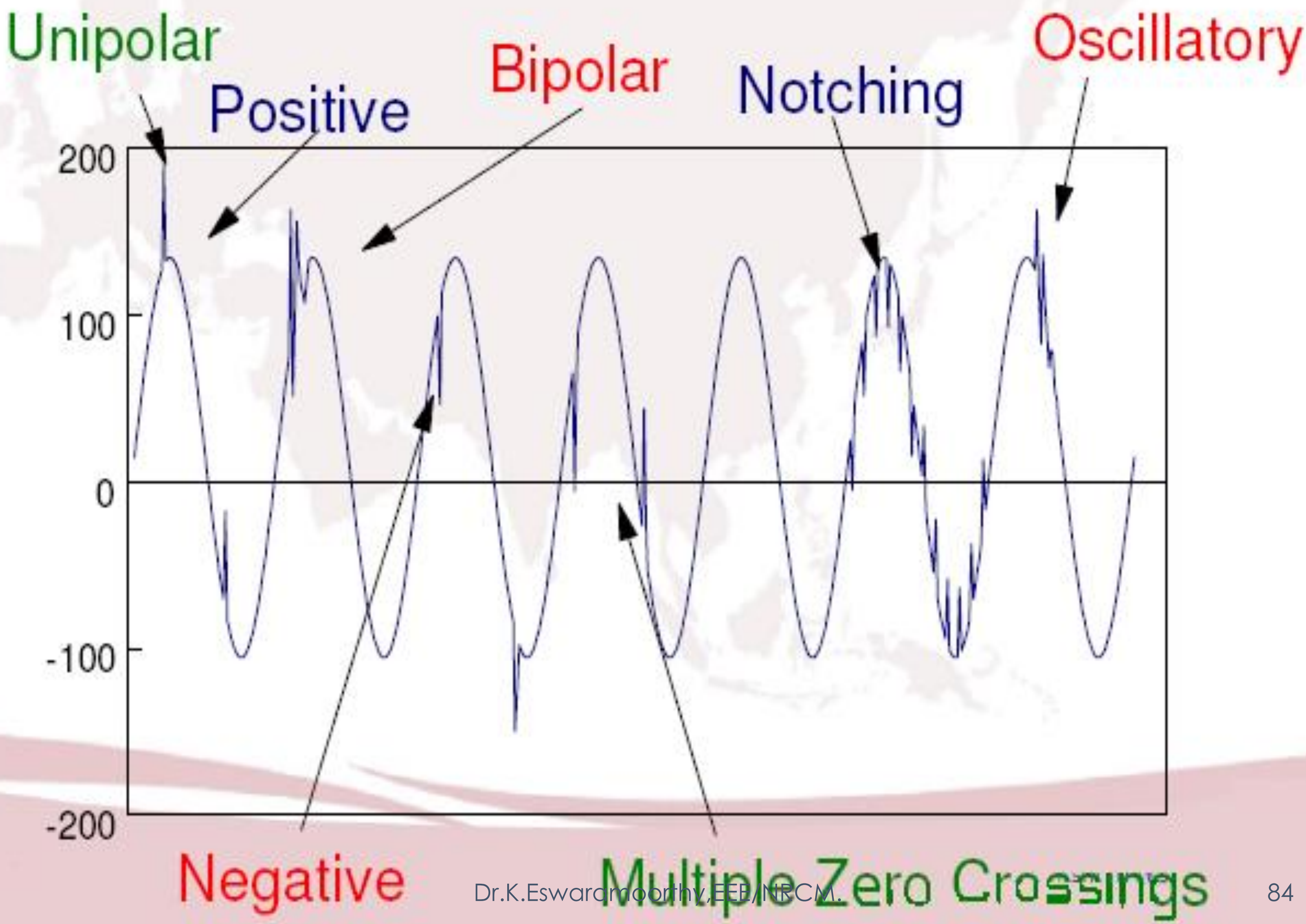
Causes:

- Lightning.
- Switching of lines or power factor correction capacitors.
- Disconnection of heavy loads.

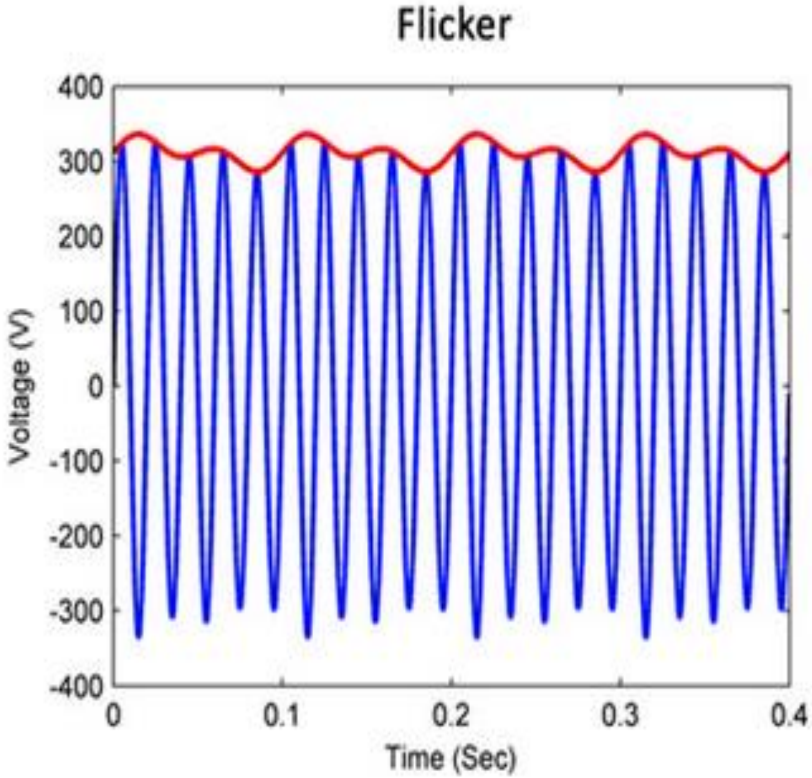
Consequences:

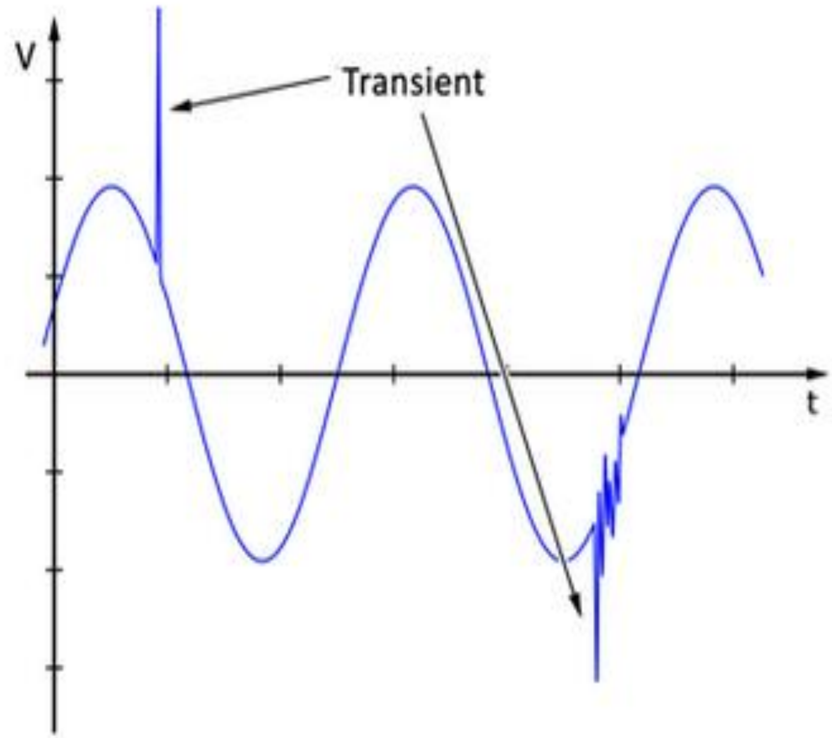
- Destruction of components and of insulation materials.
- Data processing errors or data loss.
- Electromagnetic interference.

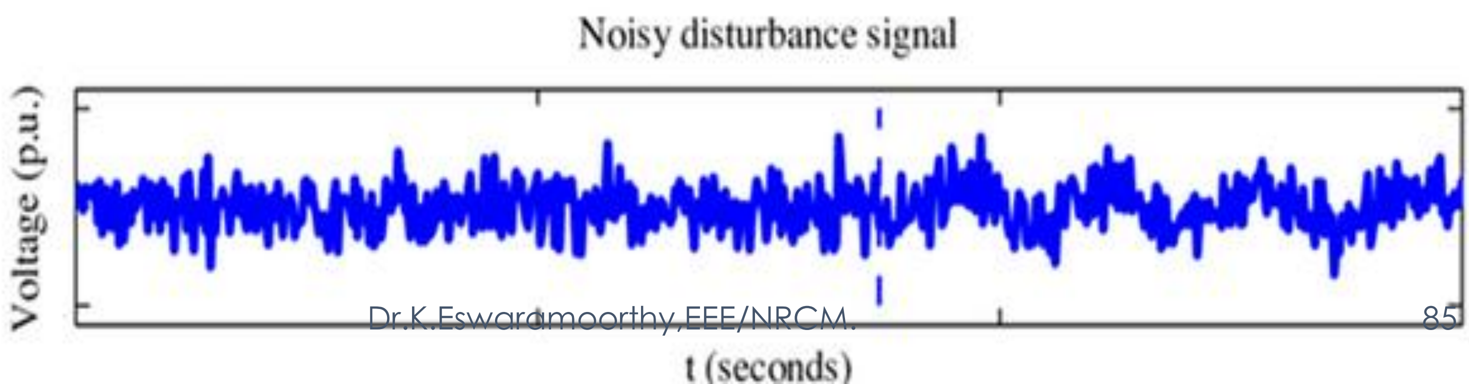
Transients


Unipolar
Positive
Bipolar
Notching
Oscillatory
200
100
0
-100
-200
Negative
Multiple Zero Crossings

Flicker, Transients and Noise

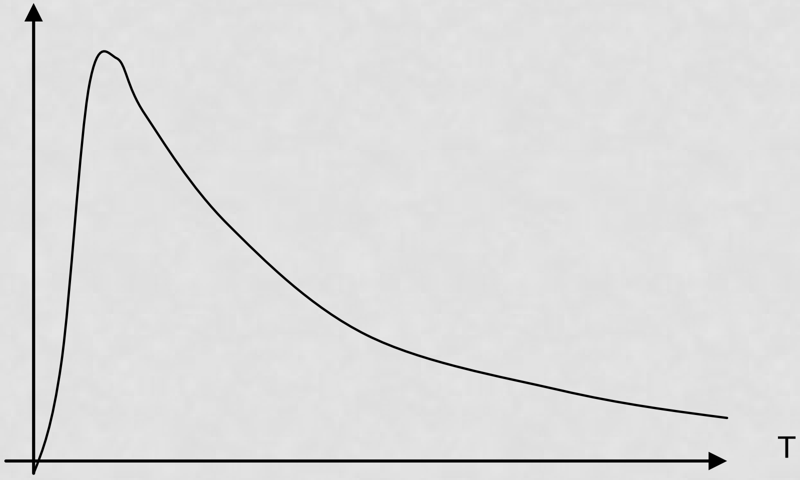






TYPICAL LIGHTNING SURGE

- A typical lightning surge rises quickly to a maximum in about 1 microsecond and falls away in about 50 microseconds – the so-called “1/50” type shape.
- Compared to power frequency, the lightning transient is very fast and contains frequencies in the mega Hz range. Thus the power system’s response can only be analysed by considering the distributed nature of the transmission elements.



Typical Lightning Surge – “1/50” Shape

WAVES DUE TO LIGHTNING STRIKE

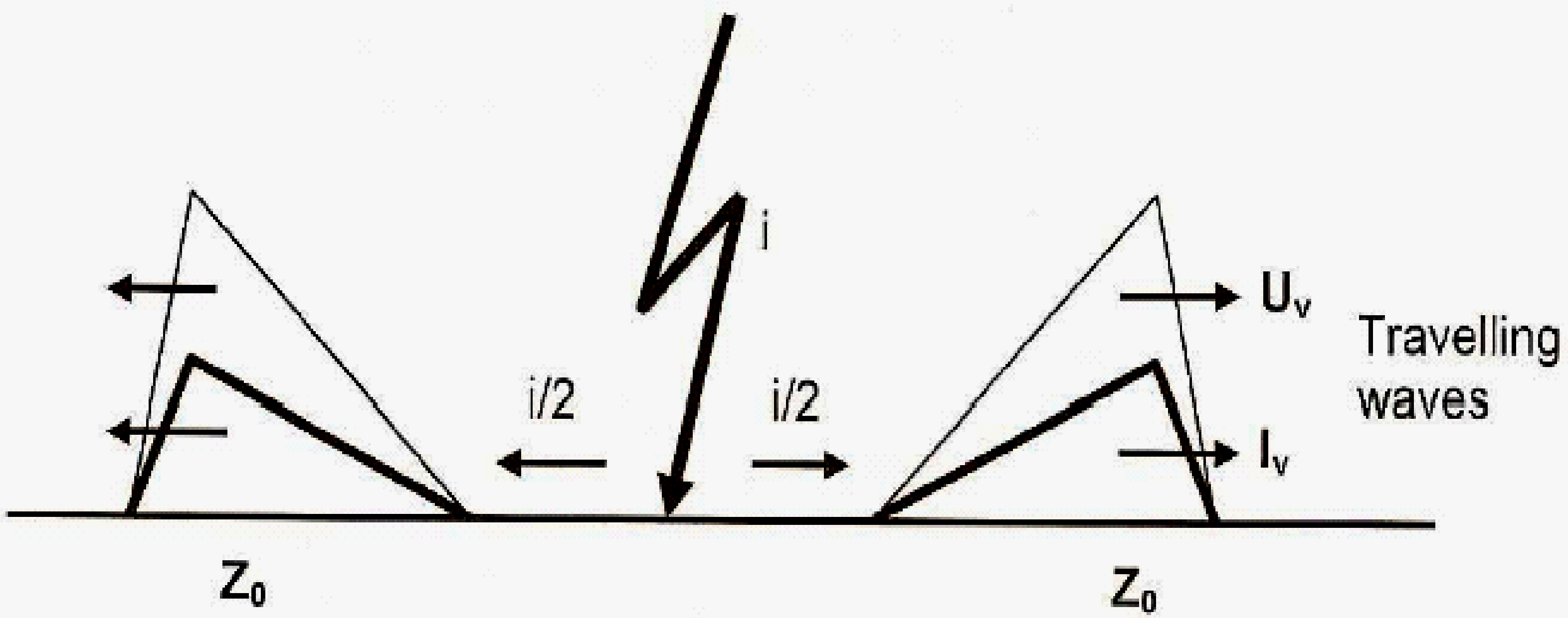


Figure 7: Travelling waves due to a lightning strike.

- Integral Energy Power Quality Centre

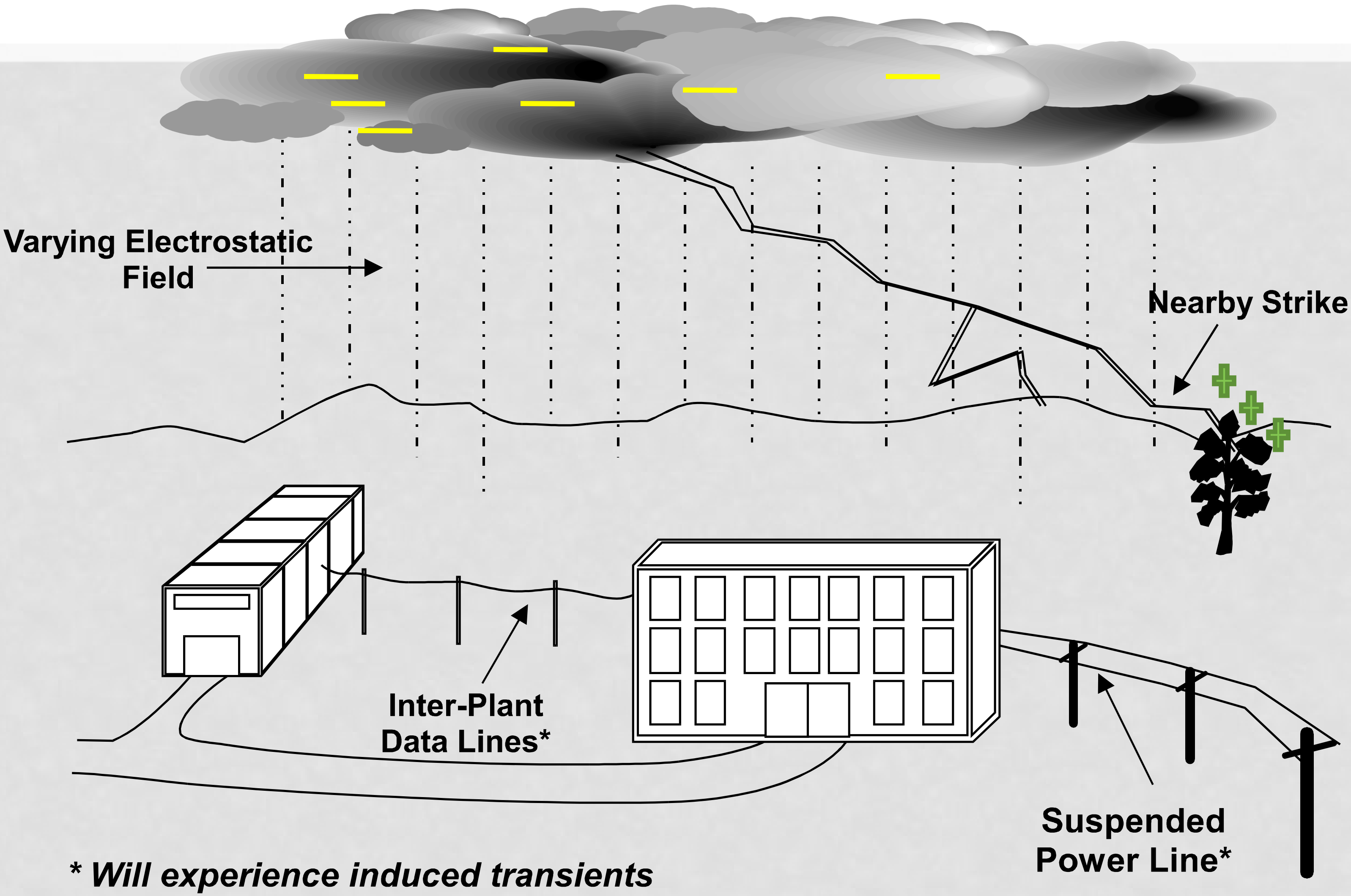
- A lightning strike to nearby strike creates two waves, travelling away in opposite directions from the source. Reflections at termination and connection points on the network cause multiple patterns. The peak current in a heavy lightning flash can reach 30-40 kA.

- As the travelling waves meet junctions and terminations they reflect, causing standing wave patterns which often overstress insulation on cables and transformers.

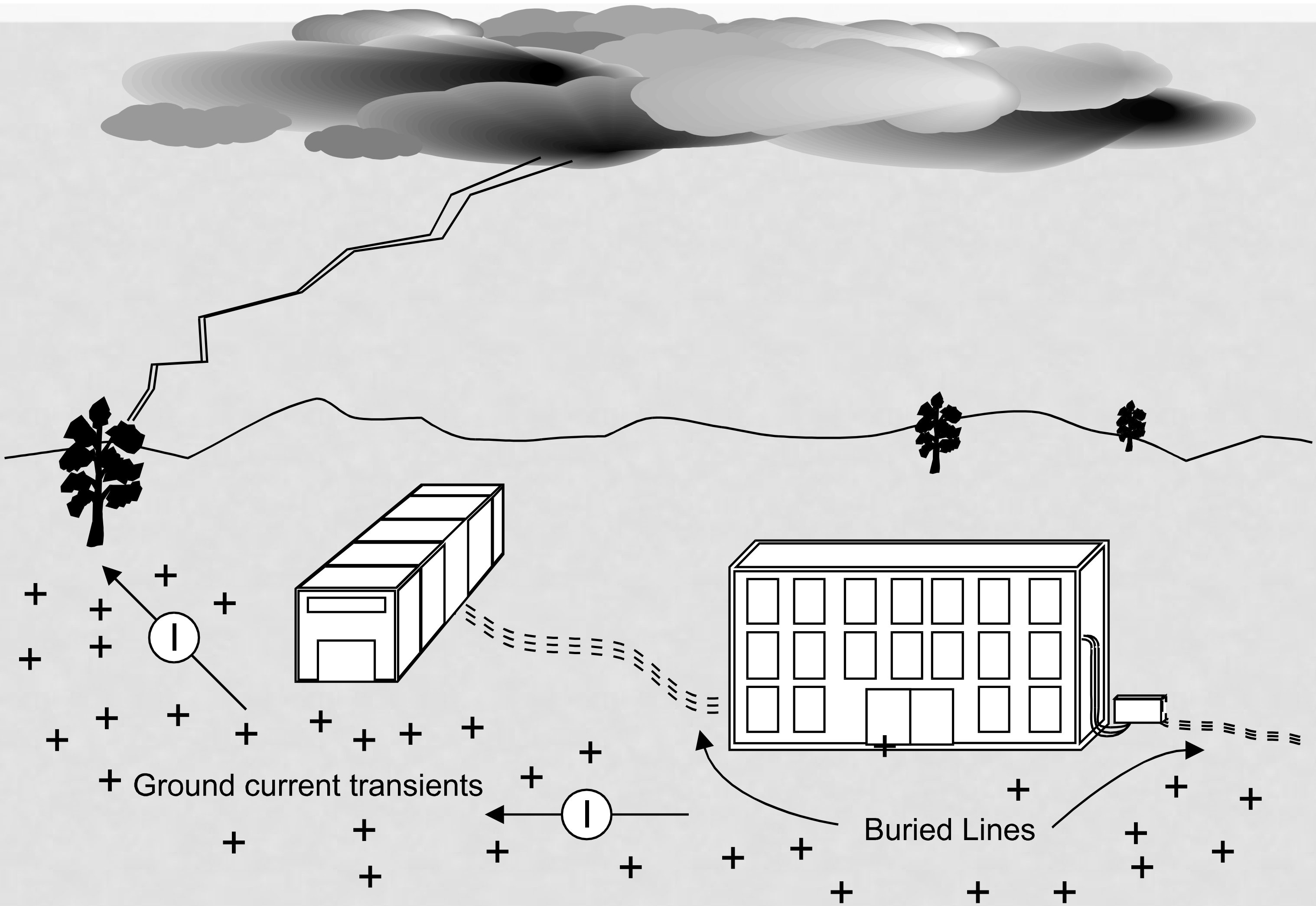
- The lightning does not have to actually strike a line. A close by strike to earth will raise local earth potential above remote ("true") earth, due to earth resistivity. This raised earth potential can cause a "flash-back" to one or more of the phases on the electricity system. The same thing can happen to communication equipment, eg modems (refer tutorial exercise).

- Earthed or "shield" conductors are often placed above phase conductors to induce the lightning to strike them instead of the phase conductors (the lightning is always trying to find the easiest path to earth).

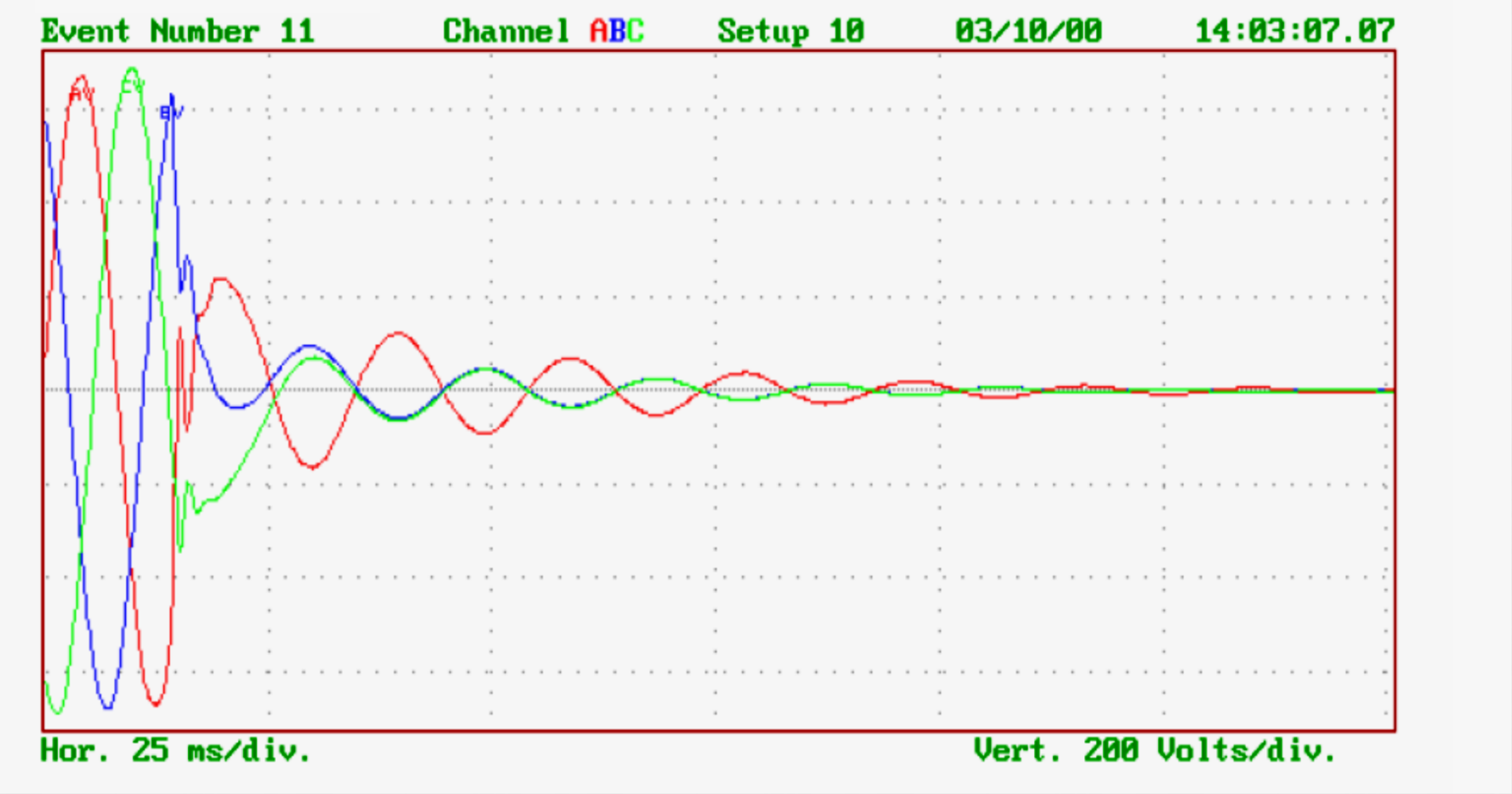
INDUCED TRANSIENT FROM LIGHTNING



INDUCED TRANSIENT FROM GROUND



OUTAGE



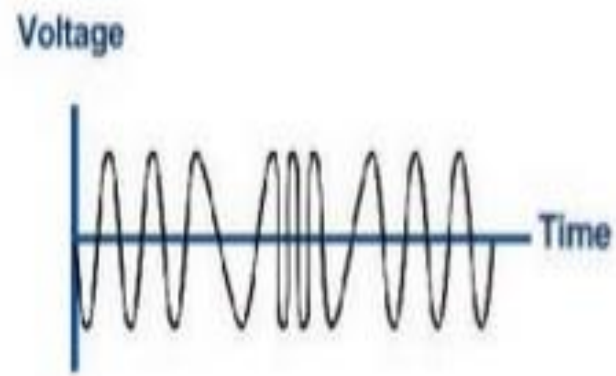
Event Number 11
Channel ABC
Setup 10
03/10/00
14:03:07.07
AV
CV
BV
Hor. 25 ms/div.
Vert. 200 Volts/div.

POWER FREQUENCY VARIATIONS

"Deviation of the power system fundamental frequency from it specified nominal value (e.g., 50 or 60 Hz)"

CAUSE

- Poor speed regulation of alternator



EFFECTS

- System crash
- Speed variation in motors

SOLUTION

- Power Conditioners.
- VDF, UPS

MAX PERMISSIBLE RANGE

49.2 to 50.3 Hz

VOLTAGE PROBLEMS

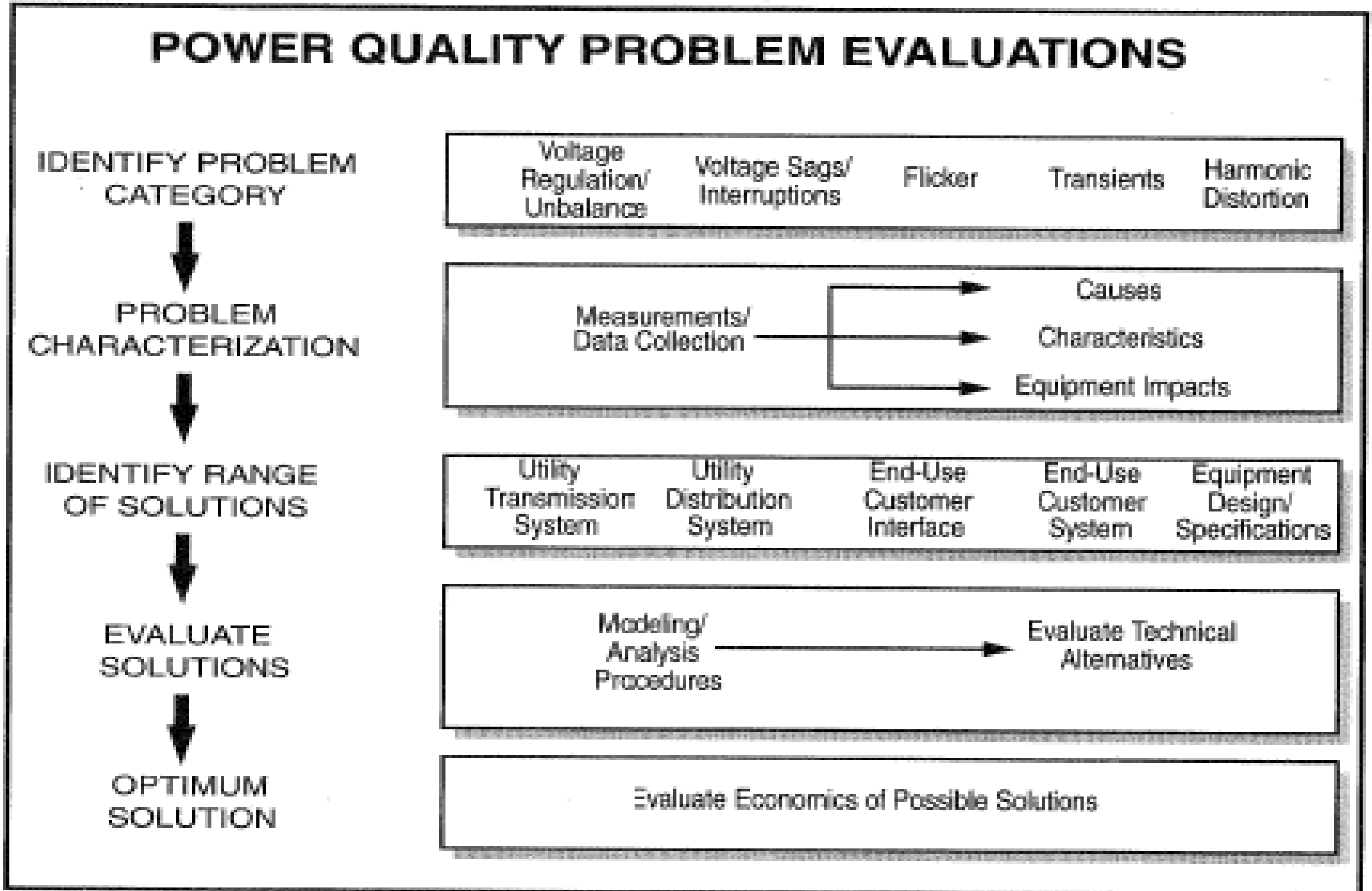
Problem	Typical Duration	Typical Voltage Change from Nominal	Typical Incidence Frequency/Cost
Transient*	<50 ns – 5 ms	Thousands of %	Low/$$$$
Sag*	0.5 cycles – 60 s	10 – 90%	High/$-$$$
Swell	0.5 cycles – 60 s	110 – 180%	Low/$
Interruption*	0.5 cycles – >1 hour	<10%	Very Low/$$-$$$
Undervoltage*	>1 minute	90 – 99%	Medium/$$-$$$
Overvoltage*	>1 minute	101 – 110%	Medium/$$-$$$
Harmonics	Constant	0 – 20%	Low/$-$$
Noise	Constant	0 – 1%	Low/$-$$
Notching	Constant		Very Low/$
Unbalance	Fluctuating	0 – 15% Phase-Phase	Medium/$-$$

Most Problematic *

EFFECTS OF POWER QUALITY PROBLEMS

- Motors overheating, adjustable speed drives tripping off, computers shutting down, flickering lights, and stopped production.
- Computers, consumer products, lighting, meters, ferromagnetic equipment, telephones, manufacturing processes, and capacitors.
- Computers and computer-controlled equipment-freeze up and lose data-caused by voltage variations.
- digital clocks, microwave ovens, television sets, video cassette recorders, and stereo equipment.
- Most consumer products are affected by voltage sags and outages causing the electronic timer to shut down and blinking clock.
- Lighting includes incandescent, high-intensity discharge, and fluorescent lights.
- Incandescent lights often dim during a voltage sag.
- when arc furnaces and arc welders cause the voltage to fluctuate.
- Meters will give erroneous readings in the presence of harmonics.
- Ferromagnetic equipment include transformers and motors-overheat and lose life.
- Telephones will experience noise induced by adjacent electrical equipment-overheat and lose life.
- Adjustable-speed drives-The frequent shutdown of an adjustable-speed drive - excessive harmonics
- Many manufacturing processes-shutdowns due to voltage sags.

TYPICAL PQ EVALUATION PROCESS



POWER QUALITY MEASUREMENT

- Types of equipment for monitoring power quality:
  - Digital multimeter
  - Oscilloscope
  - Disturbance analyzer
  - Spectrum and harmonic analyzer

Solution to Power Quality Problem..

- **Earthing practices**
  - Power quality problem is caused by incorrect earthing practices.
  - Verification of earthing arrangement should be conducted in power quality investigation.
- **Reducing the number of faults**
  - For examples tree-trimming, animal guards, shielding wires and replacing overhead lines by underground lines.
  - Normally used to solve voltage dip problem.
- **Faster fault clearing**
  - Need to improve protection techniques.
  - Development of a new generation of circuit breakers and relay at the transmission level.

- **Static breaker**
  - Allow the isolation of faulted circuits in the shortest possible time frame, while other nearby loads will improve the power quality of the network.

- **Transfer switch**
  - Used to transfer a load connection from one supply to another, allowing the choice of two supplies for the load (or sub network).
  - One of the supply will handle the power disturbances on the system whereas the other one will be automatically switched on to reduce the possibility of supply disruption to the load.

- **Local or embedded generation**
  - A form of local generation, i.e. diesel generator, can be connected to allow for any shortfall (or loss) in the main capacity and also to provide ride-through for power quality disturbances.
  - Expensive solution since the cost to keep a diesel generator running online.

MITIGATION EQUIPMENT AT THE INTERFACE..

- UPS (Uninterruptible power supply)
  - Standby, online and hybrid UPS
- Dual feeder with static transfer
  - Static VAR Compensator (SVC)
  - STATCOM (static synchronous compensator)
  - DVR (dynamic voltage restorer)
- Various line-voltage regulators
  - Constant voltage transformer
  - Transformer with tap changer
- Harmonic filter
  - Passive and active filters
- Motor-generator sets
- Surge suppressor
- Isolation transformer
- Noise filter
- Energy storage system

POWER QUALITY STANDARDS

S. No.	Abbreviation	The standard name
1	IEEE	Institute of Electrical and Electronics Engineer
2	IEC	International Electro technical Communication
3	CENELEC	European committee for Electro technical Standardization
4	ANSI	American National Standards Institute
5	NER	National Electricity Regulator
6	SEMI	Semiconductor Equipment and Material International
7	UIE	International Union for Electricity Applications

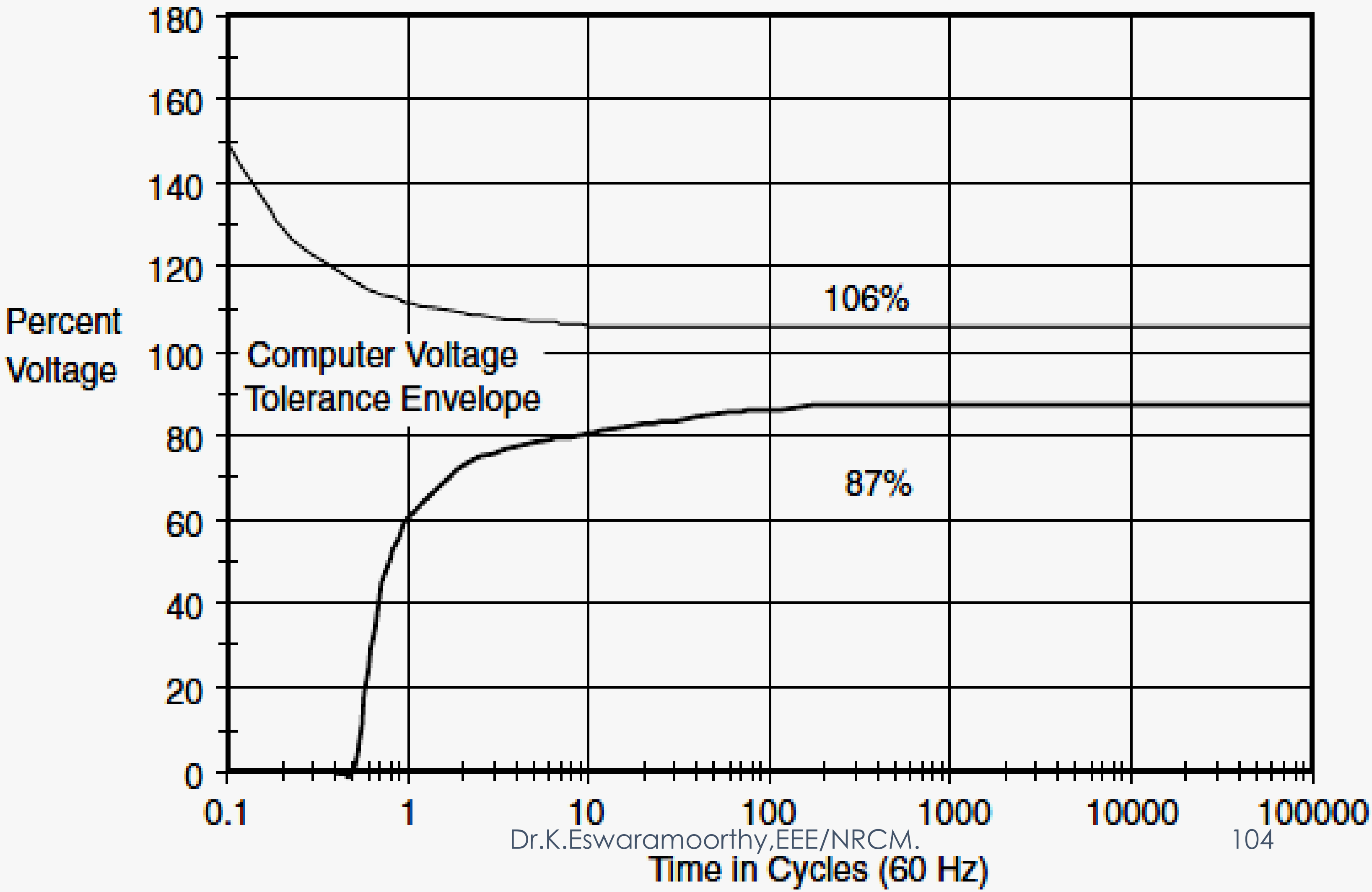
POWER QUALITY STANDARDS

- IEEE P1433: Power quality definitions
- IEEE P1453: Voltage flicker
- IEEE P1564: Voltage sag indices
- IEEE 1159: Recommended practice for monitoring electric power quality
- IEEE 519: Recommended practices and requirements for harmonic control in electrical power system
- IEC SC77A/WG1: Harmonics and other low frequency disturbances
- IEC TC77/WG1: Terminology
- IEC SC77A/WG8: Electromagnetic interference related to the network frequency
- IEC SC77A/WG9: Power quality measurement methods

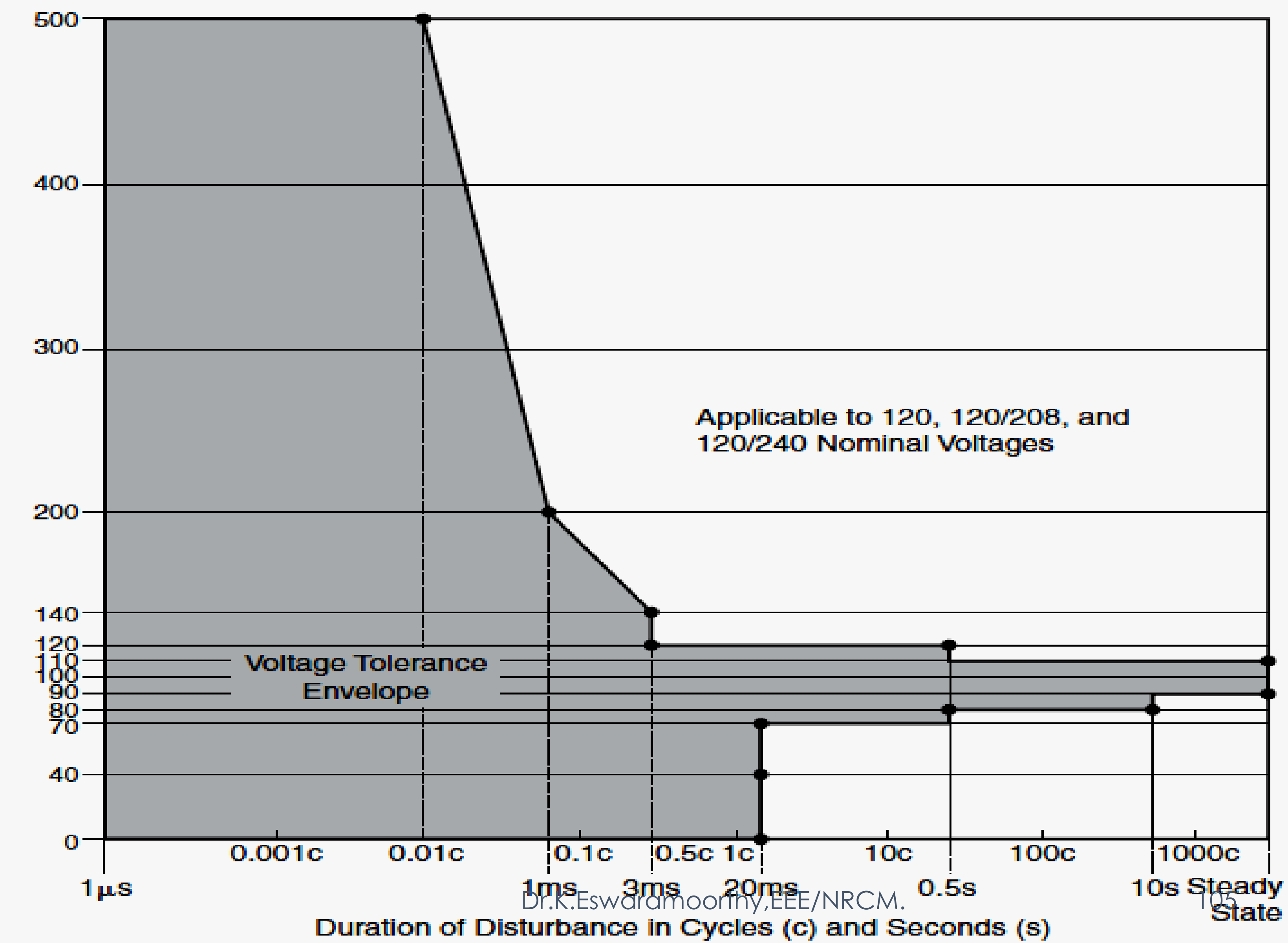
CBEMA AND ITI CURVES

- One of the most frequently employed displays of data to represent the power quality is the so-called CBEMA curve.
- This curve was originally developed by CBEMA to describe the tolerance of mainframe computer equipment to the magnitude and duration of voltage variations on the power system.
- The axes represent magnitude and duration of the event.
- Points below the envelope are presumed to cause the load to drop out due to lack of energy.
- Points above the envelope are presumed to cause other malfunctions such as insulation failure, overvoltage trip, and over excitation.
- The upper curve is actually defined down to 0.001 cycle where it has a value of about 375 percent voltage.
- curve only from 0.1 cycle and higher due to limitations in power quality monitoring instruments and differences in opinion over defining the magnitude values in the subcycle time frame.

A PORTION OF THE CBEMA CURVE COMMONLY USED AS A DESIGN TARGET FOR EQUIPMENT AND A FORMAT FOR REPORTING POWER QUALITY VARIATION DATA



ITI CURVE FOR SUSCEPTIBILITY OF 120V COMPUTER EQUIPMENT



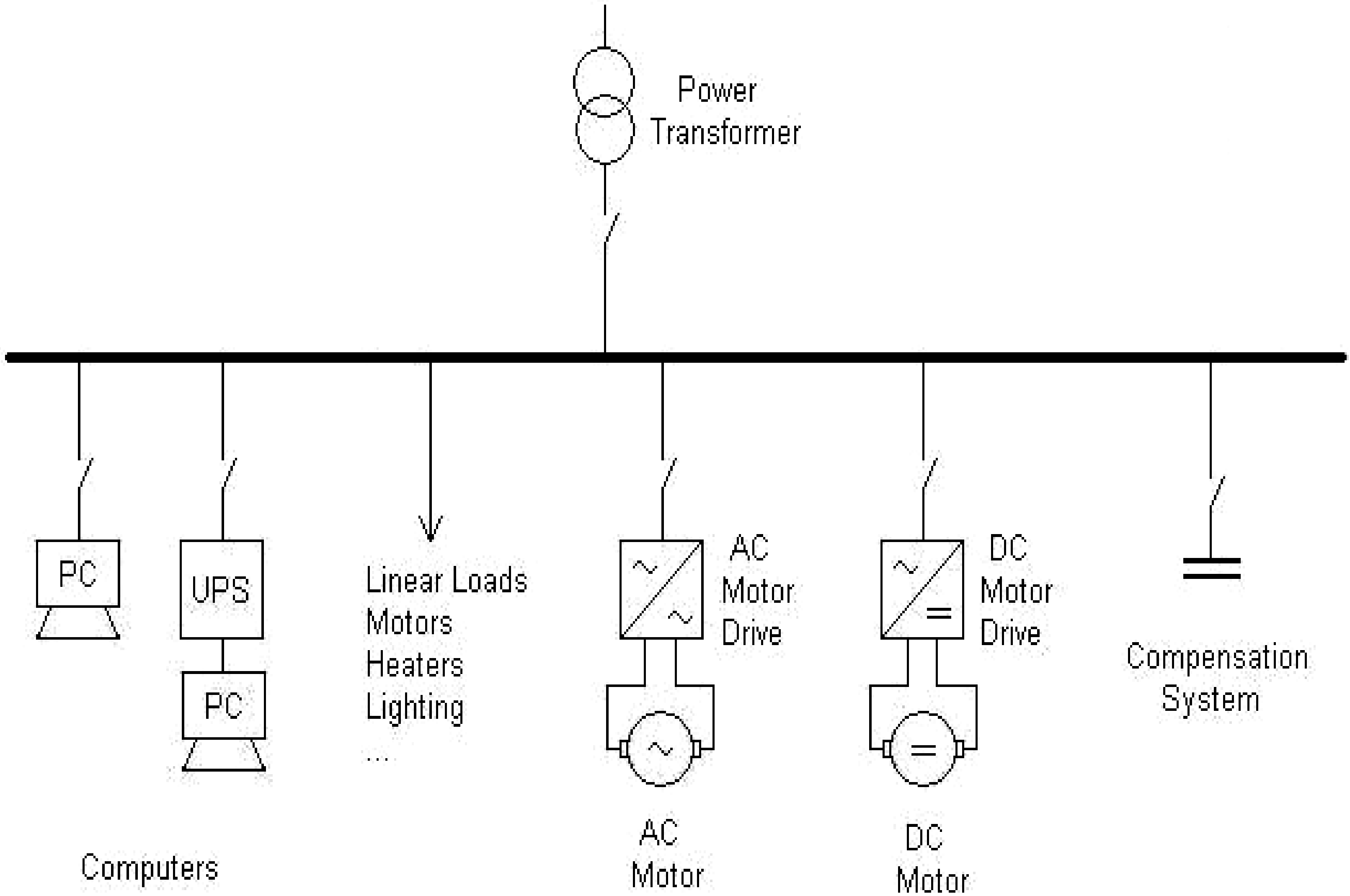
WHEN TO MONITOR?

- Before installation of plant / Equipment
- Before expansion
- After problem occurrence / suspect
- Annually / Periodically
- Formulation of guidelines
- Continuously

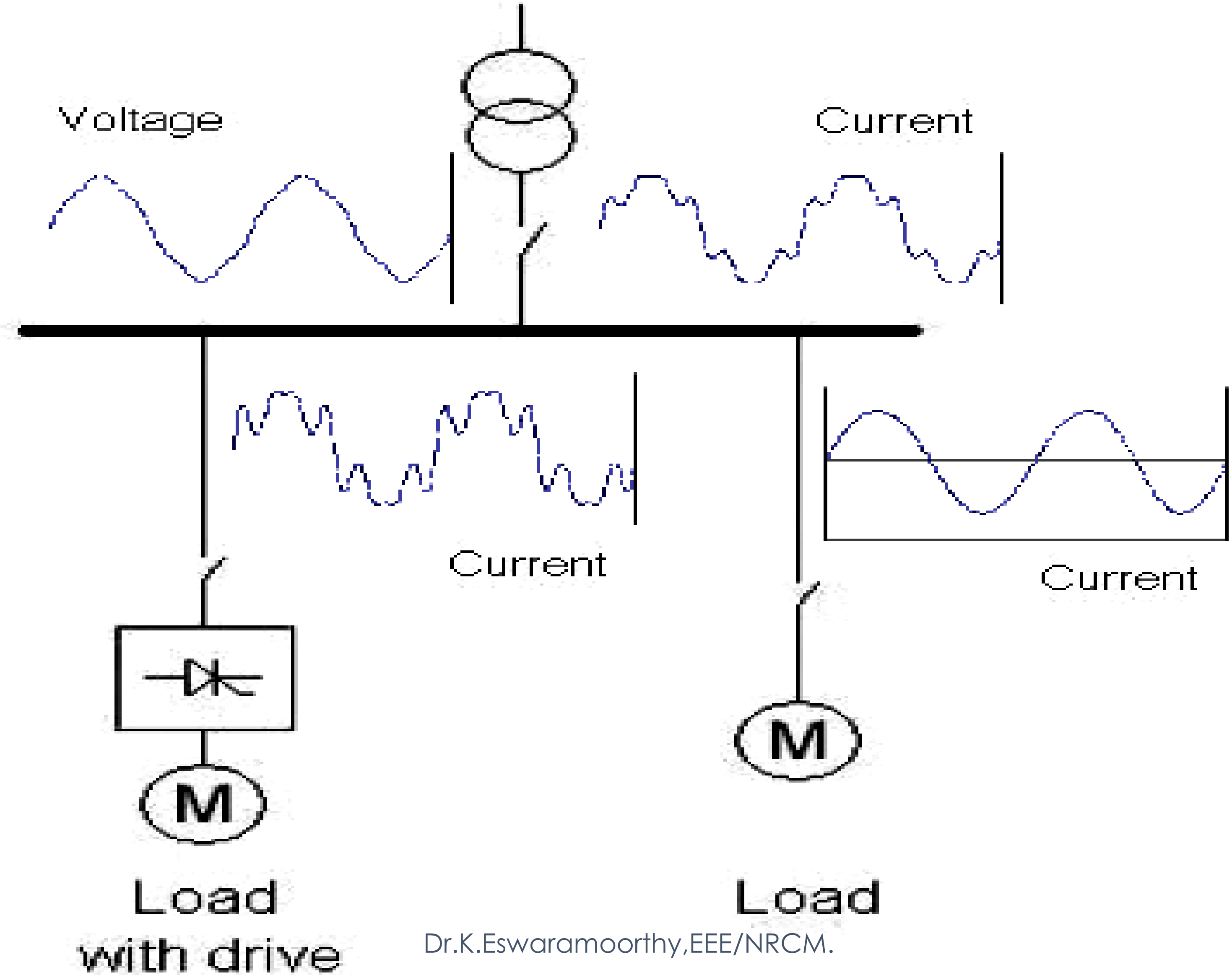
WHERE TO MONITOR?

- Close to sensitive /critical equipment
- Close to source
- PCC / metering point
- Major Nodes / Branches

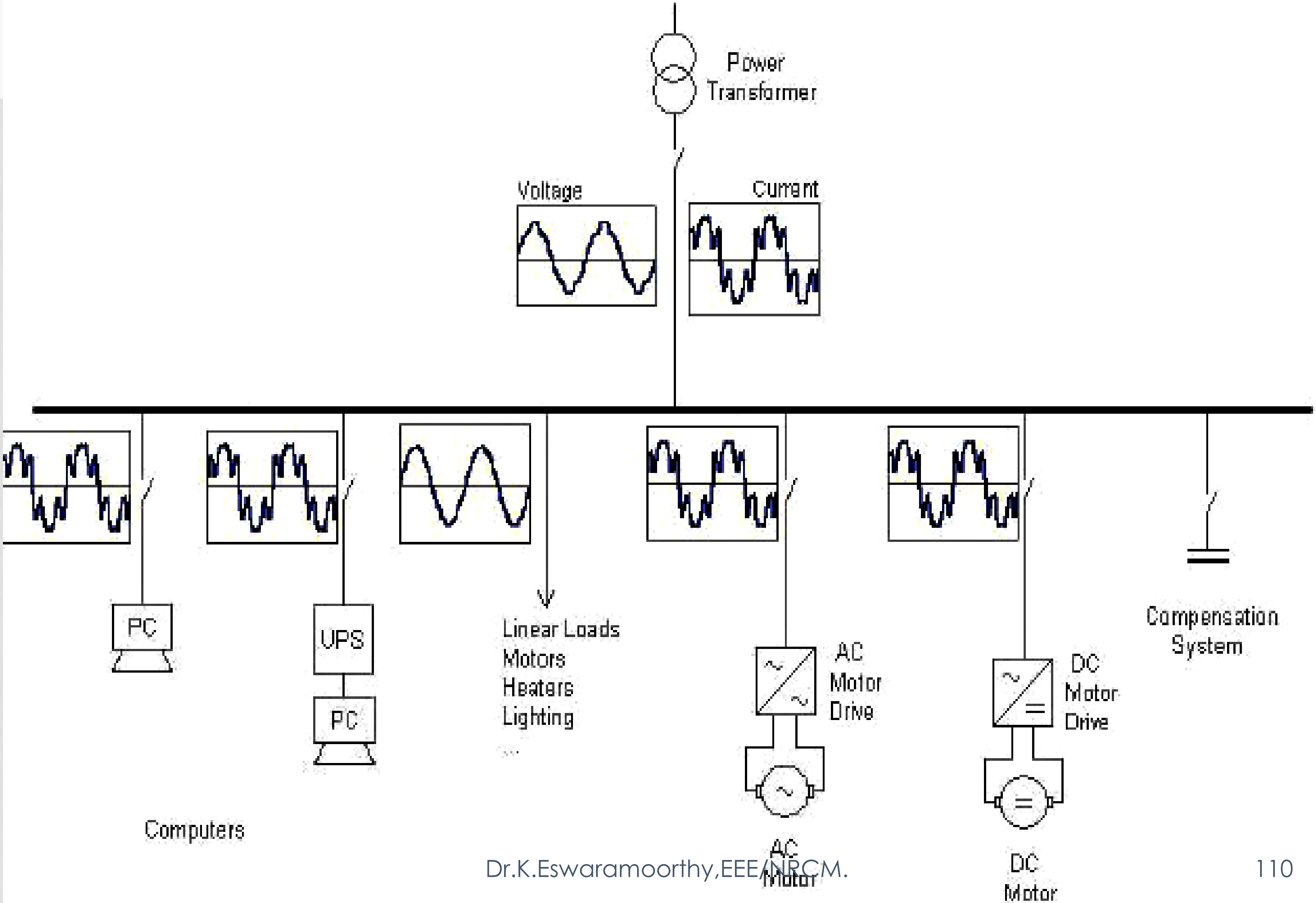
EXAMPLES OF LOADS



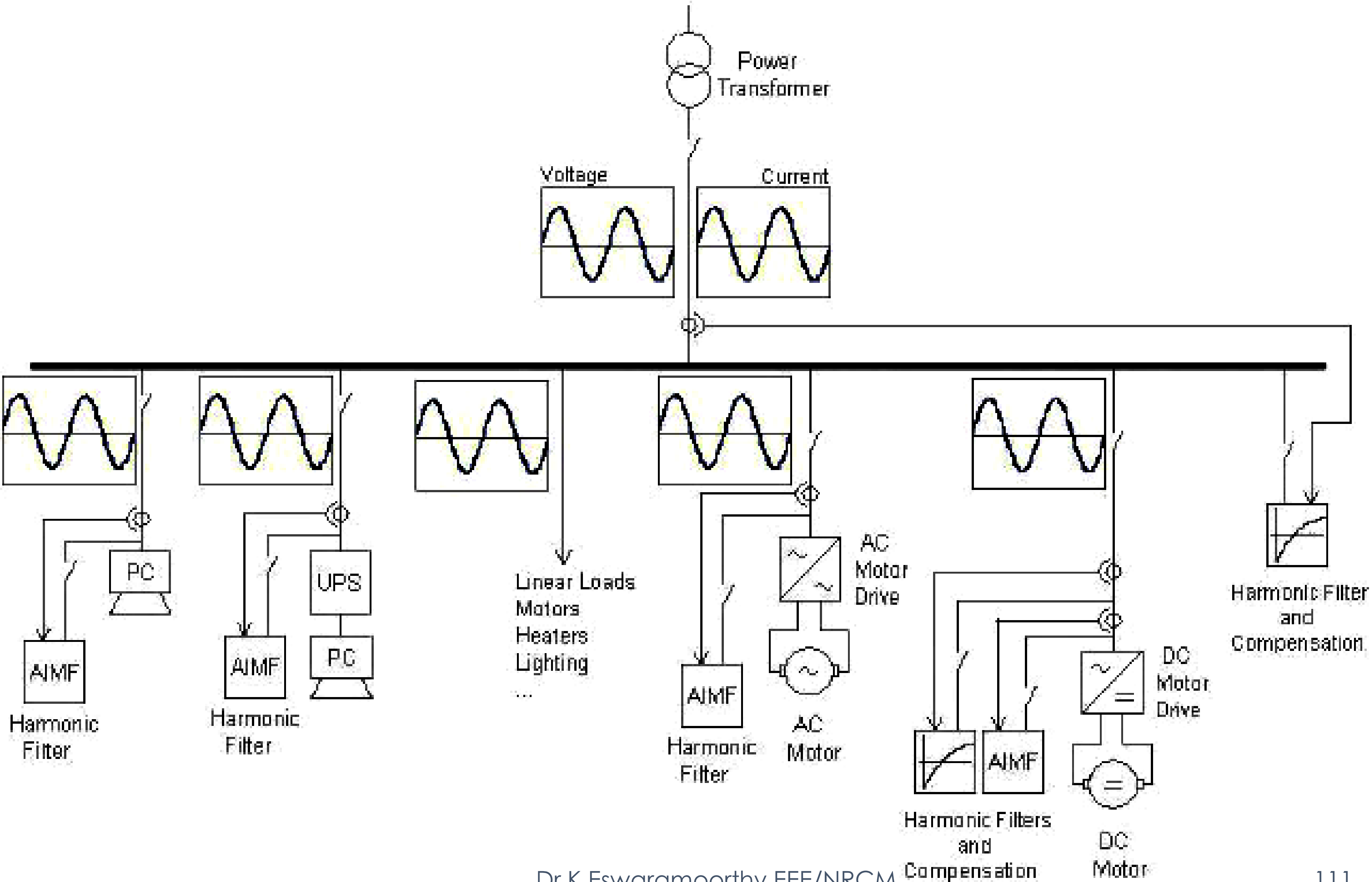
HARMONICS IN POWER SYSTEMS



EFFECTS OF LOAD HARMONICS



WITHOUT HARMONICS



HOW TO MONITOR?

- Level
  - – Basic monitors
    - DSO, multimeter, demand meters
  - – Dedicated monitors
    - Harmonic analyzer, flicker meter, event/disturbance recorders, Impedance analyzers
  - – Advanced monitors
- Mode
  - – Stand alone
  - – Integrated
  - – Continuous
- Snap shot
- Full cycle
- Continuous

WHO SHOULD MONITOR?

- Supplier of power
  - – Contractual obligations
  - – System performance monitoring & improvement
- Consumer
  - – Improvement measures
  - – Compliance
  - – Monitor performance, new installations
- Regulator
  - – To ensure compliance
  - – To formulate standards
- Manufacturer
  - – Performance guarantee
  - – Design & Development

WHAT TO DO WITH DATA? DATA ANALYSIS

- Collection of raw data
- Compilation of data
- Analysis of data
  - – Trending
  - – Limit analysis
  - – Correlation
  - – Advanced AI systems
  - – Diagnosis, Recommendations & Actions

TO SUMMARIZE (MONITOR)

- Monitoring PQ is important
- Data collection should be systematic
- Data analysis is important
- PQ monitoring equipments are available
- PQ Audit should be made mandatory for specific customers

USEFUL VIDEO LINK

- https://www.youtube.com/watch?v=q4VjsHq4LOk
- https://youtu.be/TtallnoóEBk

SHORT QUESTIONS

1) Distinguish power quality and voltage quality. [3]
2) What are the causes for swells and interruptions? [3]
3) Explain about flicker. [4]
4) Define THD and TDD of harmonic spectrum
5) Write standards of power quality monitoring.
6) Write about application of intelligent systems for power quality.
7) Write different types of non- linear loads.
8) Describe capacitor for voltage regulation
9) Differentiate voltage sag and voltage swells.
10) Write short notes on principles of regulating the voltage.
11) Explain point of common coupling.
12) Write about power quality bench marking.
13) Describe interruption.

14) Write short notes on voltage regulation and distortion factor.
15) Define power quality bench marking.
16) List the major power quality issue
17) Illustrate about notching in power quality
18) Differentiate inter harmonic and sub harmonics
19) Criticize "capacitor switching leads to overvoltage"
20) What are the reasons voltage imbalance
21) Comment transients or noise on the power line causing problems now
22) How voltage fluctuation affect the power quality
23) List out the need of power quality standards
24) Classify power quality events in short duration events
25) Classify the types of power quality solutions available on the market today

LONG QUESTIONS

1) Explain different types of transients.
2) Explain about transient over voltages.
3) Explain about long duration and short duration voltage variations.
4) Explain different modes of wave form distortion. Explain different sources of voltage sags and interruptions.
5) Write about different sources of harmonics.
6) What are major power quality issues and explain them?
7) Explain different modes of waveform distortion and causes for it.
8) Discuss voltage imperfections in power systems due to non-linear loads.
9) Write different points to be noted for selection of meter for measurement of power quality.
10) Explain various power quality monitoring standards.
11) Briefly describe about
    1) impulsive transients
    2) Oscillatory transients
12) Explain briefly about long duration and short duration voltage variations.

12) Name and explain different types of power quality issues that affects the power systems depending upon the severity?

13) Define Total Harmonic Distortion. Explain the procedure for calculation the Total Harmonic Distortion (THD) due to disturbance in the power system.

14) Discuss the following characteristics of power quality issue

    (a) Short duration variations

    (b) Long duration variations

15) Discuss in detail about transients

16) Describe the CBEMA and ITI curve

17) Define waveform distortion and explain the waveform distortion categories

18) Discuss the source and effects of different categories of long duration voltage variations that affect the power Quality.

19) Explain power quality and explain the reasons for increased concern in power quality.

20) Explain the various types of power quality disturbances in power system and also explain the characteristics of each disturbance.

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Department of Electrical and Electronics Engineering

Subject Code & Name:	**EE811PE & POWER QUALITY AND FACTS**
UNIT- II **Transmission Lines and Series/Shunt Reactive Power Compensation**	
Faculty Name :	**Dr.K.Eswaramoorthy**

Syllabus

- **Transmission Lines and Series/Shunt Reactive Power Compensation:** Basics of AC Transmission. Analysis of uncompensated AC transmission lines. Passive Reactive Power Compensation. Shunt and series compensation at the mid-point of an AC line. Comparison of Series and Shunt Compensation.

Department of Electrical and Electronics Engineering

Subject Code & Name:	**EE811PE & POWER QUALITY AND FACTS**
UNIT- II **Transmission Lines and Series/Shunt Reactive Power Compensation**	
Topic Name :	**Introduction-Reactive Power**
Faculty Name :	**Dr.K.Eswaramoorthy**

1.Introduction - REACTIVE POWER

- an understanding of reactive power associated with power transmission networks is developed.
- To make transmission networks operate within desired voltage limits, methods of making up or taking away reactive power and it control is reactive-power control.
- Upon energization, the ac networks and the devices connected to them create associated time-varying electrical fields related to the applied voltage, as well as magnetic fields dependent on the current flow.
- As they build up, these fields store energy that is released when they collapse.
- Apart from the energy dissipation in resistive components, all energy-coupling devices, including transformers and energy-conversion devices (e.g., motors and generators), operate based on their capacity to store and release energy

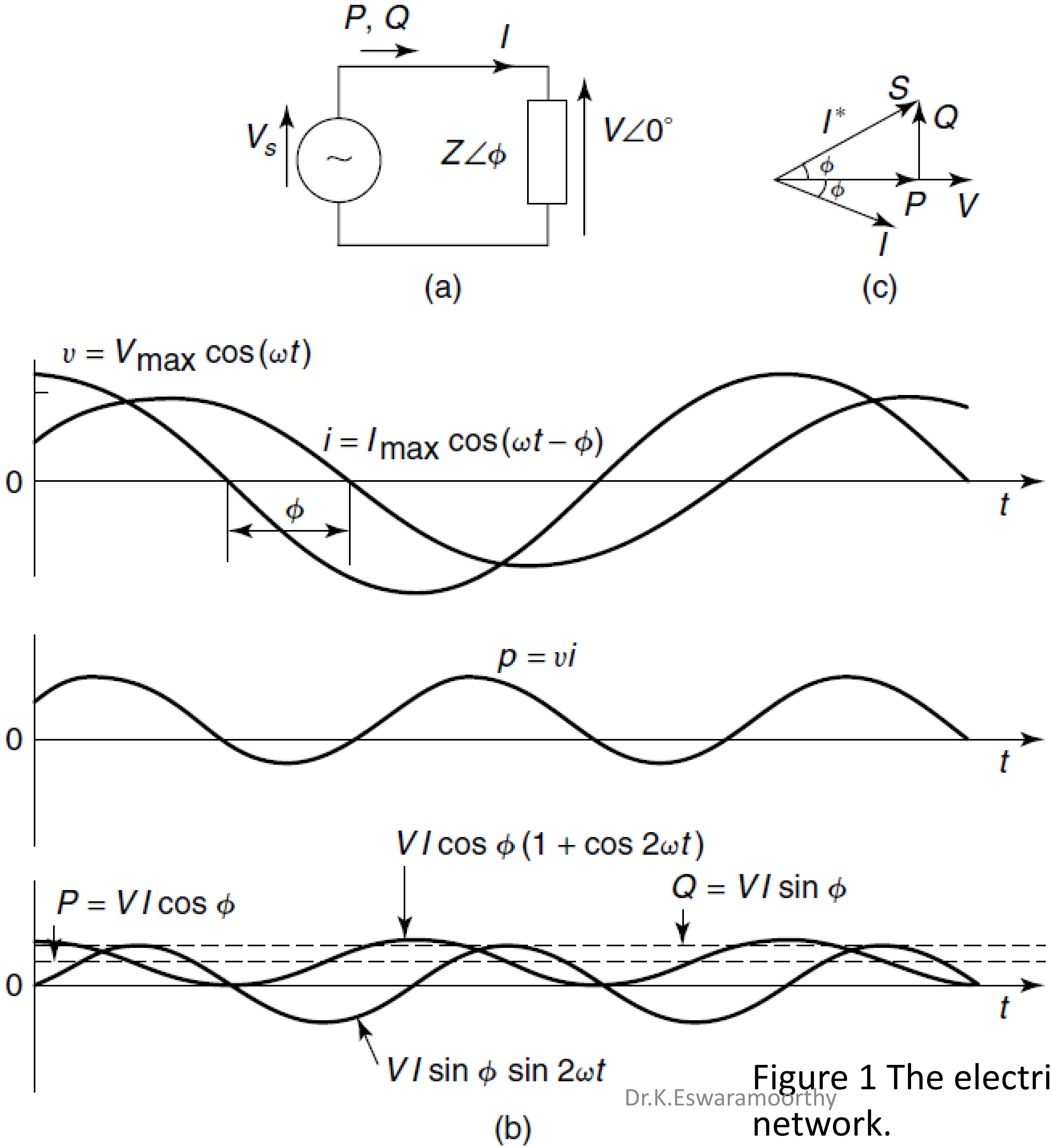

Figure 1 The electrical parameters in an ac network.

- For the ac circuit shown in Fig. 1(a), instantaneous power from the voltage source to the load $Z\angle\phi$, in terms of the instantaneous voltage v and current i, is given as
- $$p = vi \qquad \text{----1}$$

In the steady state, where $v = V_{\max}\cos(\omega t)$ and $i = I_{\max}\cos(\omega t - \phi)$:

$$p = \frac{V_{\max} I_{\max}}{2}\left[\cos\phi + \cos(2\omega t - \phi)\right]$$

- $$= VI\cos\phi(1 + \cos 2\omega t) + VI\sin\phi\sin 2\omega t \qquad \text{-----2}$$

- where *V* and *I* are the respective root mean square (rms) values of *v* and *i*.

- Equations (1) and (2) are pictorially represented in Fig. 1(b). Equation (2) comprises two double-frequency (2ω) components.
- The first term has an average value as well as a peak magnitude of VI cos ϕ.
- This average value is the active power, P, flowing from the source to the load.
- The second term has a zero average value, but its peak value is VI sinϕ.
- Written in phasor domain, the complex power in the network in Fig. 1(a) is given by
- $S = \overline{V} \cdot \overline{I}^*$
- $= P + jQ = VI\cos\phi + jVI\sin\phi$ -----3
- where P is called the active power, which is measured in watts (W), and Q is called the reactive power, which is measured in volt–ampere reactives (var).

- The reactive power is essential for creating the needed coupling fields for energy devices.
- It constitutes voltage and current loading of circuits but does not result in an average (active) power consumption and is, in fact, an important component in all ac power networks.
- In high-power networks, active and reactive powers are measured in megawatts (MW) and MVAR, respectively.
- Electromagnetic devices store energy in their magnetic fields.
- These devices draw lagging currents, thereby resulting in positive values of Q; therefore, they are frequently referred to as the absorbers of reactive power.
- Electrostatic devices, on the other hand, store electric energy in fields.
- These devices draw leading currents and result in a negative value of Q; thus they are seen to be suppliers of reactive power.
- The convention for assigning signs to reactive power is different for sources and loads, for which reason readers are urged to use a consistent notation of voltage and current, to rely on the resulting sign of Q, and to not be confused by absorbers or suppliers of reactive power.

Department of Electrical and Electronics Engineering

Subject Code & Name:	EE811PE & POWER QUALITY AND FACTS
UNIT- II Transmission Lines and Series/Shunt Reactive Power Compensation	
Topic Name :	Uncompensated Transmission Lines
Faculty Name :	Dr.K.Eswaramoorthy

2.UNCOMPENSATED TRANSMISSION LINES

- To develop a good, qualitative understanding of the need for reactive-power control, let us consider a simple case of a lossless short-transmission line connecting a source *Vs* to a load $Z\angle\phi$. (For simplicity, the line is represented only by its inductive reactance X_l.)
- Figure 2 shows such a network with its parameters, as well as a phasor diagram showing the relationship between voltages and currents.
- From Fig. 2(b), it is clear that between the sending- and the receiving-end voltages, a magnitude variation, as well as a phase difference, is created.
- The most significant part of the voltage drop in the line reactance $(\Delta V_1 = j\bar{I}_x X_l)$ is due to the reactive component of the load current, *Ix*.
- To keep the voltages in the network at nearly the rated value, two control actions seem possible:

 1. load compensation, and

 2. system compensation

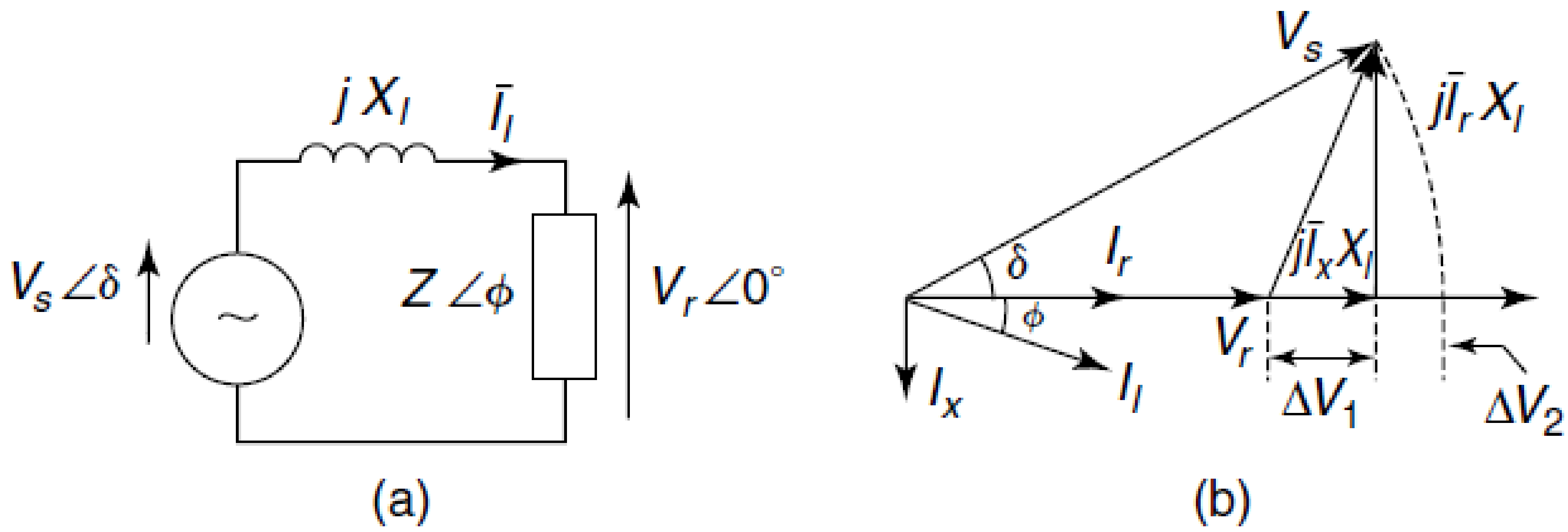

Figure 2 A short, lossless transmission line feeding a load.

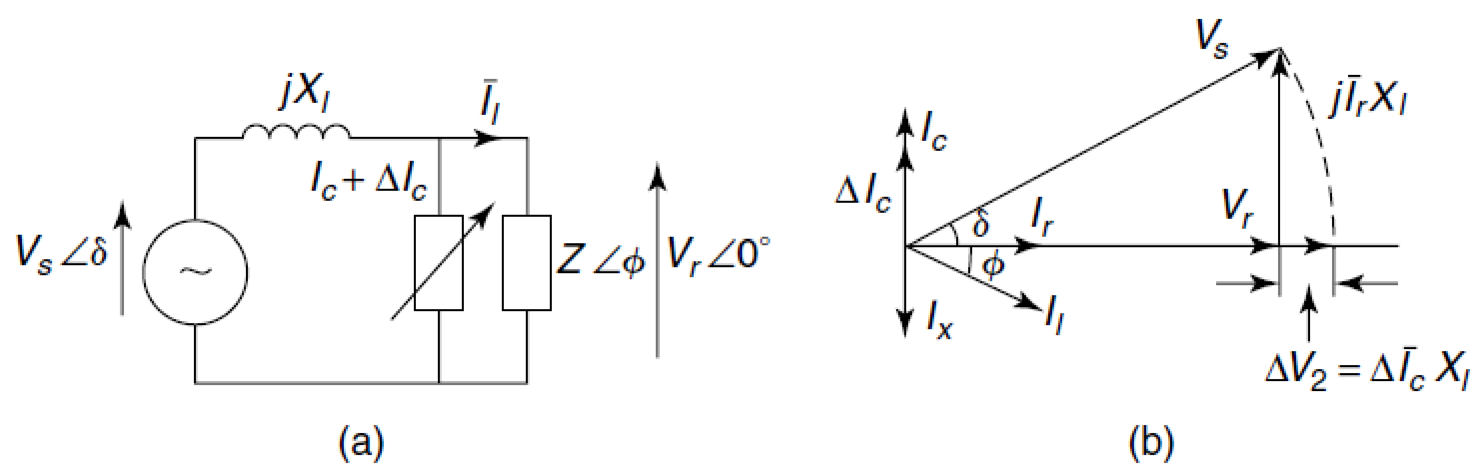

Figure 3 The reactive-power control for voltage regulation

1. Load Compensation

- It is possible to compensate for the reactive current Ix of the load by adding a parallel capacitive load so that $I_c = -I_x$.
- Doing so causes the effective power factor of the combination to become unity.
- The absence of Ix eliminates the voltage drop ΔV_1, bringing Vr closer in magnitude to Vs; this condition is called load compensation.
- Actually, by charging extra for supplying the reactive power, a power utility company makes it advantageous for customers to use load compensation on their premises.
- Loads compensated to the unity power factor reduce the line drop but do not eliminate it; they still experience a drop of ΔV_2 from $j\, I_r X_l$.

2 System Compensation

- To regulate the receiving-end voltage at the rated value, a power utility may install a reactive-power compensator as shown in Fig. 3.
- This compensator draws a reactive current to overcome both components of the voltage drop ΔV_1 and ΔV_2 as a consequence of the load current Il through the line reactance X_l.
- To compensate for ΔV_2, an additional capacitive current, ΔI_c, over and above Ic that compensates for I_x, is drawn by the compensator.
- When $\Delta I_c X_l = \Delta V_2$, the receiving-end voltage, Vr, equals the sending-end voltage, Vs.
- Such compensators are employed by power utilities to ensure the quality of supply to their customers

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Department of Electrical and Electronics Engineering

Subject Code & Name:	EE811PE & POWER QUALITY AND FACTS

UNIT- II
Transmission Lines and Series/Shunt Reactive Power Compensation

Topic Name :	Lossless Distributed Parameter Lines & Symmetrical Lines
Faculty Name :	Dr.K.Eswaramoorthy

2.1 Lossless Distributed Parameter Lines

- Most power-transmission lines are characterized by distributed parameters:
  - series resistance, r;
  - series inductance, l;
  - shunt conductance, g;
  - and shunt capacitance, c—all per-unit (pu) length.
- These parameters all depend on the conductors size, spacing, clearance above the ground, and frequency and temperature of operation.
- In addition, these parameters depend on the bundling arrangement of the line conductors and the nearness to other parallel lines.
- The characteristic behavior of a transmission line is dominated by its l and c parameters.
- Parameters r and g account for the transmission losses.
- The fundamental equations governing the propagation of energy along a line are the following wave equations:

- $$\frac{d^2\overline{V}}{dx^2} = zy\overline{V}$$ ------------4.a
- $$\frac{d^2\overline{I}}{dx^2} = zy\overline{I}$$ -------------4.b

where $zy = (r + j\omega l)(g + j\omega c)$.

- For a lossless line, the general solutions are given as
- $$\overline{V}(x) = \overline{V}_s \cos \beta x - jZ_0\overline{I}_s \sin \beta x$$ ------5a. & b
  $$\overline{I}(x) = \overline{I}_s \cos \beta x - j \frac{\overline{V}_s}{Z_0} \sin \beta x$$
- These equations are used to calculate voltage and current anywhere on line, at a distance x from the sending end, in terms of the sending-end voltage and current and the line parameters.

$$Z_0 = \sqrt{\frac{l}{c}}\ \Omega = \text{the surge impedance or characteristic impedance}$$

$$\beta = \omega\sqrt{lc}\ \text{rad/km} = \text{the wave number}$$

$$\beta a = \omega\sqrt{lca}\ \text{rad} = \text{the electrical length of an } a\text{-km line}$$

- where *l* is the line inductance in henries per kilometer (H/ km), *c* is the line shunt capacitance in farads per kilometer (F/ km), and 1/f*lc* is the propagation velocity of electromagnetic effects on the transmission line. (It is less than the velocity of light.)

- From 5b

$$\overline{I}_s = \frac{\overline{V}_s \cos \beta a - \overline{V}_r}{jZ_0 \sin \beta a}$$

If $\overline{V}_s = V_s \angle 0^\circ$ and $\overline{V}_r = V_r \angle - \delta = V_r(\cos \delta - j \sin \delta)$, then

- $$\overline{I}_s = \frac{V_r \sin \delta + j(V_r \cos \delta - V_s \cos \beta a)}{Z_0 \sin \beta a} \quad \text{--------6}$$

Therefore, the power at the sending end is given as

$$S_s = P_s + jQ_s = \overline{V}_s \overline{I}_s^*$$

$$= \frac{V_s V_r \sin \delta}{Z_0 \sin \beta a} + j \frac{V_s^2 \cos \beta a - V_s V_r \cos \delta}{Z_0 \sin \beta a} \quad \text{-----7}$$

Likewise, power at the receiving end is given as

$$S_r = P_r + jQ_r = -\frac{V_s V_r \sin \delta}{Z_0 \sin \beta a} + j \frac{V_r^2 \cos \beta a - V_s V_r \cos \delta}{Z_0 \sin \beta a} \quad \text{--------8}$$

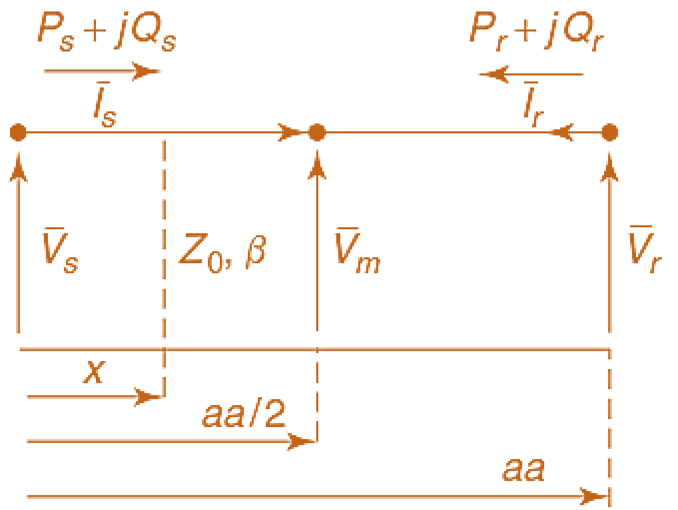

Figure 4 The power on a lossless distributed line.

- Comparing Eqs. (7) and (8) and taking the directional notation of Fig. 4 into account, it is concluded that for a lossless line, *Ps* = − *Pr* , as expected.
- However, *Qs* ≠ *Qr* because of the reactive-power absorption/ generation in the line.
- From Eqs. (7) and (8), the power flow
- from the sending end to the receiving end
- is expressed as

$$P = \frac{V_s V_r \sin\,\delta}{Z_0 \sin\,\beta a}$$

- In electrically short power lines, where $\beta\alpha$ is very small, it is possible to make a simplifying assumption that sin $\beta\alpha = \beta\alpha$ or Z_0 sin $\beta\alpha = Z_0\beta\alpha = \omega la$, where ω la = Xl is the total series reactance of a line. This substitution results in the following well-recognized power equation:

$$P = \frac{V_s V_r}{X_l} \sin\,\delta \qquad \text{------------9}$$

Accordingly, the maximum power transfer is seen to depend on the line length. When the power-transfer requirement for a given length of a line increases, higher transmission voltages of Vs and Vr must be selected

Symmetrical Lines

- When the voltage magnitudes at the two ends of a line are equal, that is, Vs =Vr = V, the line is said to be symmetrical.
- Because power networks operate as voltage sources, attempts are made to hold almost all node voltages at nearly rated values.
- A symmetrical line, therefore, presents a realistic situation. From Eqs. (7) and (8) the following relationships are derived:

$$P_s = -P_r = \frac{V^2}{Z_0 \sin \beta a} \sin \delta \qquad \text{-------------10}$$

$$Q_s = Q_r = \frac{V^2 \cos \beta a - V^2 \cos \delta}{Z_0 \sin \beta a} \qquad \text{-------------11}$$

Active and reactive powers of a transmission line are frequently normalized by choosing the surge-impedance load (SIL) as the base. The SIL is defined as $P_0 = V_{nom}^2/Z_0$, where V_{nom} is the rated voltage. When $V_s = V_r = V_{nom}$,

$$\frac{P_s}{P_0} = -\frac{P_r}{P_0} = \frac{\sin \delta}{\sin \beta l} \qquad \text{-------------12}$$

$$\frac{Q_s}{Q_0} = \frac{Q_r}{Q_0} = \frac{\cos \beta a}{\sin \beta a} \frac{\cos \delta}{\sin \beta a} \qquad \text{-------------13}$$

Midpoint Conditions of a Symmetrical Line

- The magnitude of the midpoint voltage depends on the power transfer.
- This voltage influences the line insulation and therefore needs to be well understood.
- For a symmetrical line where the end voltages are held at nominal values, the midpoint voltage shows the highest magnitude variation.
- In terms of the midpoint voltage *Vm*, the receiving-end voltage of a symmetrical line, from Eq. (4), is given as

$$\overline{V}_r = \overline{V}_m \cos\frac{\beta a}{2} - jZ_0\overline{I}_m \sin\frac{\beta a}{2} \qquad \text{-------------14}$$

- For simplification, define $\overline{V}_m = V_m \angle 0^\circ$ as the reference phasor.
- Because the line is symmetrical and lossless, that is, Ps=Pr= Pm = P and Qm =0, the midpoint current Im is given by Im = P/ Vm.

$$\overline{V}_r = V_m \cos\frac{\beta a}{2} - jZ_0 \frac{P}{V_m} \sin\frac{\beta a}{2}$$

$$V_r^2 = V_m^2 \cos^2\frac{\beta a}{2} + Z_0^2 \frac{P^2}{V_m^2} \sin^2\frac{\beta a}{2}$$

Setting $V_r = V_{\text{nom}}$ and $V_{\text{nom}}^2/Z_0 = P_0$, we get

$$\frac{V_r^2}{V_{\text{nom}}^2} = \left(\frac{V_m}{V_{\text{nom}}}\right)^2 \cos^2\frac{\beta a}{2} + \left(\frac{Z_0}{V_{\text{nom}}^2}\right)^2 P^2 \left(\frac{V_{\text{nom}}}{V_m}\right)^2 \sin^2\frac{\beta a}{2}$$

If we let $V_m/V_{\text{nom}} = \tilde{V}_m$ (per-unit voltage at the midpoint), then considerng that $(V_r/V_{\text{nom}}) = 1$, we have

$$\tilde{V}_m^4 - \frac{\tilde{V}_m^2}{\cos^2\frac{\beta a}{2}} + \left(\frac{P}{P_0}\right)^2 \tan^2\frac{\beta a}{2} = 0$$

$$\tilde{V} = \left[\frac{1}{2\cos^2\frac{\beta a}{2}} \pm \sqrt{\frac{1}{4\cos^2\frac{\beta a}{2}} - \left(\frac{P}{P_0}\right)^2 \tan^2\frac{\beta a}{2}}\right]^{1/2} \qquad \text{-------15}$$

- Equation (15) determines the midpoint voltage of a symmetrical line as a
- function of the power flow P on it.
- Practical Considerations In general, the values of line parameters l and c
- remain reasonably independent of the transmission voltage. For example, typical values of l and c may lie in the following ranges:
- L= the line inductance/ km= 0.78–0.98 mH/ km
- C=the line capacitance/ km= 12.1–15.3 nF/ km
- On the basis of these parameters, the surge impedance, $Z_0 = \sqrt{\frac{l}{c}}$, lies in the range of 225 to 285

Department of Electrical and Electronics Engineering

Subject Code & Name:	**EE811PE & POWER QUALITY AND FACTS**
UNIT- II **Transmission Lines and Series/Shunt Reactive Power Compensation**	
Topic Name :	**Passive Compensation**
Faculty Name :	**Dr.K.Eswaramoorthy**

3. PASSIVE COMPENSATION

- A lossless line was analyzed, and the case study presented and it provided many numerical results and highlighted the problems of voltage control and the need to exercise reactive-power control to make a system workable.
- Reactive-power control for a line is often called *reactive-power compensation.*
- External devices or subsystems that control reactive power on transmission lines are known as *compensators.*
- Truly speaking, a compensator mitigates the undesirable effects of the circuit parameters of a given line.
- The objectives of line compensation are invariably
  - 1. to increase the power-transmission capacity of the line, and/ or
  - 2. to keep the voltage profile of the line along its length within acceptable bounds to ensure the quality of supply to the connected customers as well as to minimize the line-insulation costs.

- Because reactive-power compensation influences the power-transmission capacity of the connected line, controlled compensation can be used to improve the system stability (by changing the maximum power-transmission capacity), as well as to provide it with positive damping.
- Like other system components, reactive-power compensators are dimensioned, and their types are selected on the basis of both their technical and cost effectiveness.

1.Shunt Compensation

- Passive reactive-power compensators include series capacitors and shunt-connected inductors and capacitors.
- Shunt devices may be connected permanently or through a switch.
- Shunt reactors compensate for the line capacitance, and because they control overvoltages at no loads and light loads, they are often connected permanently to the line, not to the bus.
- Figure 12 shows the arrangements of shunt reactors on a long-distance, high-voltage ac line.
- Many power utilities connect shunt reactors via breakers, thereby acquiring the flexibility to turn them off under heavier load conditions.
- Shunt reactors are generally gapped-core reactors and, sometimes, air-cored.
- Shunt capacitors are used to increase the power-transfer capacity and to compensate for the reactive-voltage drop in the line.
- The application of shunt capacitors requires careful system design.
- The circuit breakers connecting shunt capacitors should withstand high-charging in-rush currents and also, upon disconnection, should withstand more than 2-pu voltages, because the capacitors are then left charged for a significant period until they are discharged through a large time-constant discharge circuit.
- Also, the addition of shunt capacitors creates higher-frequency–resonant circuits and can therefore lead to harmonic overvoltages on some system buses.

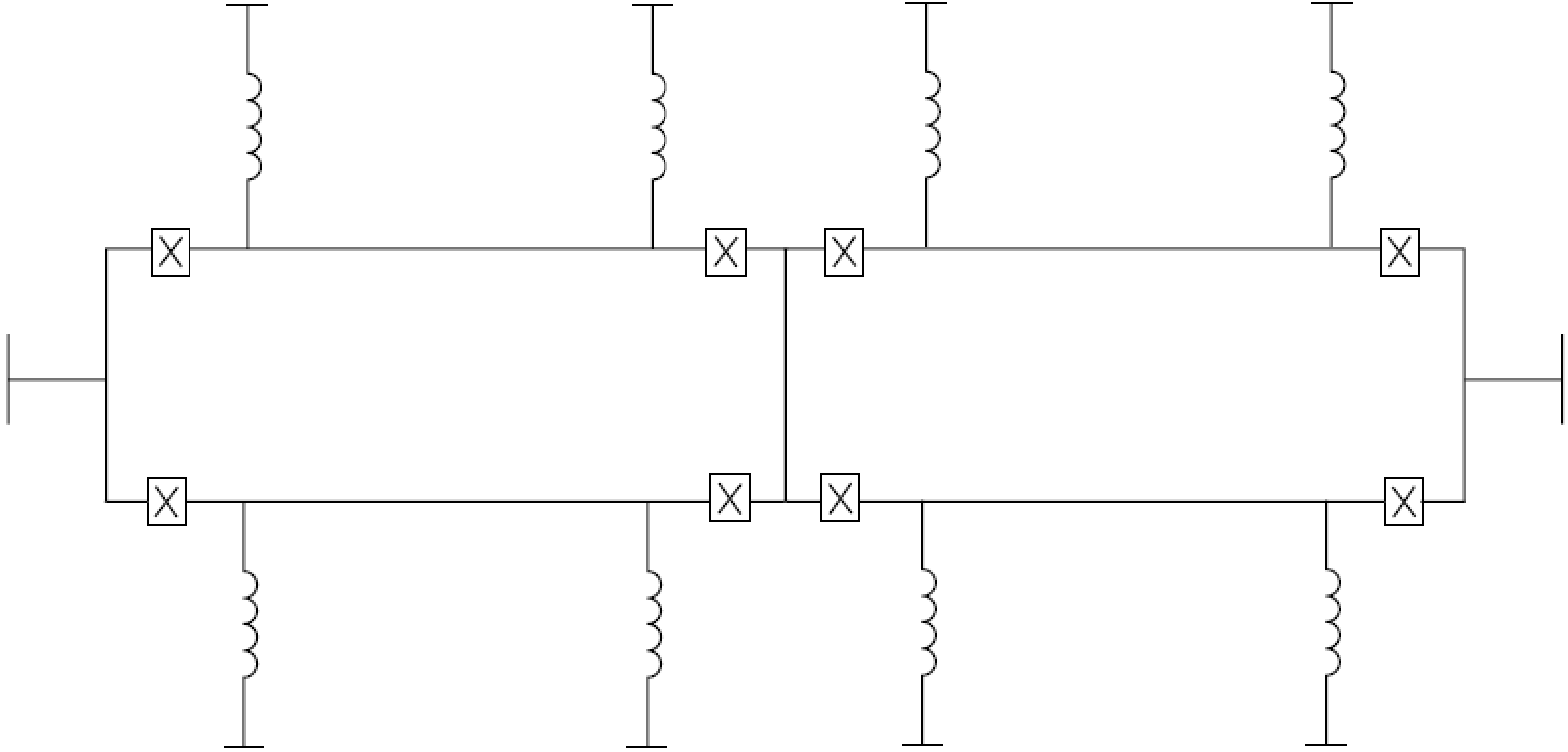

Figure 12 The two sections of a double-circuit high-voltage ac line for long-distance transmission

2 Series Compensation

- Series capacitors are used to partially offset the effects of the series inductances of lines.
- Series compensation results in the improvement of the maximum power-transmission capacity of the line.
- The net effect is a lower load angle for a given power-transmission level and, therefore, a higher-stability margin.
- The reactive-power absorption of a line depends on the transmission current, so when series capacitors are employed, automatically the resulting reactive-power compensation is adjusted proportionately.
- Also, because the series compensation effectively reduces the overall line reactance, it is expected that the net line-voltage drop would become less susceptible to the loading conditions.

- In an interconnected network of power lines that provides several parallel paths, for power flow between two locations, it is the series compensation of a selected line that makes it the principal power carrier.
- Series compensation is defined by the degree of compensation; for example, a 1-pu compensation means that the effective series reactance of a line will be zero.
- A practical upper limit of series compensation, on the other hand, may be as high as 0.75 pu.
- One impact of the passive compensation of lines is that whereas the shunt-inductive compensation makes the line electrically resonant at a supersynchronous frequency, the series compensation makes the line resonant at a subsynchronous frequency.
- The subsynchronous resonance (SSR) can lead to problematic situations for steam turbine–driven generators connected to a series-compensated transmission line.
- These generators employ multiple turbines connected on a common shaft with the generator.
- This arrangement constitutes an elastically coupled multimass mechanical system that exhibits several modes of low-frequency torsional resonances, none of which should be excited as a result of the subsynchronous-resonant electrical transmission system.

- The application of series compensation requires several other careful considerations.
- The application of series capacitors in a long line constitutes placing a lumped impedance at a point.
- Therefore, the following factors need careful evaluation:
  - 1. The voltage magnitude across the capacitor banks (insulation);
  - 2. The fault currents at the terminals of a capacitor bank;
  - 3. The placement of shunt reactors in relation to the series capacitors (resonant overvoltages); and
  - 4. The number of capacitor banks and their location on a long line (voltage profile).

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Department of Electrical and Electronics Engineering

Subject Code & Name:	EE811PE & POWER QUALITY AND FACTS
UNIT- II Transmission Lines and Series/Shunt Reactive Power Compensation	
Topic Name :	Effect on Power-Transfer Capacity
Faculty Name :	Dr.K.Eswaramoorthy

3 Effect on Power-Transfer Capacity

- The consideration of series compensation invariably raises the issue of its comparison with shunt compensation.
- A simple system analysis can be performed to develop a basic understanding of the effect of shunt and series compensation on power-transmission capacity.
- Consider a short, symmetrical electrical line as shown in Fig.13.
- For an uncompensated line, and assuming Vs=Vr= V, the power equation (9) become

$$P = \frac{V^2}{X_l} \sin \delta = \frac{V^2}{X_l} 2 \sin \frac{\delta}{2} \cos \frac{\delta}{2} \qquad \text{------------21}$$

- From the voltage-phasor equations and the phasor diagram in Fig. 13(a),
-

$$I_l = \frac{2V}{X_l} \sin \frac{\delta}{2} \qquad \text{------------22}$$

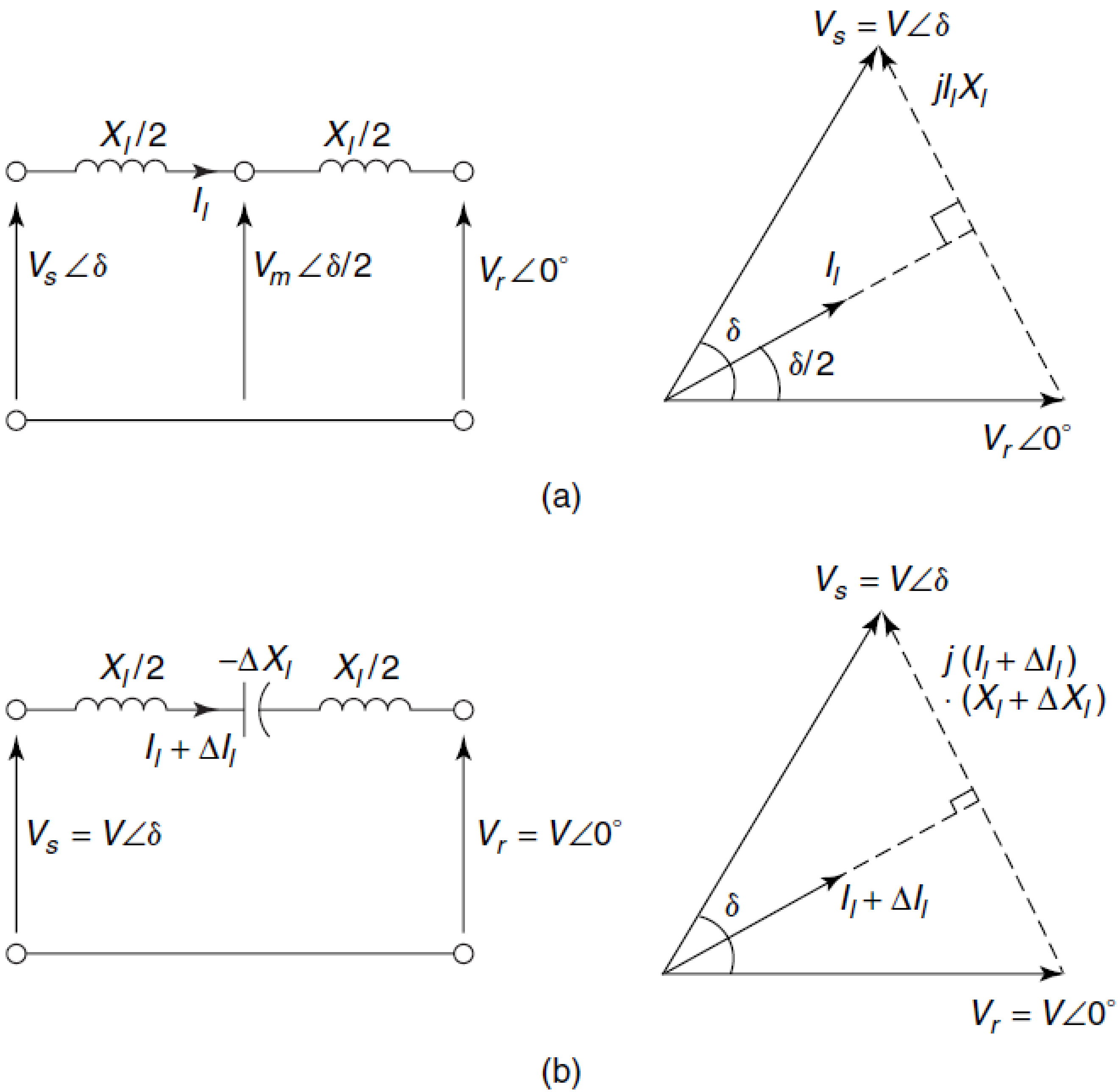

Figure 13 The series compensation of a short, symmetrical transmission line.

1. Series Compensation

- If the effective reactance of a line is controlled by inserting a series capacitor, and if the line terminal voltages are held unchanged, then a ΔX_l change in the line reactance will result in a ΔI_l change in the current, where

$$\Delta I_l = -\frac{2V}{X_l^2}\ \sin\ \frac{\delta}{2}\ X_l = -I_l\ \frac{\Delta X_l}{X_l} \qquad \text{---------23}$$

- Therefore, from Eq. (21), the corresponding change in the power transfer will be

$$\Delta P = -\frac{V^2}{X_l^2}\ 2\sin\ \frac{\delta}{2}\ \cos\ \frac{\delta}{2}\ \Delta X_l \qquad \text{---------24}$$

- Using Eqs. (22) and (23), Eq. (24) may be written as

$$\Delta P = \frac{1}{2\tan\ \frac{\delta}{2}}\ (-\Delta X_l I_l^2)$$

- As $-\Delta X_l$ is the reactance added by series capacitors, $\Delta X_l I_l^2 = \Delta Q_{se}$ represents the incremental var rating of the series capacitor. Therefore

$$\frac{\Delta P}{\Delta Q_{se}} = \frac{1}{2 \tan \frac{\delta}{2}}$$

2 Shunt Compensation

- Reconsider the short, symmetrical line described in Fig. 13(a).
- Apply a shunt capacitor at the midpoint of the line so that a shunt susceptance is incrementally added (Δ *Bc*), as shown in Fig. 14.
- For the system in this figure, the power transfer in terms of the midpoint voltage on the line is

$$P = \frac{V V_m}{\frac{X_l}{2}} \sin \frac{\delta}{2} \qquad \text{------------26}$$

- The differential change in power, Δ P, as a result of a differential change, Δ Vm, is given as

$$\Delta P = \frac{2V}{X_l} \sin \frac{\delta}{2} \Delta V_m \qquad \text{------------27}$$

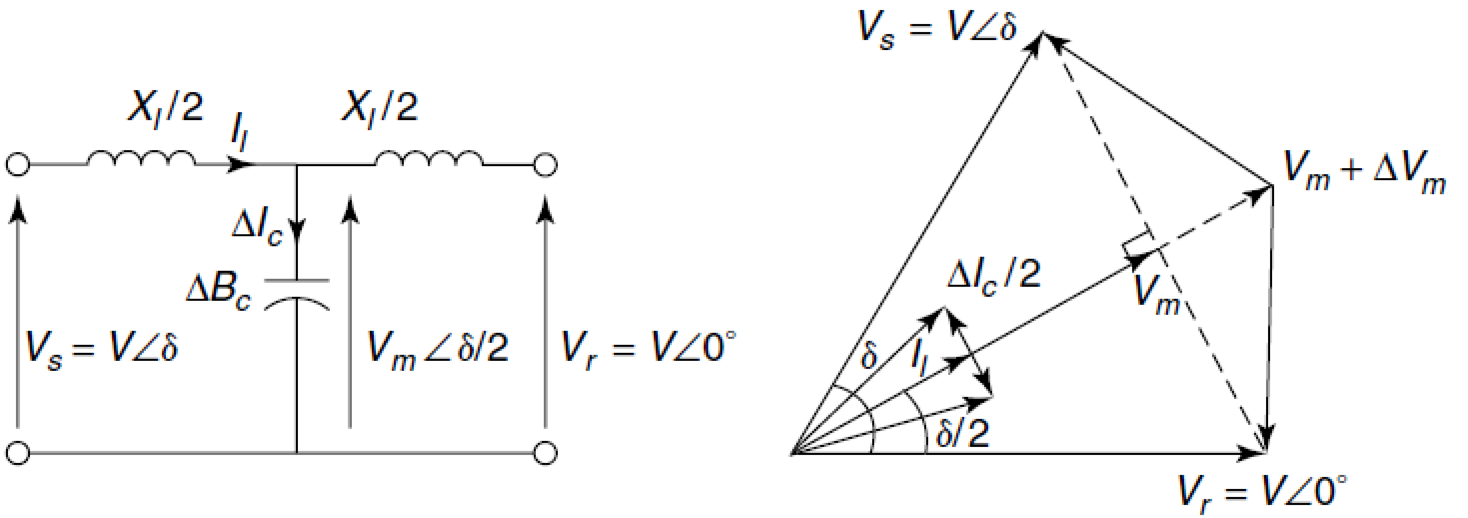

Figure 14 The midpoint-capacitor compensation of a short, symmetrical line.

Also as shown in Fig. 14, $\Delta I_c = V_m \Delta B_c$

The current ΔI_c in the midline shunt capacitor modifies the line currents in the sending and receiving ends of the line to the following:

$$I_{ls} = I_l - \frac{\Delta I_c}{2} \quad \text{and} \quad I_{lr} = I_l + \frac{\Delta I_c}{2}$$

As $V_m = V_r + jI_{lr}X_l/2$,

$$\Delta V_m = \frac{\Delta I_c X_l}{4} = \frac{V_m X_l}{4} \Delta B_c \qquad \text{-------------28}$$

- Substituting the results of Eq. (28) in Eq. (27), we get

$$\Delta P = \frac{V V_m}{2} \sin \frac{\delta}{2} \Delta B_c$$

If the midpoint voltage of the line is approximately equal to $V \cos \delta/2$, then the incremental rating of the shunt-capacitor compensation will be $\Delta Q_{\text{sh}} = V_m^2 \Delta B_c$, or

$$\frac{\Delta P}{\Delta Q_{\text{sh}}} = \frac{1}{2} \tan \frac{\delta}{2} \qquad \text{-----------------29}$$

- By comparing Eqs. (25) and Eqs. (29), we deduce that for an equivalent power transfer on a short electrical line,

$$\frac{\Delta Q_{\text{se}}}{\Delta Q_{\text{sh}}} = \left(\tan \frac{\delta}{2} \right)^2$$

Assuming an operating load angle $\delta = 30^\circ$, we get the ratio of the ratings of series (ΔQ_{se}) to shunt (ΔQ_{sh}) compensators to be 0.072, or 7.2%.

- From the foregoing discussion, it is clear that the var net rating of the series compensator is only 7.2% of that required of a shunt compensator for the same change in power transfer.
- Therefore, one concludes that the series-capacitive compensation is not only achieved with a smaller MVAR rating, but also that it is automatically adjusted for the entire range of the line loading.
- However, the cost of the compensator is not directly related only to the MVAR-rating series capacitor costs increase because they carry full line current and also both their ends must be insulated for the line voltage.
- Practical application of series capacitors requires isolation and bypass arrangements as well as protection and monitoring arrangements.

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Department of Electrical and Electronics Engineering

Subject Code & Name:	**EE811PE & POWER QUALITY AND FACTS**
UNIT- III Static Shunt Compensators	
Topic Name :	
Faculty Name :	**Dr.K.Eswaramoorthy**

UNIT- III
Static Shunt Compensators

- Objectives of shunt compensation, Methods of controllable VAR generation, Static Var Compensator, its characteristics, TCR, TSC, FC-TCR configurations, STATCOM, basic operating principle, control approaches and characteristics.

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Subject Code & Name:	EE811PE & POWER QUALITY AND FACTS
UNIT- III Static Shunt Compensators	
Topic Name :	OBJECTIVES OF SHUNT COMPENSATION
Faculty Name :	Dr.K.Eswaramoorthy

OBJECTIVES OF SHUNT COMPENSATION

- It has long been recognized that the steady-state transmittable power can be increased and the voltage profile along the line controlled by appropriate reactive shunt compensation.
- The purpose of this reactive compensation is to change the natural electrical characteristics of the transmission line to make it more compatible with the prevailing load demand.
- Thus, shunt connected, fixed or mechanically switched reactors are applied to minimize line overvoltage under light load conditions, and shunt connected, fixed or mechanically switched capacitors are applied to maintain voltage levels under heavy load conditions.
- The ultimate objective of applying reactive shunt compensation in a transmission system is to increase the transmittable power.
- This may be required to improve the steady-state transmission characteristics as well as the stability of the system.
- Var compensation is thus used for voltage regulation at the midpoint (or some intermediate) to segment the transmission line and at the end of the (radial) line to prevent voltage instability, as well as for dynamic voltage control to increase transient stability and "damp power oscillations.

1. Midpoint Voltage Regulation for Line Segmentation
2. End of Line Voltage Support to Prevent Voltage Instability.
3. Improvement of Transient Stability
4. Power Oscillation Damping
5. Summary of Compensator Requirements

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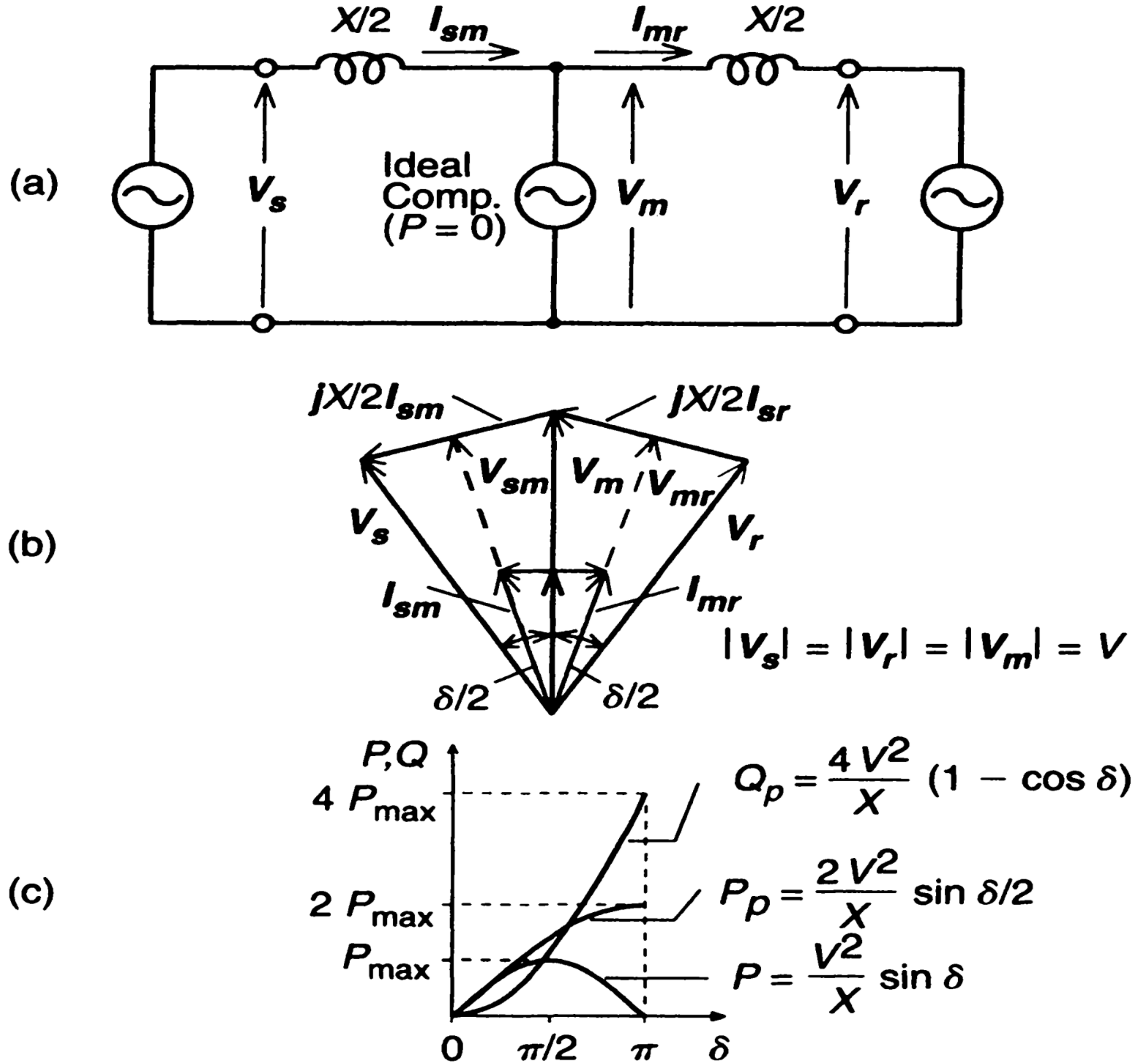
Department of Electrical and Electronics Engineering

Subject Code & Name:	EE811PE & POWER QUALITY AND FACTS
UNIT- III **Static Shunt Compensators**	
Topic Name :	1.Midpoint Voltage Regulation for Line Segmentation
Faculty Name :	Dr.K.Eswaramoorthy

1.Midpoint Voltage Regulation for Line Segmentation

- Consider the simple two-machine (two-bus) transmission model in which an ideal var compensator is shunt connected at the midpoint of the transmission line, as shown in Figure 1(a).
- For simplicity, the line is represented by the series line inductance.
- The compensator is represented by a sinusoidal ac voltage source (of the fundamental frequency), in-phase with the midpoint voltage, *Vm* and with an amplitude identical to that of the sending- and receiving-end voltages *(Vm = Vs = Vr = V)*
- The midpoint compensator in effect segments the transmission line into two independent parts: the

Figure 1 Two-machine power system with an ideal midpoint reactive compensator (a), corresponding phasor diagram (b), and power transmission vs. angle characteristic showing the variation of real power *P,* and the reactive power output of the compensator *Qp* with angle *B* (c).



- first segment, with an impedance of *X/2,* carries power from the sending end to the midpoint, and the second segment, also with an impedance of *X/2,* carries power
- from the midpoint to the receiving end. The relationship between voltages, *Vs ,Vr Vm,* (together with *Vsm, Vrm),* and line segment currents *Ism* and Imr*,* is shown by the phasor diagram in Figure 1(b).
- Note that the midpoint var compensator exchanges only reactive power with the transmission line in this process.
- For the lossless system assumed, the real power is the same at each terminal (sending end, midpoint, and receiving end) of the line, and it can be derived readily from the phasor diagram of Fig. 1(b).

$$V_{sm} = V_{mr} = V\cos\frac{\delta}{4}; \qquad I_{sm} = I_{mr} = I = \frac{4V}{X}\sin\frac{\delta}{4}$$

the transmitted power is

$$P = V_{sm}I_{sm} = V_{mr}I_{mr} = V_mI_{sm}\cos\frac{\delta}{4} = VI\cos\frac{\delta}{4}$$

$$P = 2\frac{V^2}{X}\sin\frac{\delta}{2}$$

$$Q = VI\sin\frac{\delta}{4} = \frac{4V^2}{X}\left(1 - \cos\frac{\delta}{2}\right)$$

- The relationship between real power *P,* reactive power Q, and angle δ for the case of ideal shunt compensation is shown plotted in Figure 1(c).
- It can be observed that the midpoint shunt compensation can significantly increase the transmittable power (doubling its maximum value) at the expense of a rapidly increasing reactive power demand on the midpoint compensator (and also on the end-generators).
- This is because the voltage sag along the uncompensated transmission line is the largest at the midpoint.
- Also, the compensation at the midpoint breaks the transmission line into two equal segments for each of which the maximum transmittable power is the same.
- For unequal segments, the transmittable power of the longer segment would clearly determine the overall transmission limit.

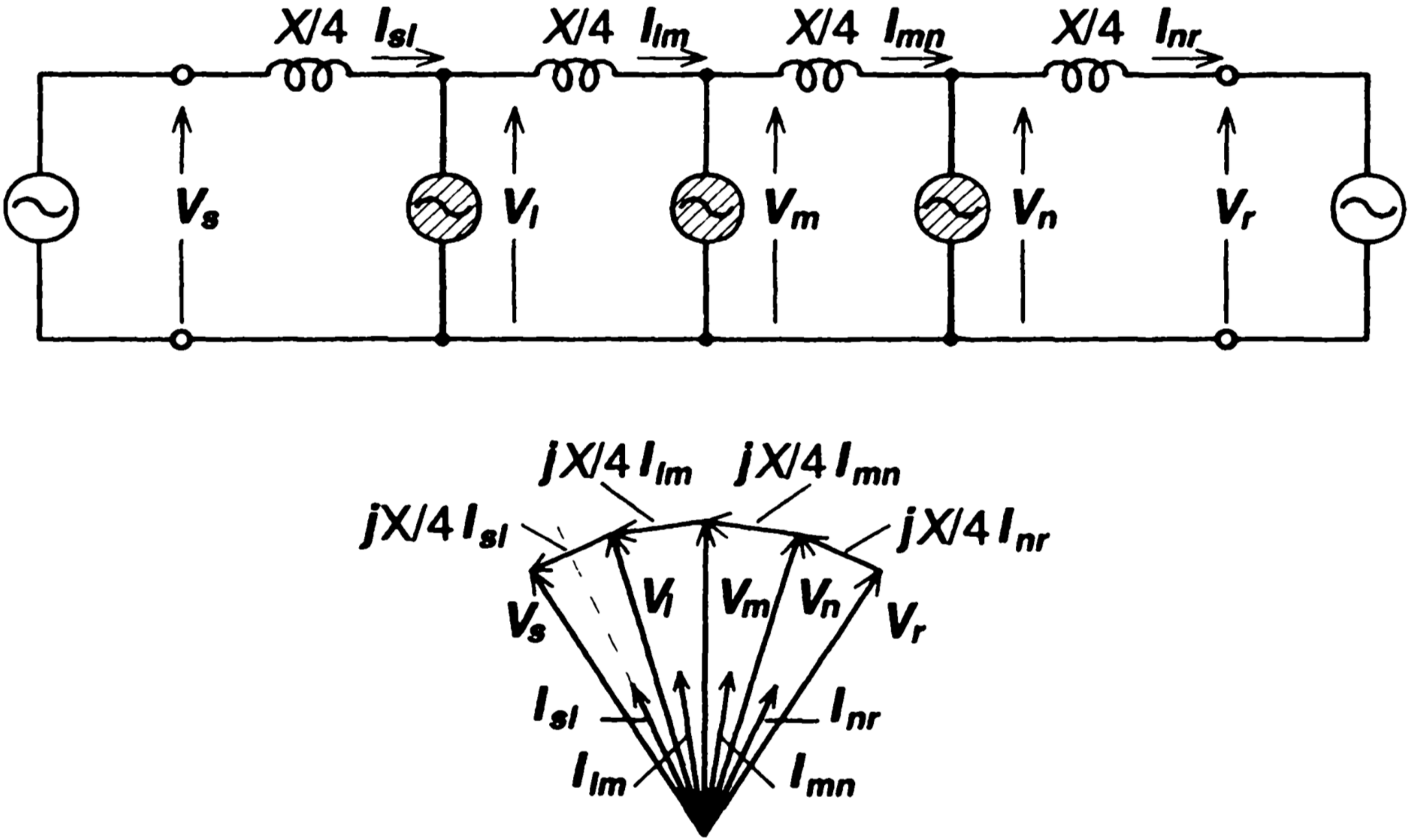


Figure 2 Two-machine system with ideal reactive compensators maintaining constant transmission voltage profile by line segmentation, and associated phasor diagram

- Theoretically, the transmittable power would double with each doubling of the segments for the same overall line length.
- Furthermore, with the increase of the number of segments, the voltage variation along the line would rapidly decrease, approaching the ideal case of constant voltage profile.
- It is to be appreciated that such a distributed compensation hinges on the instantaneous response and unlimited var generation and absorption capability of the shunt compensators employed, which would have to stay in synchronism with the prevailing phase of the segment voltages and maintain the predefined amplitude of the transmission voltage, independently of load variation.

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Department of Electrical and Electronics Engineering

Subject Code & Name:	EE811PE & POWER QUALITY AND FACTS
UNIT- III Static Shunt Compensators	
Topic Name :	End of Line Voltage Support to Prevent Voltage Instability
Faculty Name :	Dr.K.Eswaramoorthy

2. End of Line Voltage Support to Prevent Voltage Instability

- The midpoint voltage support of a two-machine transmission power system discussed above can easily extend to the more special case of radial transmission.
- Indeed, if a passive load, consuming power P at voltage V, is connected to the midpoint in place of the receiving-end part of the system (which comprises the receiving-end generator and transmission link X/2), the sending-end generator with the X/2 impedance and load would represent a simple radial system. Clearly, without compensation the voltage at the midpoint (which is now the receiving end) would vary with the load (and load power factor).
- A simple radial system with feeder line reactance of X and load impedance Z, is shown in Figure 3(a) together with the normalized terminal voltage V, versus power P plot at various load power factors, ranging from 0.8 lag and 0.9 lead.
- The "nose-point" at each plot given for a specific power factor represents the voltage instability corresponding to that system condition.
- It should be noted that the voltage stability limit decreases with inductive loads and increases with capacitive loads.
- The inherent circuit characteristics of the simple radial structure, and the V, versus P plots shown, clearly indicate that shunt reactive compensation can effectively increase the voltage stability limit by supplying the reactive load and regulating the terminal voltage (V - V, = 0) as illustrated in Figure 3(b).
- It is evident that for a radial line, the end of the line, where the largest voltage variation is experienced, is the best location for the compensator.

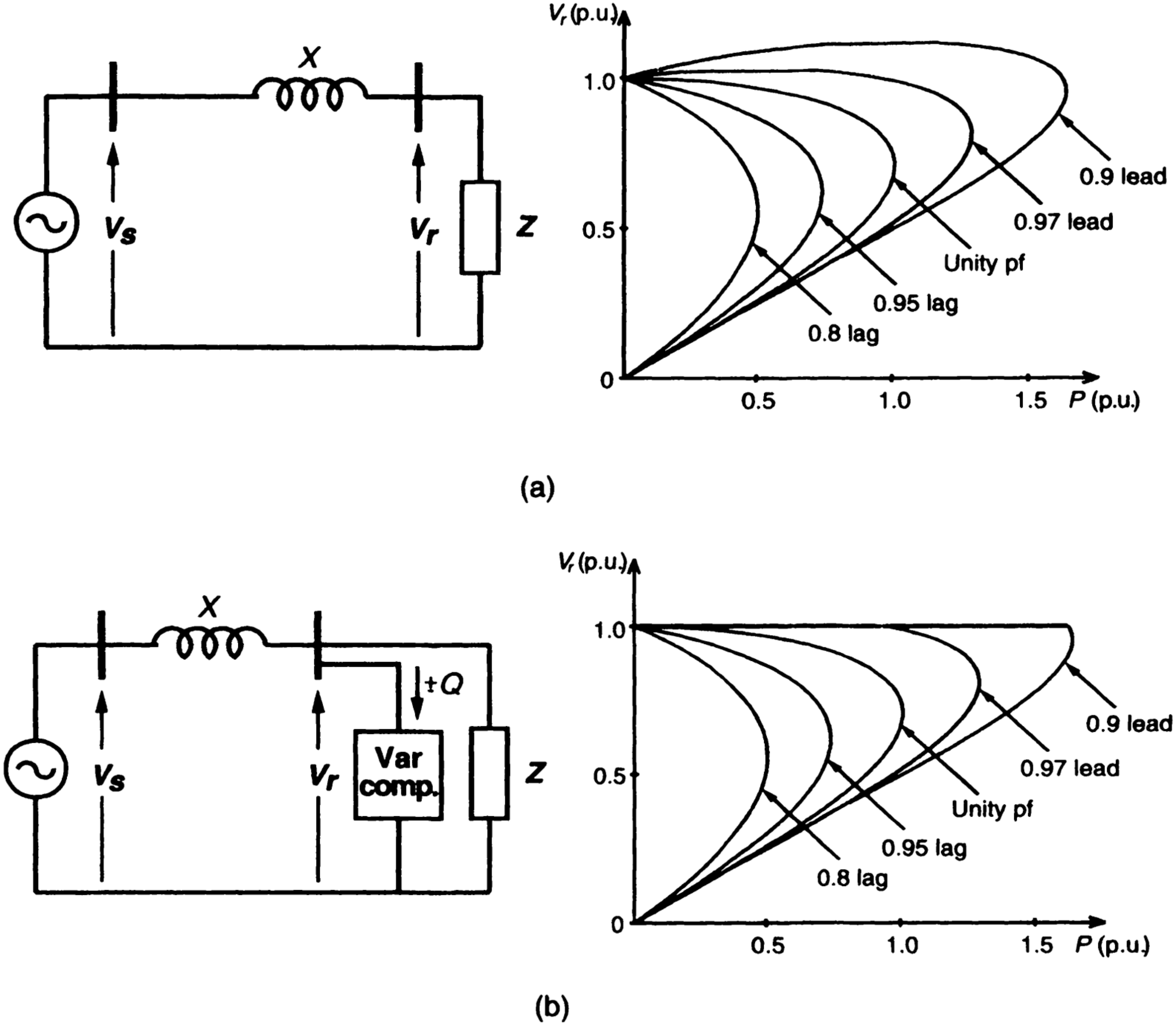

Figure 3 Variation of voltage stability limit of a radial line with load and load power factor (a), and extension of this limit by reactive shunt compensation (b).

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Department of Electrical and Electronics Engineering

Subject Code & Name:	EE811PE & POWER QUALITY AND FACTS
UNIT- III Static Shunt Compensators	
Topic Name :	Improvement of Transient Stability
Faculty Name :	Dr.K.Eswaramoorthy

3.Improvement of Transient Stability

- The potential effectiveness of shunt (as well as other compensation and flow control techniques) on transient stability improvement can be conveniently evaluated by the equal area criterion.
- The meaning of the equal area criterion is explained with the aid of the simple two machine (the receiving end is an infinite bus), two line system shown in Figure 4(a) and the corresponding P versus δ curves shown in Figure 4(b).
- Assume that the complete system is characterized by the P versus δ curve "a" and is operating at angle δ t to transmit power PI when a fault occurs at line segment "I."
- During the fault the system is characterized by the P versus δ curve "b" and thus, over this period, the transmitted electric power decreases significantly while mechanical input power to the sending-end generator remains substantially constant corresponding to P; As a result, the generator accelerates and the transmission angle increases from δ1 to δ 2 at which the protective breakers disconnect the faulted line segment "1" and the sending-end generator 'absorbs accelerating energy, represented by area "A1.“
- After fault clearing, without line segment "1" the degraded system is characterized by the P versus Bcurve "c." At angle B2 on curve "c" the transmitted power exceeds the mechanical input power PI and the sending end generator starts to decelerate; however, angle B further increases due to the kinetic energy stored in the machine.
- The maximum angle reached at B3, where the decelerating energy, represented by area "A2, " becomes equal to the accelerating energy represented by area "AI". The limit of transient stability is reached at δ3 = δcri, beyond which the decelerating energy
- would not balance the accelerating energy and synchronism between the sending end and receiving end could not be restored. The area "Amargin," between δ 3 and δcrit represent the transient stability margin of the system.

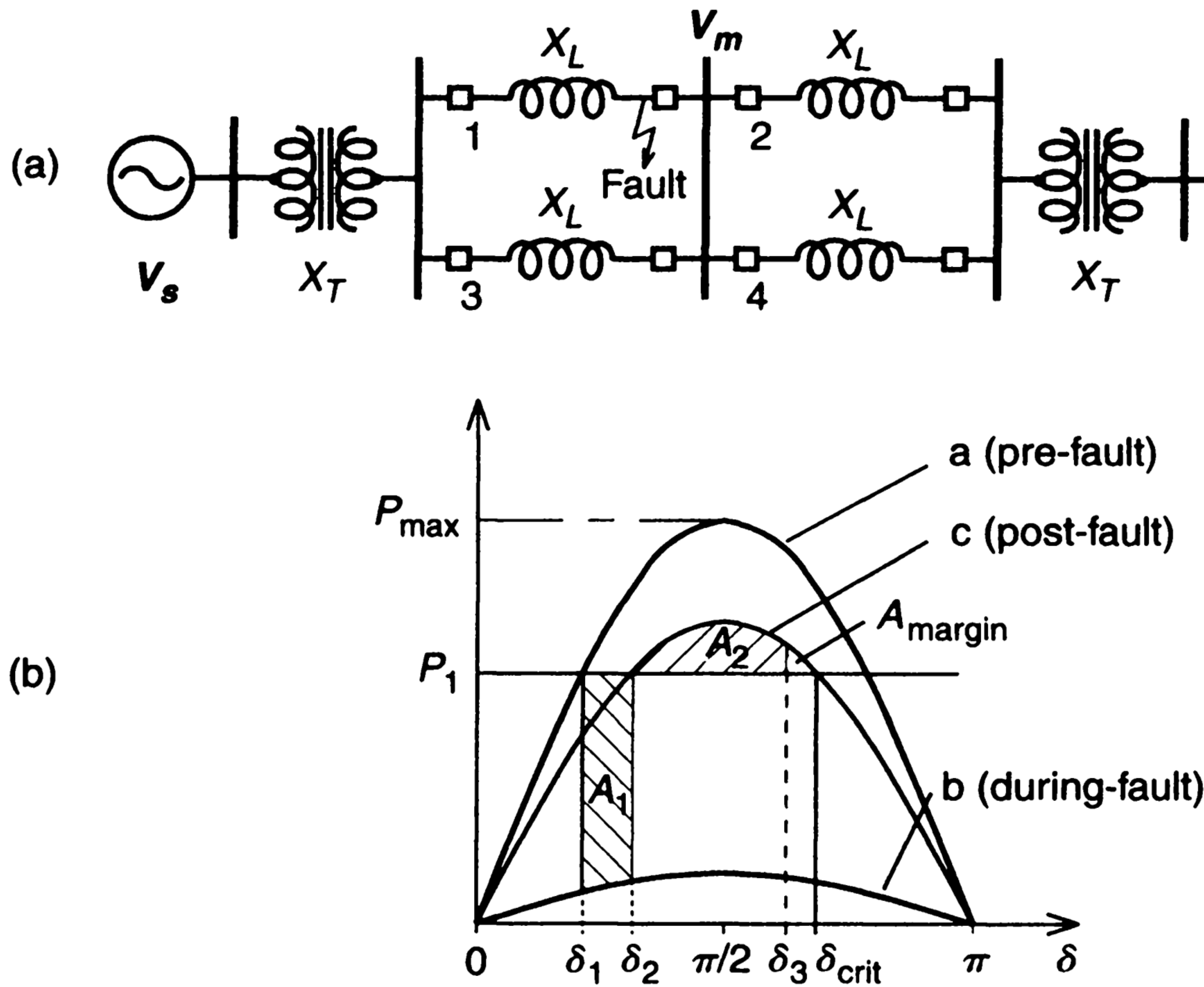
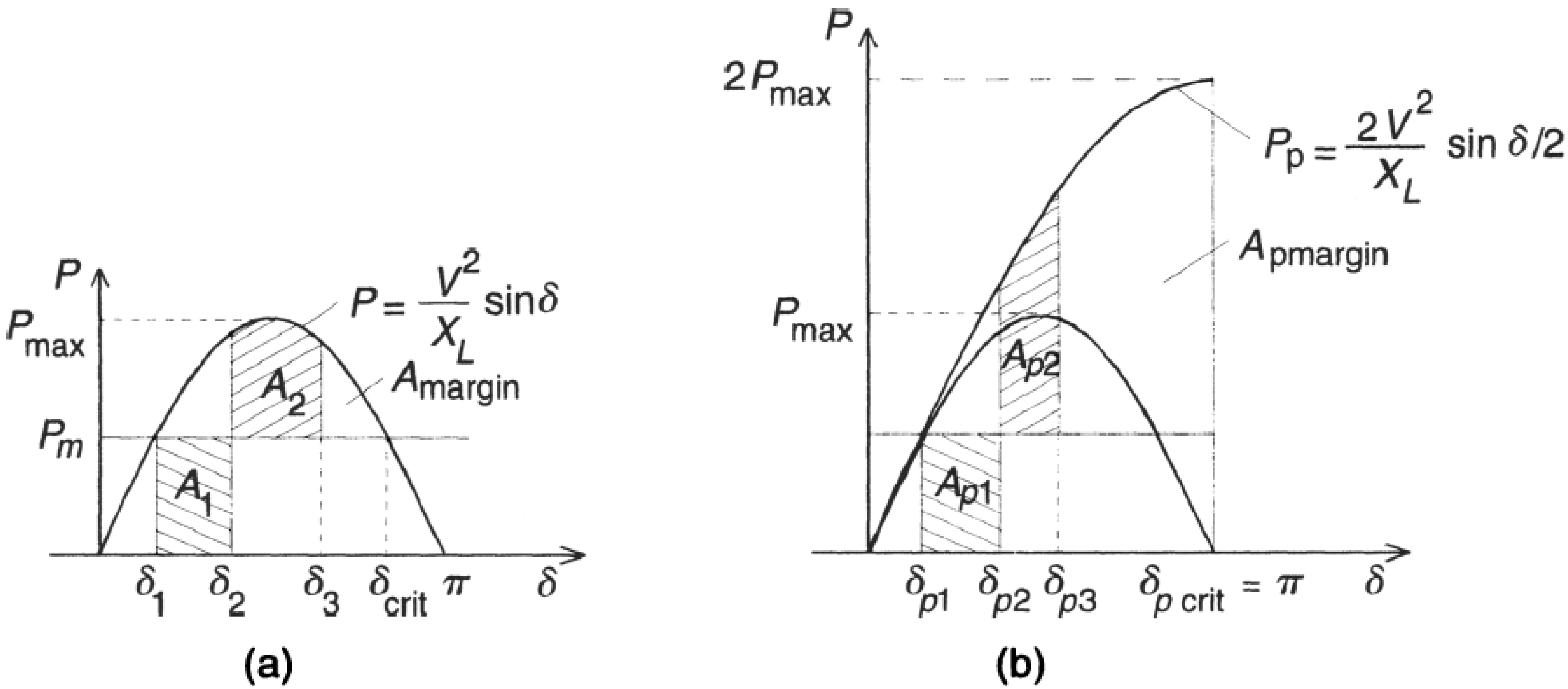


Figure 4 Illustration of the equal area criterion for transient stability of a twomachine,two-line power system.

Figure 5 Equal area criterion to illustrate the transient stability margin for a simple two machine system without compensation (a), and with an ideal midpoint compensator (b).



- During the fault, the transmitted electric power (of the single line system considered) becomes zero while the mechanical input power to the generators remains constant *(Pm).*
- Therefore, the sending-end generator accelerates from the steady-state angles δ1 and δp1 to angles δ2 and δ*p2,* respectively, when the fault clears.
- The accelerating energies are represented by areas *Al* and *Apt.* After fault clearing, the transmitted electric power exceeds the mechanical input power and the sending-end machine decelerates, but the accumulated kinetic energy further increases until a balance between the accelerating and decelerating energies, corresponding to areas *AI, Apt* and *A2, Ap2,* respectively, is reached at 63 and *6p3,* representing the maximum angular swings for the two cases.
- The areas between the *P* versus 6 curve and the constant *Pm* line over the intervals defined by angles δ3 and δcrih and δ*p3* and δpcrit respectively, determine the margin of transient stability, that is, the "unused" and still available decelerating energy, represented by areas Amargin and Apmargin.
- It is important to note that from the standpoint of transient stability, and thus of overall system security, the post-fault system is the one that counts.
- That is, power systems are normally designed to be transiently stable, with defined pre-fault contingency scenarios and post-fault system degradation, when subjected to a major disturbance (fault).
- Because of this (sound) design philosophy, the actual capacity of transmission systems is considerably higher than that at which they are normally used.
- Thus, it may seem technically plausible (and economically savvy) to employ fast acting compensation techniques, instead of overall network compensation, specifically to handle dynamic events and increase the transmission capability of the degraded system under the contingencies encountered.

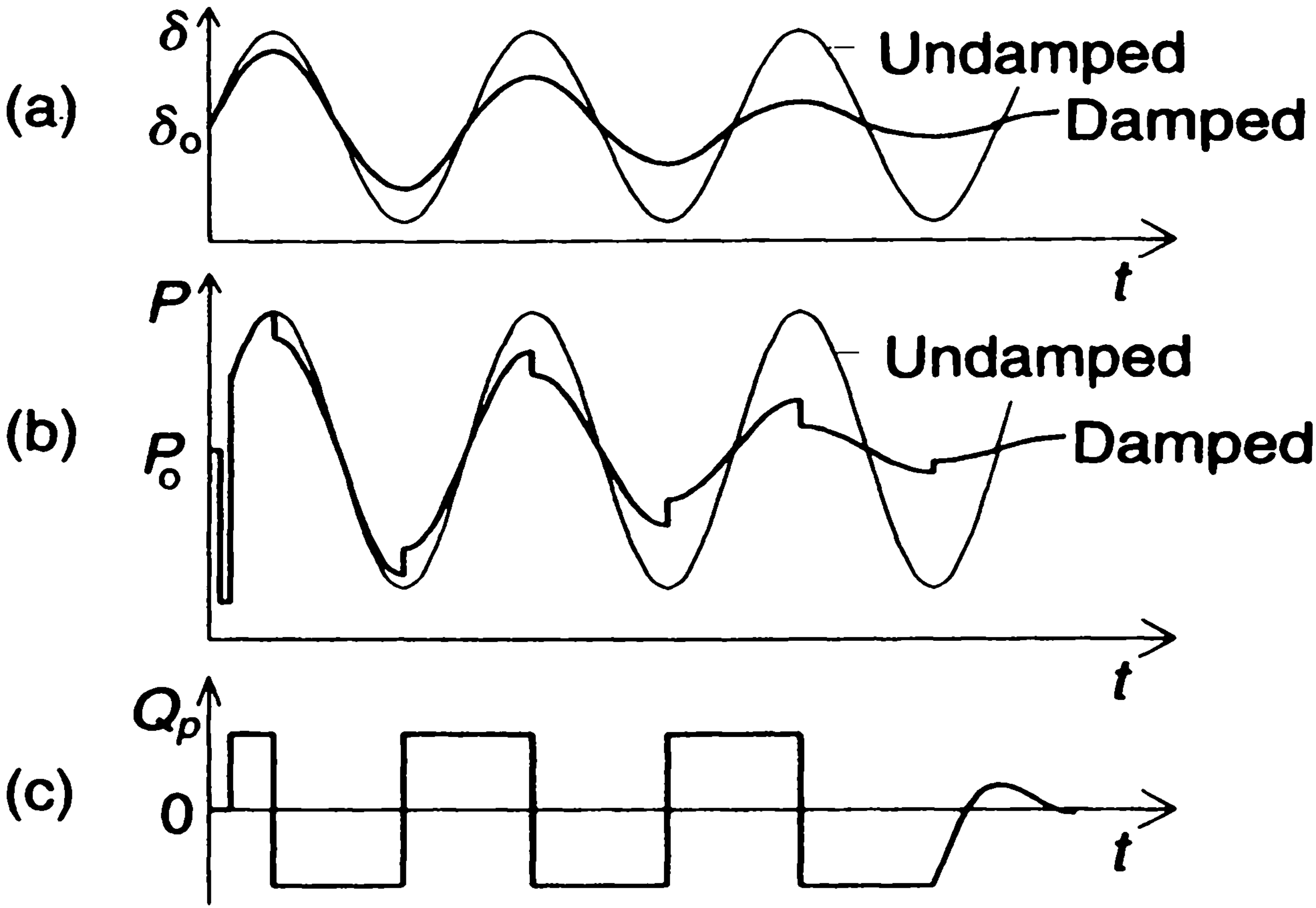
Department of Electrical and Electronics Engineering

Subject Code & Name:	EE811PE & POWER QUALITY AND FACTS
UNIT- III Static Shunt Compensators	
Topic Name :	Power Oscillation Damping
Faculty Name :	Dr.K.Eswaramoorthy

4 Power Oscillation Damping

- Since power oscillation is a sustained dynamic event, it is necessary to vary the applied shunt compensation, and thereby the (midpoint) voltage of the transmission line, to counteract the accelerating and decelerating swings of the disturbed machine(s).
- That is, when the rotationally oscillating generator accelerates and angle δ increases ($d\delta/dt > 0$), the electric power transmitted must be increased to compensate for the excess mechanical input power.
- Conversely, when the generator decelerates and angle δ decreases ($d\delta/dt < 0$), the electric power must be decreased to balance the insufficient mechanical input power. (The mechanical input power is assumed to be essentially constant in the time frame of an oscillation cycle.)
- The requirements of var output control, and the process of power oscillation damping, is illustrated by the waveforms in Figure 6. Waveforms in Figure 6(a) show the undamped and damped oscillations of angle B around the steady-state value $\delta 0$.
- Waveforms in Figure 6(b) show the undamped and damped oscillations of the electric power P around the steady-state value Po. (The momentary drop in power shown at the beginning of the waveform represents an assumed disturbance that initiated the oscillation.)
- Waveform c shows the reactive power output Qp of the shunt-connected var compensator. The capacitive (positive) output of the compensator increases the midpoint voltage and hence the transmitted power when $dB/dt > 0$, and it decreases those when $d\delta/dt < 0$.

Figure 6 Waveforms illustrating power oscillation damping by reactive shunt compensation: (a) generator angle, (b) transmitted power, and (c) var output of the shunt compensator.



Summary of Compensator Requirements

- The functional requirements of reactive shunt compensators used for increased power transmission, improved voltage and transient stability, and power oscillation damping can be summarized as follows:
  - The compensator must stay in synchronous operation with the ac system at the compensated bus under all operating conditions including major disturbances. Should the bus voltage be lost temporarily due to nearby faults, the compensator must be able to recapture synchronism immediately at fault clearing.
  - The compensator must be able to regulate the bus voltage for voltage support and improved transient stability, or control it for power oscillation damping and transient stability enhancement, on a priority basis as system conditions may require.
  - For a transmission line connecting two systems, the best location for var compensation is in the middle, whereas for a radial feed to a load the best location is at the load end.

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Department of Electrical and Electronics Engineering

Subject Code & Name:	EE811PE & POWER QUALITY AND FACTS
UNIT- III Static Shunt Compensators	
Topic Name :	METHODS OF CONTROLLABLE VAR GENERATION
Faculty Name :	Dr.K.Eswaramoorthy

2.METHODS OF CONTROLLABLE VAR GENERATION

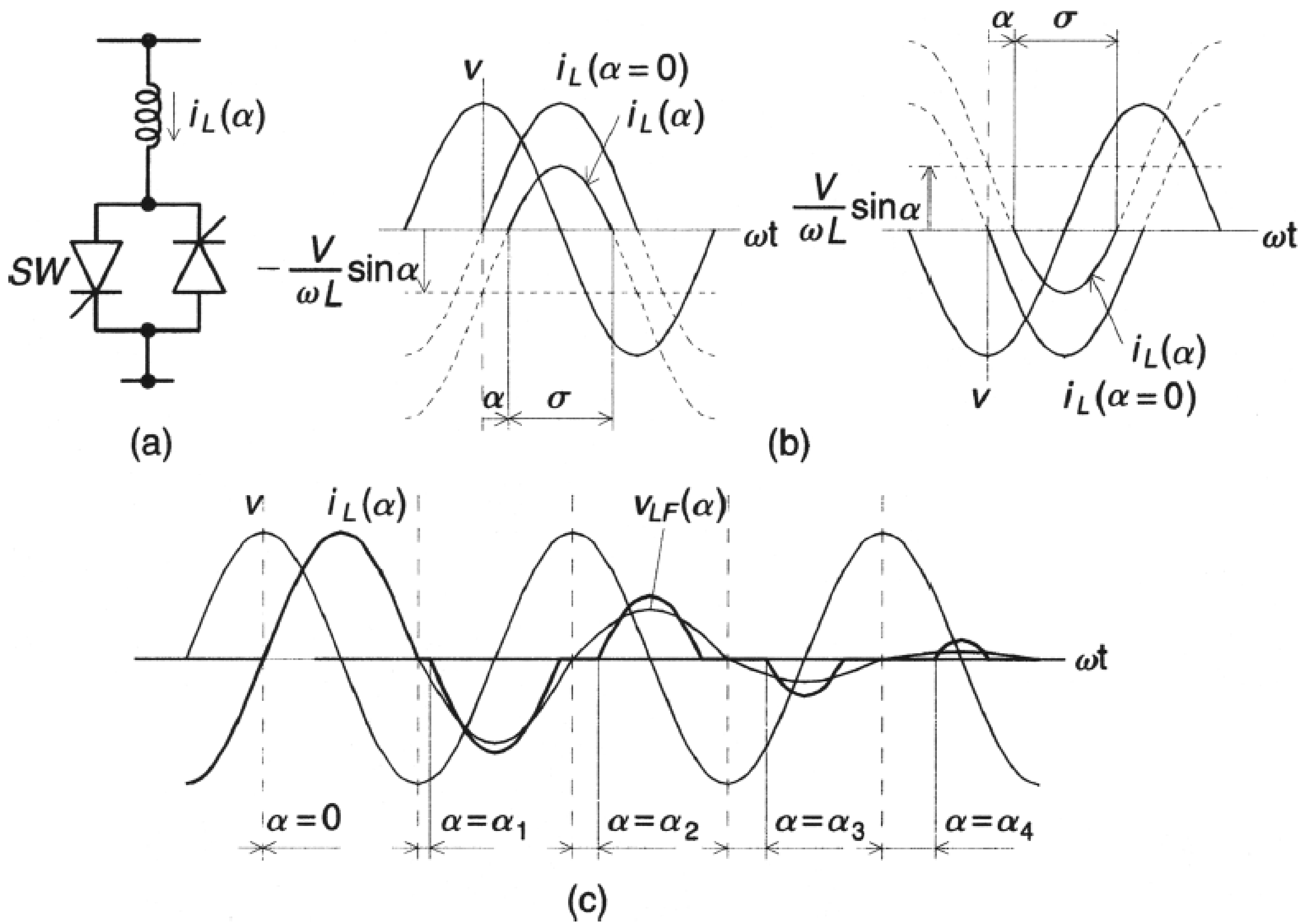
- **VARIABLE IMPEDANCE TYPE STATIC VAR GENERATORS:**
  - THYRISTOR CONTROLLED/ SWITCHED REACTOR (TCR/TSR)
  - THYRISTOR SWITCHED CAPACITOR (TSC)
  - FIXED CAPACITOR- THYRISTOR CONTROLLED REACTOR (FC-TCR).
  - THYRISTOR SWITCHED CAPACITOR-THYRISTOR CONTROLLED REACTOR
- **SWITCHING CONVERTER TYPE VAR GENERATORS:**
  - STATIC CONDENSOR & STATIC COMPENSTOR (STATCON & STATCOM)
- **HYBRID VAR GENERATORS:**
  - SWITCHING CONVERTER WITH TSC AND TCR

VARIABLE IMPEDANCE TYPE STATIC VAR GENERATORS
1. The Thyristor-Controlled and Thyristor-Switched Reactor (TCR and TSR).

- An elementary single-phase thyristor-controlled reactor (TCR) is shown in Figure 7(a).
- It consists of a fixed (usually air-core) reactor of inductance L, and a bidirectional thyristor valve (or switch) sw. Currently available large thyristors can block voltage up to 4000 to 9000 volts and conduct current up to 3000 to 6000 amperes.
- Thus, in a practical valve many thyristors (typically 10 to 20) are connected in series to meet the required blocking voltage levels at a given power rating.
- A thyristor valve can be brought into conduction by simultaneous application of a gate pulse to all thyristors of the same polarity.
- The valve will automatically block immediately after the ac current crosses zero, unless the gate signal is reapplied.
- The current in the reactor can be controlled from maximum (thyristor valve closed) to zero (thyristor valve open) by the method of firing delay angle control.
- That is, the closure of the thyristor valve is delayed with respect to the peak of the applied voltage in each half-cycle, and thus the duration of the current conduction intervals is controlled. This method of current control is illustrated separately for the positive and negative current half-cycles in Figure 7(b), where the applied voltage
- *v* and the reactor current *iL(a),* at zero delay angle (switch fully closed) and at an arbitrary *a* delay angle, are shown. When *a* = 0, the valve *sw* closes at the crest of the applied voltage and evidently the resulting current in the reactor will be the same as that obtained in steady state with a permanently closed switch.
- When the gating of the valve is delayed by an angle $(0 \leq \alpha \leq \pi/2)$ with respect to the crest of the voltage, the current in the reactor can be expressed with *v(t)* = *V* cos *wt* as follows:

$$i_L(t) = \frac{1}{L}\int_{\alpha}^{\omega t} v(t)\, dt = \frac{V}{\omega L}(\sin \omega t - \sin \alpha)$$

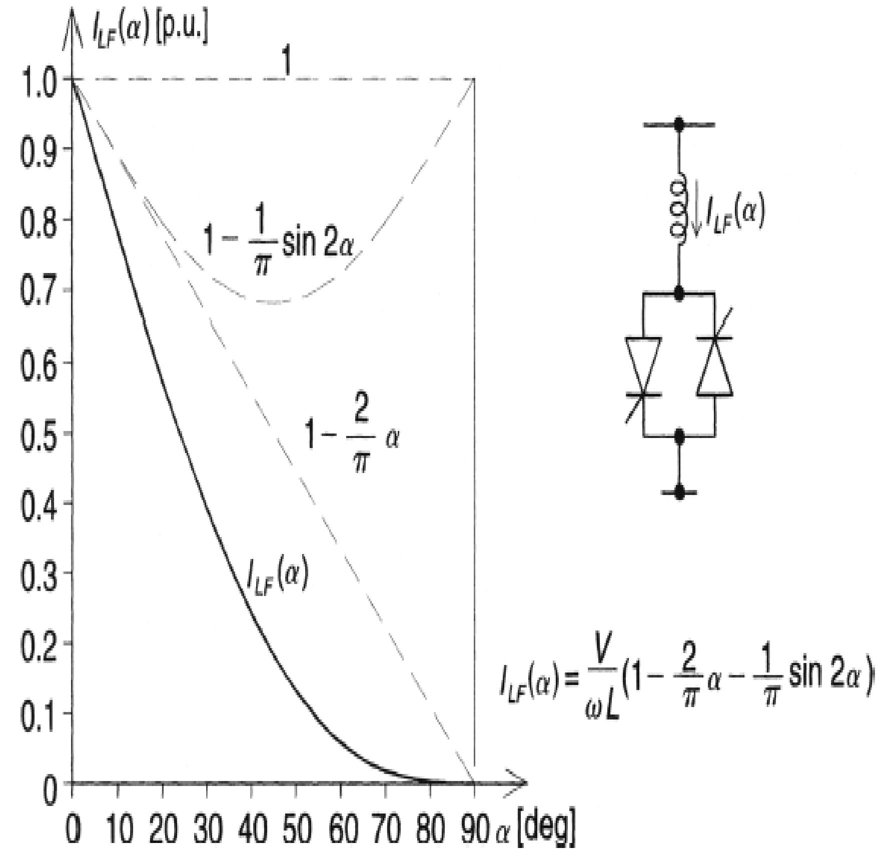
Figure 7 Basic thyristor-controlled reactor (a), firing delay angle control (b), and operating waveforms (c).



- It is clear from Figure 8 that the TCR can control the fundamental current continuously from zero (valve open) to a maximum (valve closed) as if it was a variable reactive admittance.
- Thus, an effective reactive admittance, *BL(α),* for the TCR can be defined. This admittance, as a function of angle *α,* can be written directly from

$$B_L(\alpha) = \frac{1}{\omega L}\left(1 - \frac{2}{\pi}\alpha - \frac{1}{\pi}\sin 2\alpha\right)$$

- It is evident that the magnitude of current in the reactor can be varied continuously by the method of delay angle control from maximum (α=0) to zero (α=90).
- In practice, the maximum magnitude of the applied voltage and that of the corresponding current will be limited by the ratings of the power components(reactor and thyristor valve)used.
- Thus, a practical TCR can be operated anywhere in a defined V-I area ,the boundaries of which are determined by its maximum attainable admittance, voltage and current ratings are shown in fig.



- Note: If Thyristor Controlled Reactor(TCR) switching is restricted to a fixed delay angle, usually α=0, then it becomes a thyristors – switched reactor (TSR).
- The TSR provides a fixed inductive admittance. Thus, when connected to the a.c. system, the reactive current in it will be proportional to the applied voltage as shown in fig.
- TSRs can provide at α=0, the resultant steady-state current will be sinusoidal.

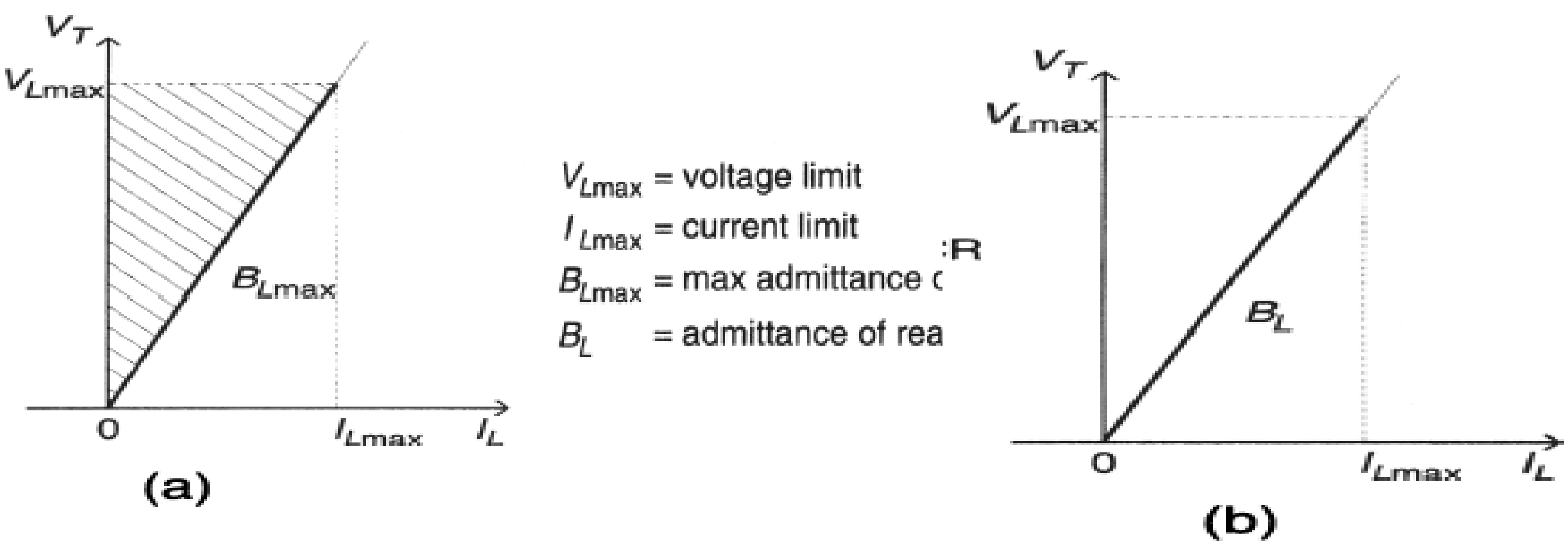


Figure Operating *V-I* area of the TCR (a) and of the TSR (b).

- In a three-phase system, three single-phase thyristor-controlled reactors are used, usually in delta connection. Under balanced conditions, the triple-n harmonic currents (3rd, 9th, 15th, etc.) circulate in the delta connected TCRs and do not enter the power system.
- The magnitudes of the other harmonics generated by the thyristor-controlled reactors can be reduced by various methods.
- One method, particularly advantageous for high power applications, employs m (m ~ 2) parallel-connected TCRs, each with 11m of the total rating required.
- The reactors are "sequentially" controlled, that is, only one of the m reactors is delay angle controlled, and each of the remaining m - 1 reactors is either fully "on" or fully "off," depending on the total reactive power required, as illustrated for four reactors in Figure-11.
- In this way, the amplitude of every harmonic is reduced by the factor m with respect to the maximum rated fundamental current.
- Furthermore, losses associated with this scheme are generally lower than those characterizing a TCR with equivalent rating due to the reduction in switching losses.
- Another method employs a 12-pulse TCR arrangement. In this, two identical three-phase delta connected thyristor-controlled reactors are used, one operated from wye-connected windings, the other from delta-connected windings of the secondary of a coupling transformer. (Other types of transformer arrangements providing two sets of three-phase voltages with 30-degree phase shift can, of course, also be used.)
- Because of the 30-degree phase shift between the related voltages of the two transformer windings, the 5th, 7th, 17th, 19th, generally the harmonic currents of order 6(2k - 1) - 1 and 6(2k - 1) + 1, k = 1,2,3, ... cancel, resulting in a nearly sinusoidal output current, at all delay angles, as illustrated by the current waveforms in Figure 12.

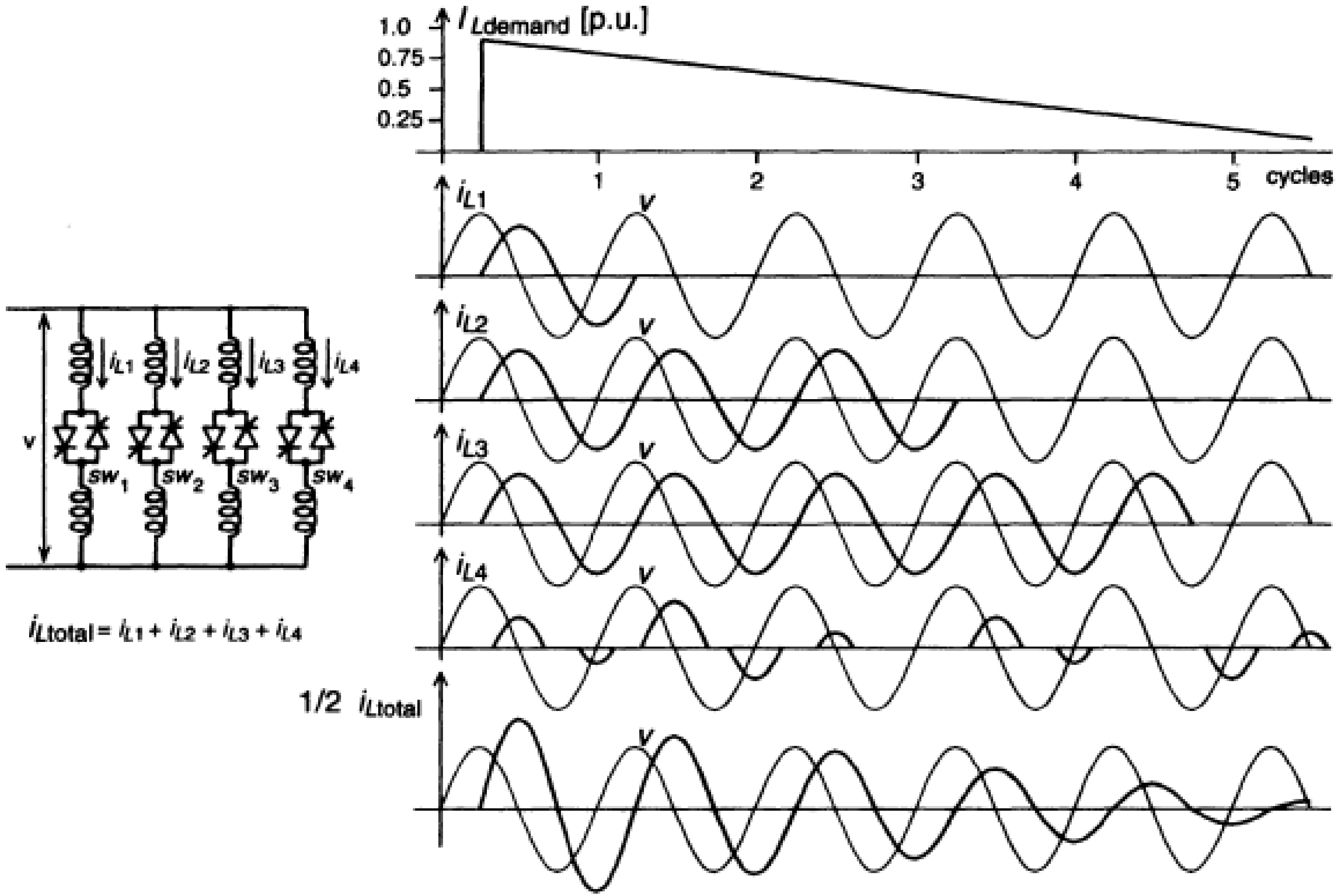
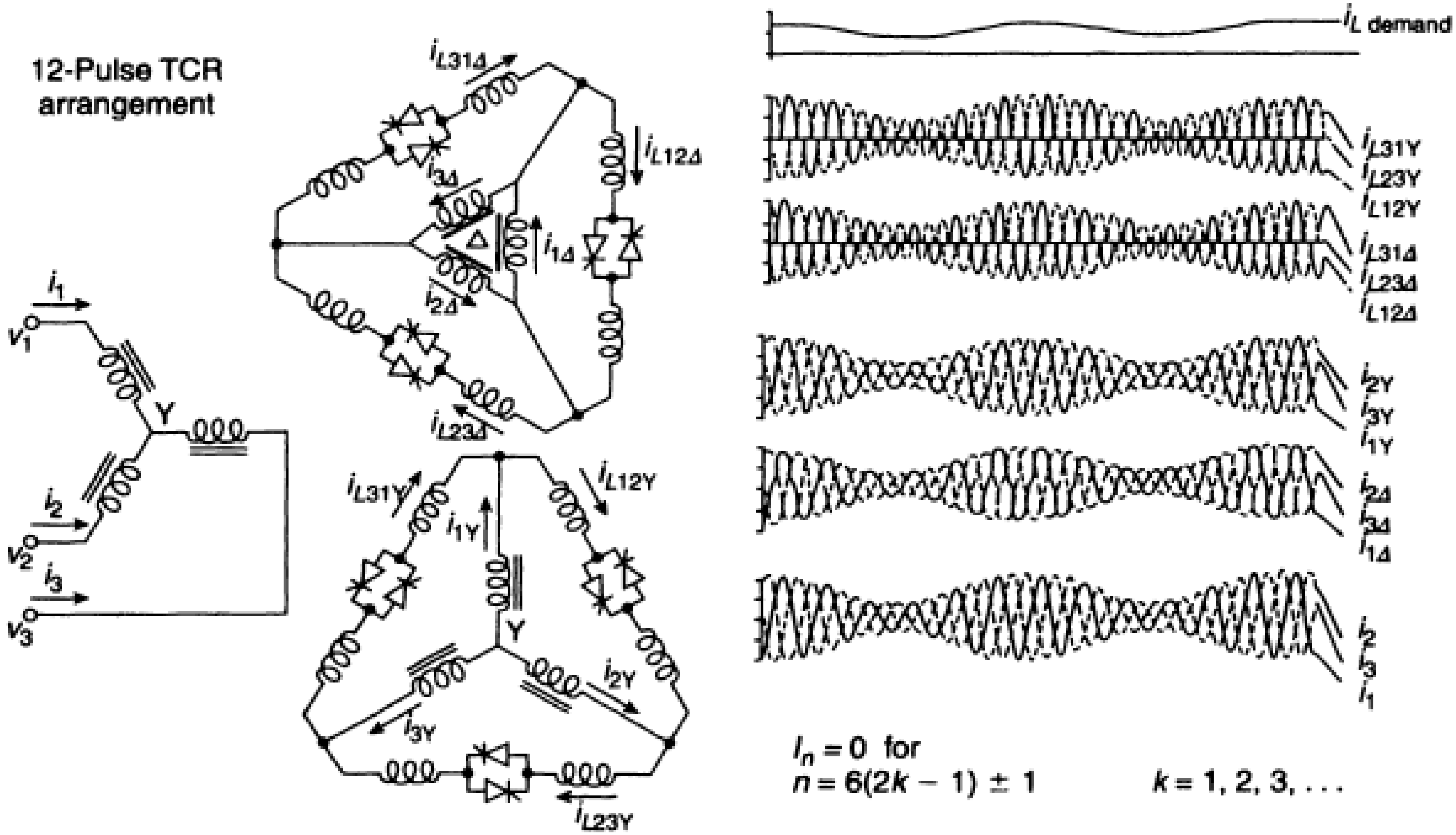


Figure S.ll Waveforms illustrating the method of controlling four TCR banks "sequentially" to achieve harmonic reduction.

Figure 12 Twelve-pulse arrangement of two sets of thyristor-controlled reactors and associated current waveforms



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Department of Electrical and Electronics Engineering

Subject Code & Name:	EE811PE & POWER QUALITY AND FACTS
UNIT- III Static Shunt Compensators	
Topic Name :	The Thyristor-Switched Capacitor (TSC)
Faculty Name :	Dr.K.Eswaramoorthy

The Thyristor-Switched Capacitor (TSC)

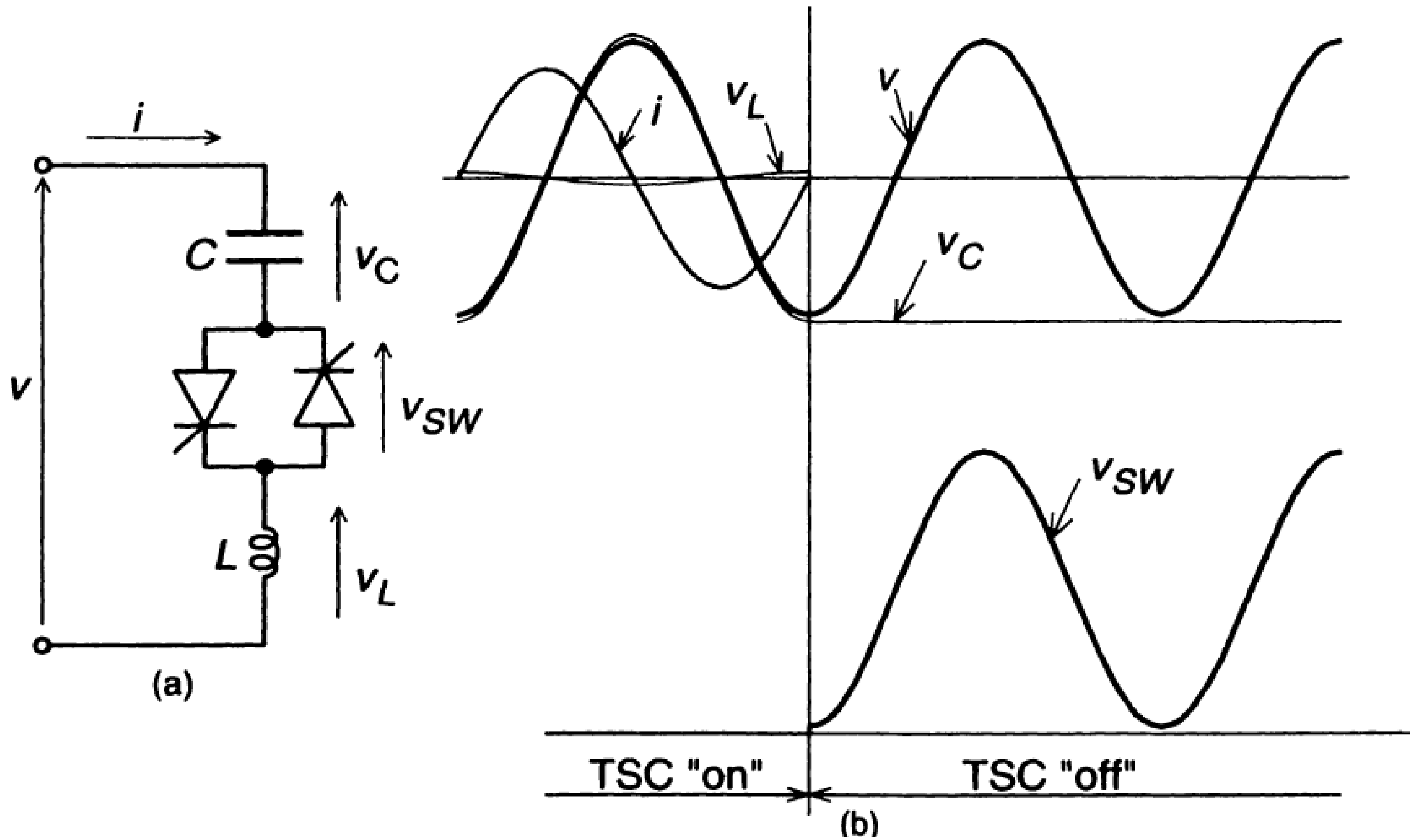
- A single-phase thyristor switched capacitor (TSC) is shown in Figure 13(a).
- It consists of a capacitor, a bidirectional thyristor valve, and a relatively small surge current limiting reactor.
- This reactor is needed primarily to limit the surge current in the thyristor valve under abnormal operating conditions (e.g., control malfunction causing capacitor switching at a "wrong time," when transient free switching conditions are not satisfied); it may also be used to avoid resonances with the ac system impedance at particular frequencies.
- Under steady-state conditions, when the thyristor valve is closed and the TSC branch is connected to a sinusoidal ac voltage source, $v = V \sin$ *on,* the current in the branch is given by

$$i(\omega t) = V \frac{n^2}{n^2 - 1} \omega C \cos \omega t$$

$$n = \frac{1}{\sqrt{\omega^2 LC}} = \sqrt{\frac{X_C}{X_L}}$$

The amplitude of the voltage across the capacitor is

$$V_C = \frac{n^2}{n^2 - 1} V$$



Fipre 13 Basic thyristor-switched capacitor (a) and associated waveforms (b).

- If the voltage across the disconnected capacitor remained unchanged, the TSC bank could be switched in again, without any transient, at the appropriate peak of the applied ac voltage, as illustrated for a positively and negatively charged capacitor in Figure 14(a) and (b), respectively

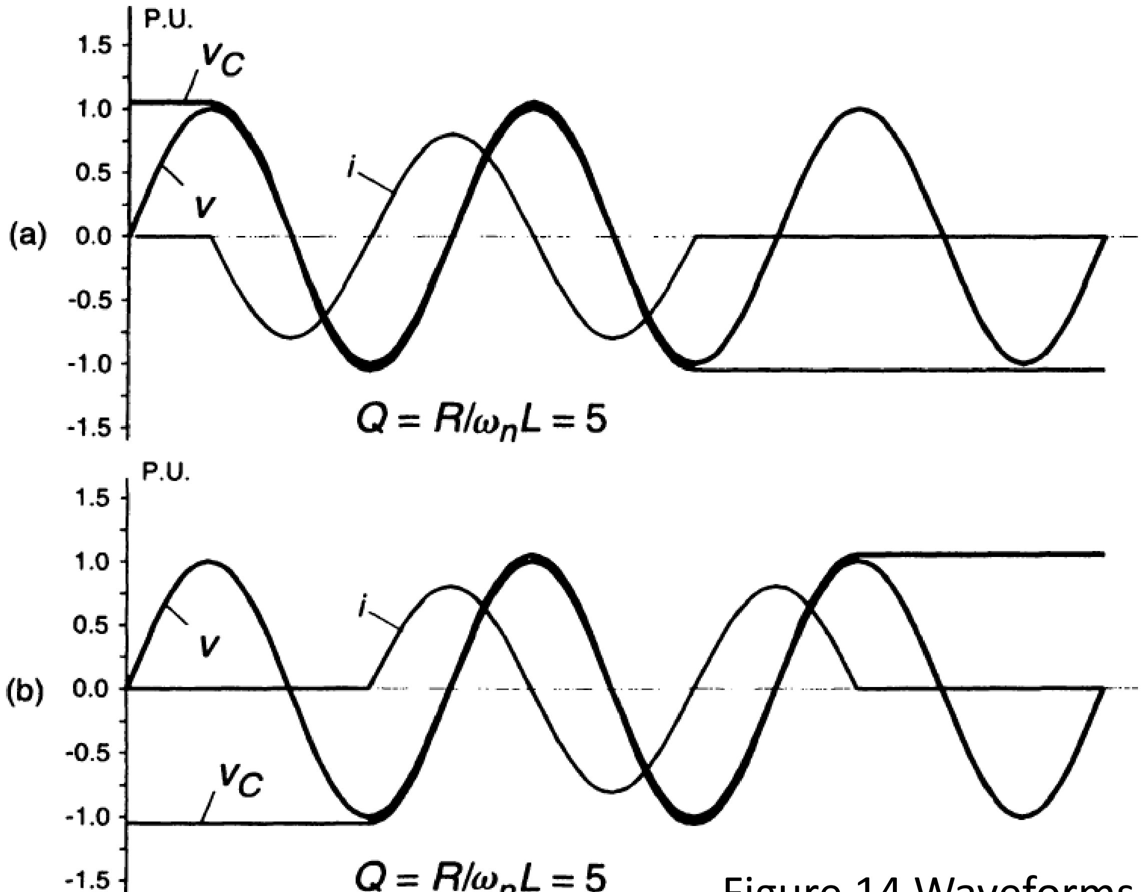


Figure 14 Waveforms illustrating transient-free switching by a thyristor switched capacitor.

- Figure 15(a) and (b) illustrate the switching transients obtained with a fully and a partially discharged capacitor.
- These transients are caused by the nonzero dv/dt at the instant of switching, which, without the series reactor, would result in an instantaneous current of ic = Cdv/dt in the capacitor. (This current represents the instantaneous value of the steady-state capacitor current at the time of the switching.)

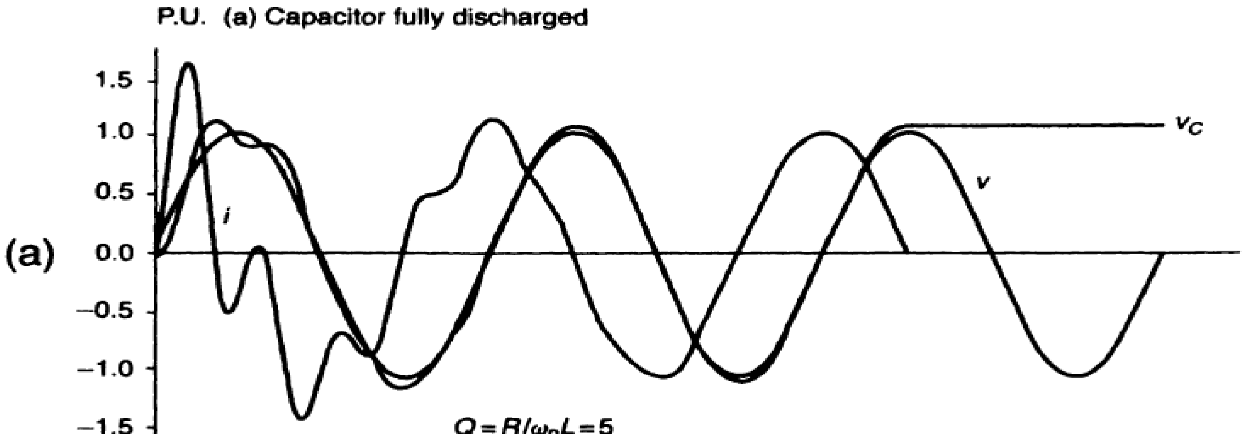
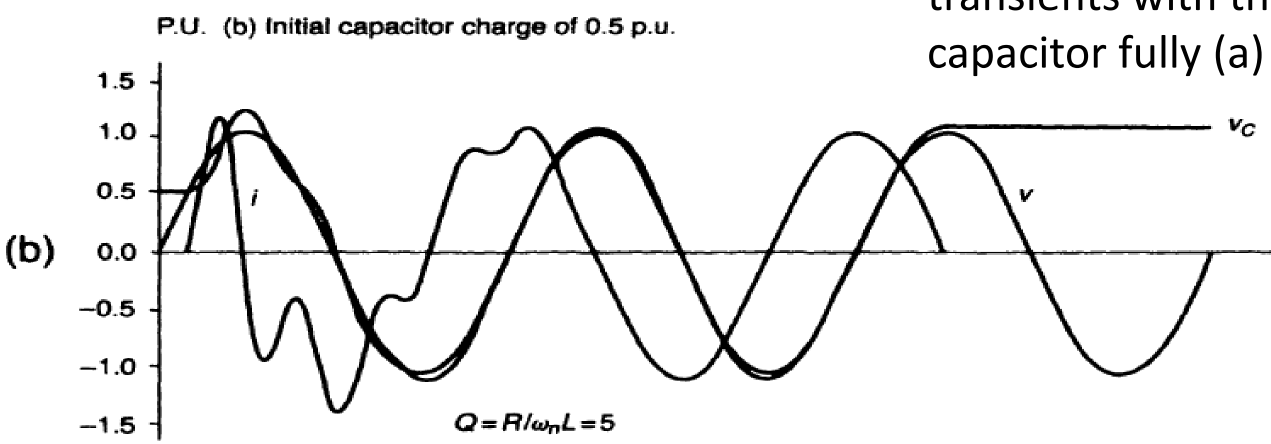


Figure 15 Waveforms illustrating the switching transients with the thyristorswitched capacitor fully (a) or partially discharged (b).



- The conditions for "transient-free" switching of a capacitor are summarized in Figure 16.
- As seen, two simple rules cover all possible
- cases: (1) if the residual capacitor voltage is lower than the peak ac voltage *($V_c < V$)*, then the correct instant of switching is when the instantaneous ac voltage becomes equal to the capacitor voltage;
- case (2) if the residual capacitor voltage is equal to or higher than the peak ac voltage *($V_c \geq V$)*, then the correct switching is at the peak of the ac voltage at which the thyristor valve voltage is minimum.

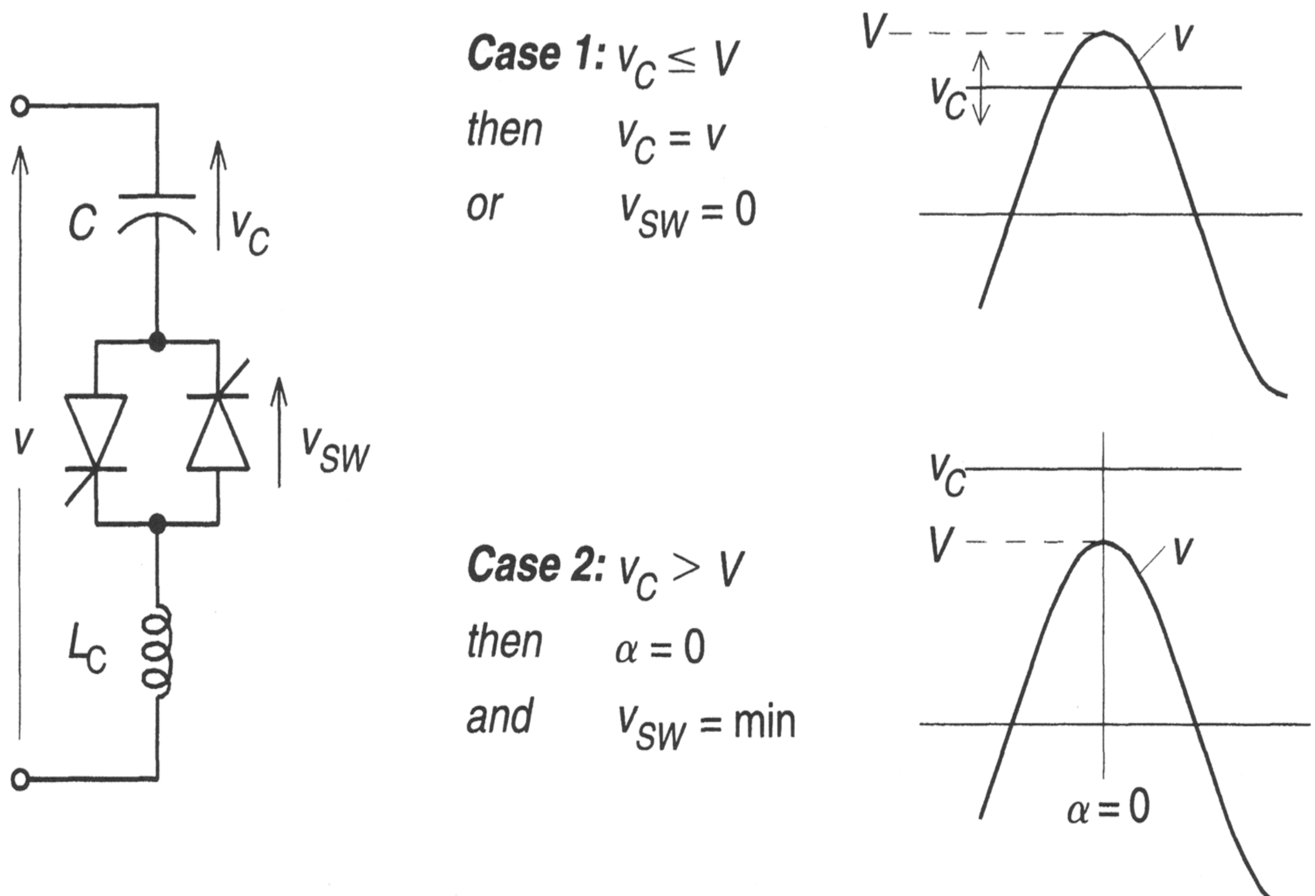
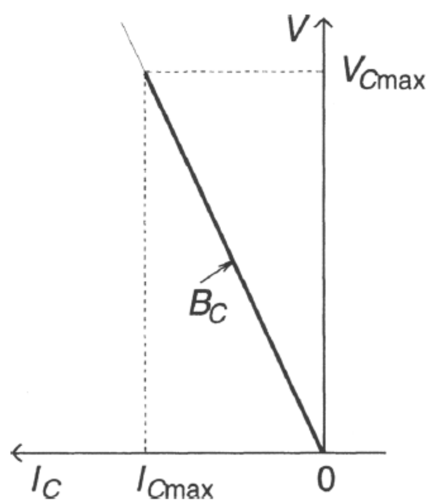


Figure 16 Conditions for "transient-free" switching for the thyristor-switched capacitor with different residual voltages.

- The TSC branch can be disconnected ("switched out") at any current zero by prior removal of the gate drive to the thyristor valve.
- At the current zero crossing, the capacitor voltage is at its peak valve.
- The disconnected capacitor stays charged to this voltage, and consequently the voltage across the non-conducting thyristors valve varied between zero and the peak-to-peak value of the applied a.c. voltage as shown in fig.(b).
- The TSC branch represents a single capacitive admittance which is either connected to, or disconnected from the a.c. system.
- The current in the TSC branch varies linearly with the applied voltage according to the admittance of the capacitor as illustrated by the V-I plot in the following fig 17.



V_{Cmax} = voltage limit
I_{Cmax} = current limit
B_C = admittance of capacitor

Figure 17 Operating *V-I* area of a single TSC

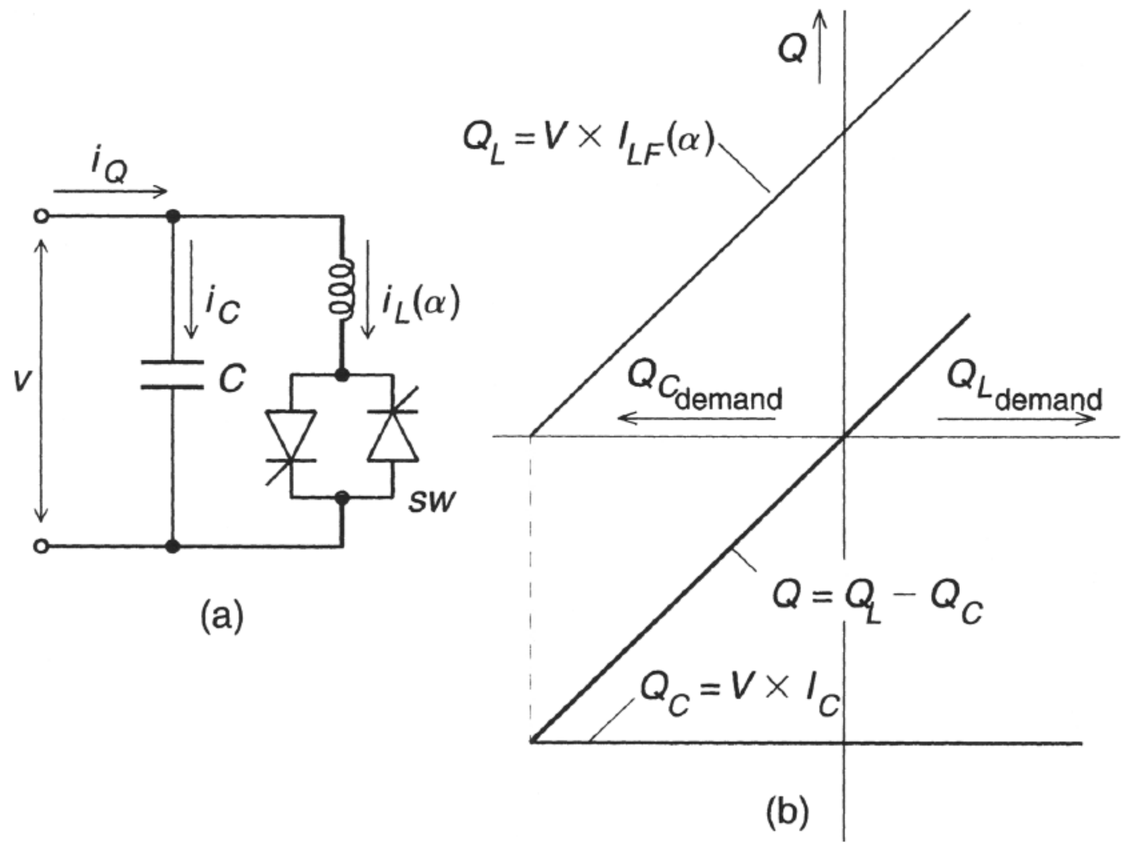
Department of Electrical and Electronics Engineering

Subject Code & Name:	**EE811PE & POWER QUALITY AND FACTS**
UNIT- III **Static Shunt Compensators**	
Topic Name :	**Fixed Capacitor, Thyristor-Controlled Reactor Type Var Generator**
Faculty Name :	**Dr.K.Eswaramoorthy**

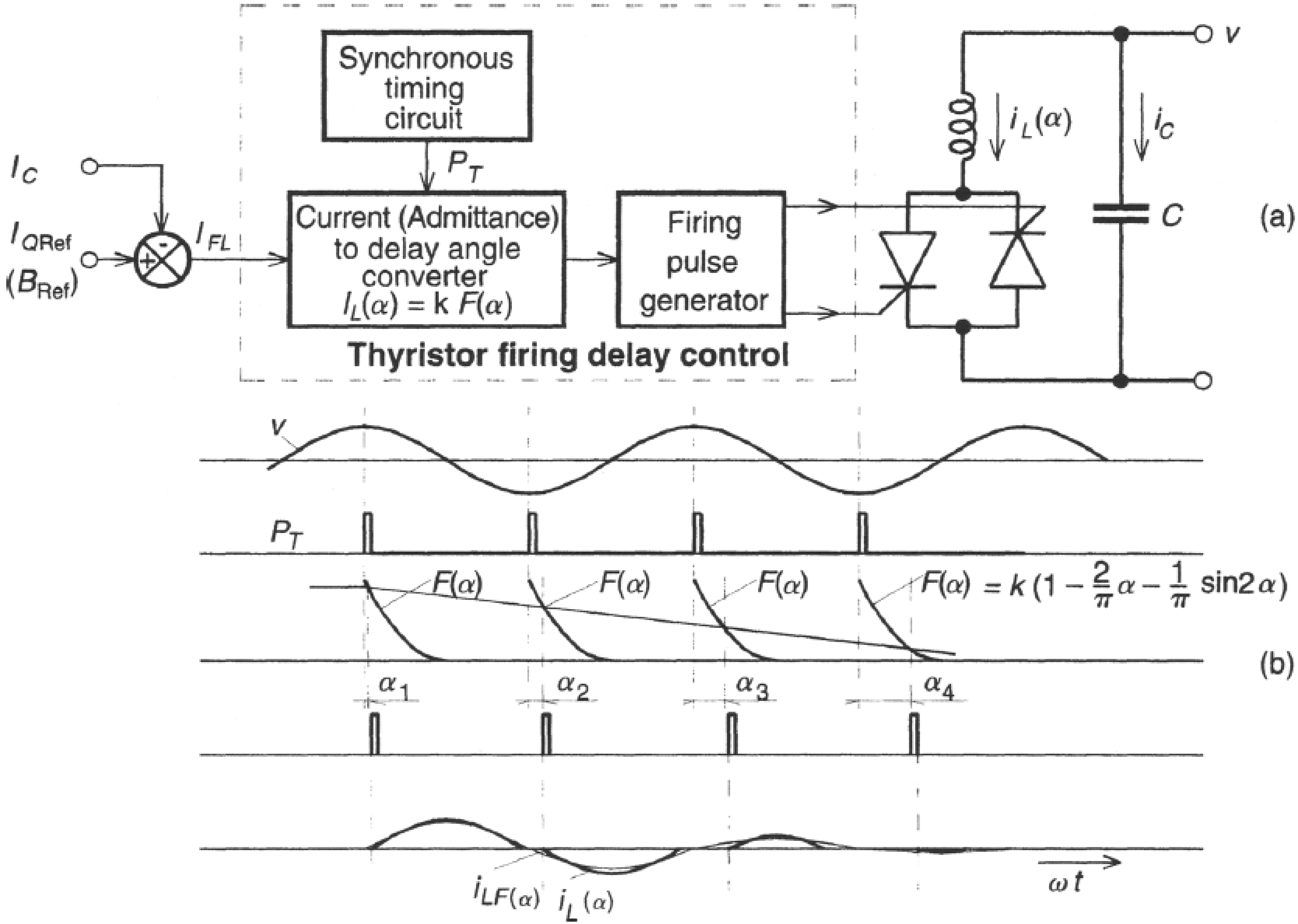
Fixed Capacitor, Thyristor-Controlled Reactor Type Var Generator

- A basic var generator arrangement using a fixed (permanently connected) capacitor with a thyristor-controlled reactor (FC-TCR) is shown functionally in Figure 18(a).
- The current in the reactor is varied by the previously discussed method of firing delay angle control.
- The fixed capacitor in practice is usually substituted, fully or partially, by a filter network that has the necessary capacitive impedance at the fundamental frequency to generate the reactive power required, but it provides a low impedance at selected frequencies to shunt the dominant harmonics produced by the TCR.
- The fixed capacitor, thyristor-controlled reactor type var generator may be considered essentially to consist of a variable reactor (controlled by delay angle *a)* and a fixed capacitor, with an overall var demand versus var output characteristic as shown in Figure 18(b).

Figure 18. Basic FC-TCR type static var generator and its var demand versus var output characteristic.

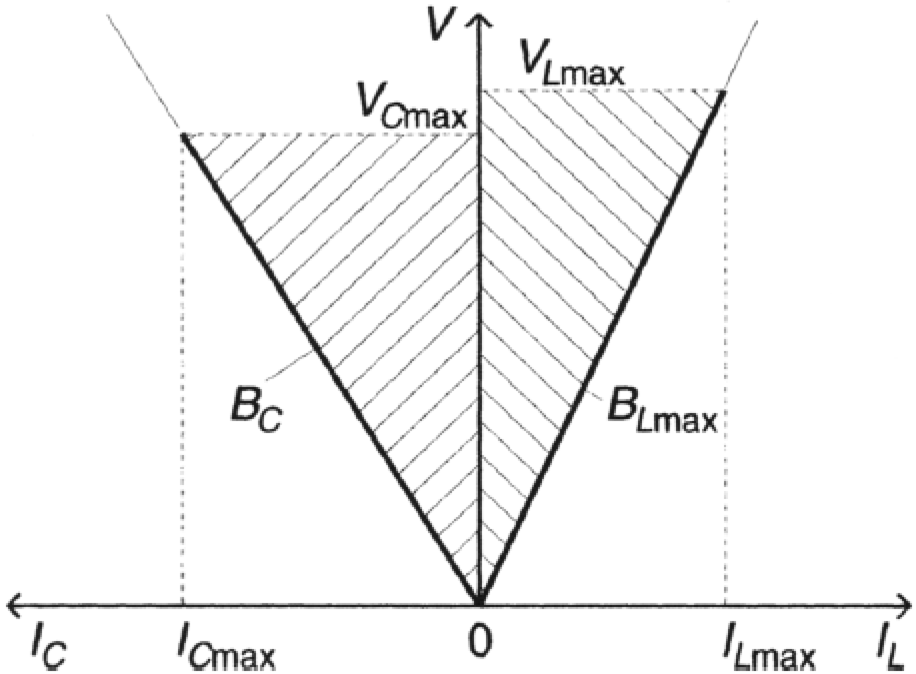


- The control of the thyristor-controlled reactor in the FC-TCR type var generator needs to provide four basic functions, as shown in Figure 19(a).
- One function is synchronous timing. This function is usually provided by a phaselocked loop circuit that runs in synchronism with the ac system voltage and generates appropriate timing pulses with respect to the peak of that voltage. (In a different approach, the ac voltage itself may be used for timing.
- However, this seemingly simple approach presents difficult problems during system faults and major disturbances when the voltage exhibits wild fluctuations and large distortion.)
- The second function is the reactive current (or admittance) to firing angle conversion.
- This can be provided by a real time circuit implementation of the mathematical relationship between the amplitude of the fundamental TCR current ILF(α) and the delay angle a given.
- Several circuit approaches are possible.
- One is an analog function generator producing in each half-cycle a scaled electrical signal that represents the ILF(α) versus a relationship. [This approach is illustrated in Figure 19(b).]
- Another is a digital "look-up table" for the normalized ILF(α) versus a function which is read at regular intervals (e.g., at each degree) starting from α = 0 (peak of the voltage) until the requested value is found, at which instant a firing pulse is initiated.
- A third approach is to use a microprocessor and compute, prior to the earliest firing angle (α = 0), the delay angle corresponding to the required ILF(α). The actual firing instant is then determined simply by a timing circuit (e.g., a counter) "measuring" a from the peak of the voltage.



- Figure 19 Functional control scheme for the FC-TCR type static var generator (a),
- and associated waveforms illustrating the basic operating principles (b).

- The third function is the *computation ofthe required fundamental reactor current* I_{FL}, from the requested total output current I_Q (sum of the fixed capacitor and the TCR currents) defined by the amplitude reference input I_{QReF} to the var generator control.
- This is simply done by subtracting the (scaled) amplitude of the capacitor current, I_C from I_{QRef}' (Positive polarity for lQReF means inductive output current, and negative polarity means capacitive output current.)
- The fourth function is the *thyristor firing pulse generation.* This is accomplished by the firing pulse generator (or gate drive) circuit which produces the necessary gate current pulse for the thyristors to turn on in response to the output signal provided by the reactive current to firing angle converter.
- The gate drive circuits are sometimes at ground potential with magnetic coupling to the thyristor gates; more often, however, they are at the (high) potential level of the thyristors. In the latter case, in order to provide sufficient insulation between the ground level control and the gate drive circuits, the gating information is usually transmitted via optical fibers ("light pipes").
- The operation of the FC-TCR type var generator is illustrated by the waveforms in Figure 19(b).



V_{Cmax} = voltage limit for capacitor
V_{Lmax} = voltage limit for TCR
I_{Cmax} = capacitive current limit
I_{Lmax} = inductive current limit
B_{Lmax} = max inductive admittance
B_C = admittance of capacitor

Figure 20 Operating V-I area of the FC-TCR type var generator.

- The *V-I* operating area of the FC-TCR var generator is defined by the maximum attainable capacitive and inductive admittances and by the voltage and current ratings of the major power components (capacitor, reactor, and thyristor valve), as illustrated in Figure 20.
- The ratings of the power components are derived from application requirements.

Department of Electrical and Electronics Engineering

Subject Code & Name:	EE811PE & POWER QUALITY AND FACTS
UNIT- III Static Shunt Compensators	
Topic Name :	SWITCHING CONVERTER TYPE VAR GENERATORS
Faculty Name :	Dr.K.Eswaramoorthy

SWITCHING CONVERTER TYPE VAR GENERATORS

- Static var generators discussed in the previous section generate or absorb controllable reactive power (var) by synchronously switching capacitor and reactor banks "in" and "out" of the network.
- The aim of this approach is to produce a variable reactive shunt impedance that can be adjusted (continuously or in a step-like manner) to meet the compensation requirements of the transmission network.
- The possibility of generating controllable reactive power directly, without the use of ac capacitors or reactors, by various switching power converters was disclosed by Gyugyi in 1976.
- These (dc to ac or ac to ac) converters are operated as voltage and current sources and they produce reactive power essentially without reactive energy storage components by circulating alternating current among the phases of the ac system.
- Synchronous machine whose reactive power output is varied by excitation control.
- Like the mechanically powered machine, they can also exchange real power with the ac system if supplied from an appropriate, usually dc energy source.
- Because of these similarities with a rotating synchronous generator, they are termed **Static Synchronous Generators (SSGs).**
- When an SSG is operated without an energy source, and with appropriate controls to function as a shunt-connected reactive compensator, it is termed, analogously to the **rotating Synchronous Compensator (condenser), a Static Synchronous Compensator (Condenser) STATCOM STATCON**

1.BASIC OPERATING PRINCIPLES

- The basic principle of reactive power generation by a voltage-sourced converter is akin to that of the conventional rotating synchronous machine.
- For purely reactive power flow, the three-phase induced electromotive forces (EMF's) Ea, Eb and Ec of the synchronous rotating machine are in phase with the system voltages, Va, Vb, and Vc.
- The reactive current I drawn by the synchronous compensator is determined by the magnitude of the system voltage V, that of the internal voltage E, and the total circuit reactance (synchronous machine reactance plus transformer leakage reactance plus system short circuit reactance X).

$$I = \frac{V - E}{X}$$

- The corresponding reactive power Q exchanged can be expressed as follows

$$Q = \frac{1 - \frac{E}{V}}{X} V^2$$

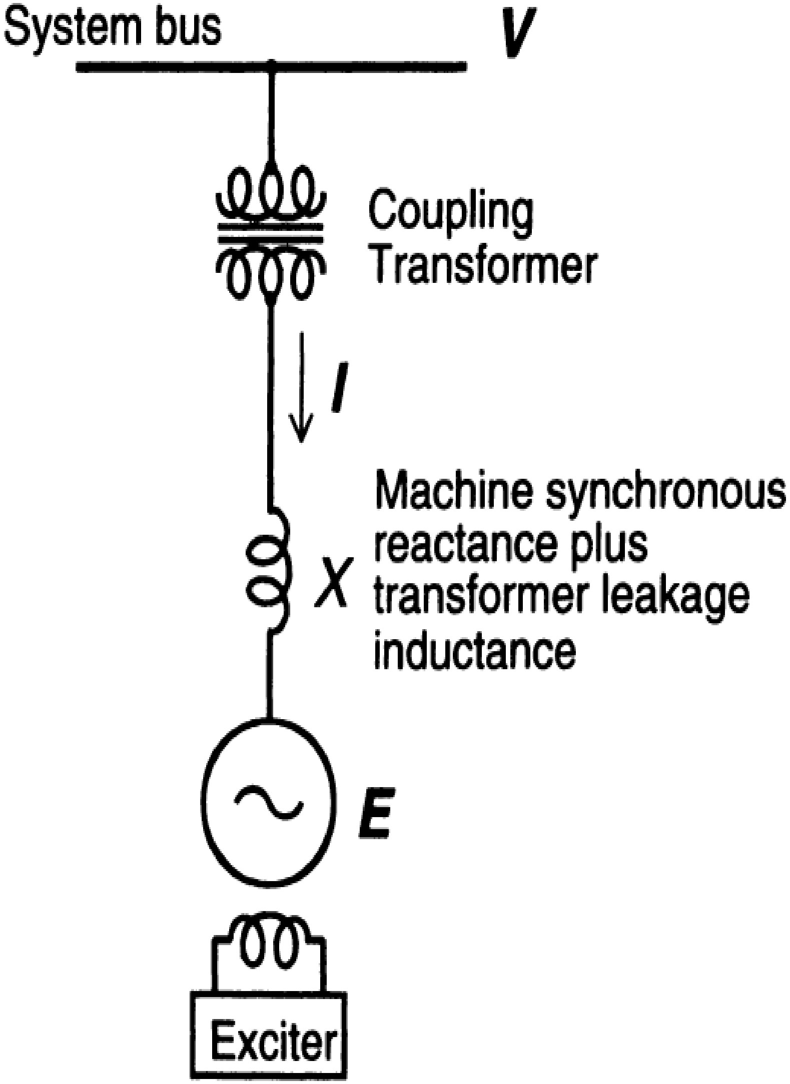


Figure 28 Reactive power generation by a rotating synchronous compensator (condenser).

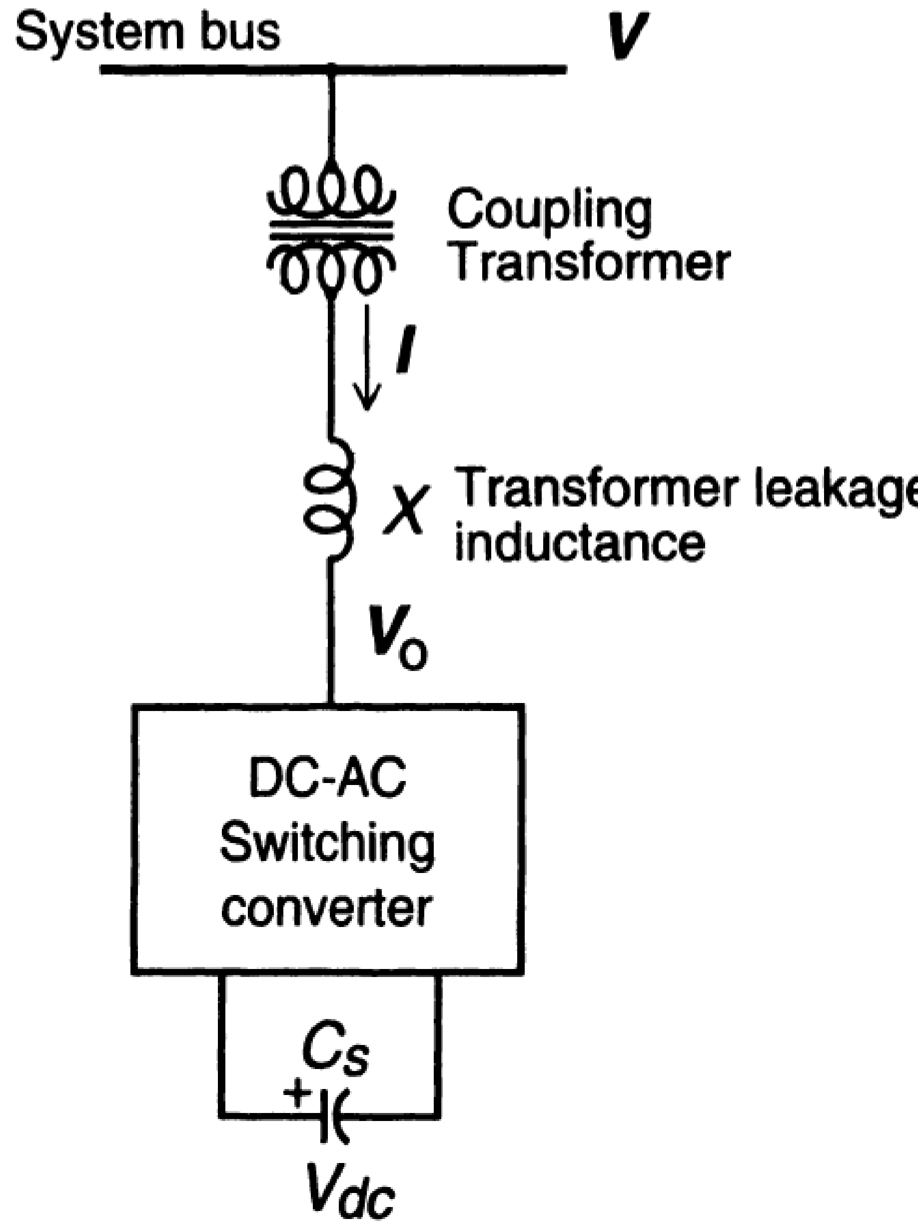


FIgure 5.29 Reactive power generation by rotating a voltage-sourced switching converter

- By controlling the excitation of the machine, and hence the amplitude E of its internal voltage relative to the amplitude V of the system voltage, the reactive power flow can be controlled.
- Increasing E above V (i.e., operating over-excited) results in a leading current, that is, the machine is "seen" as a capacitor by the ac system.
- Decreasing E below V (i.e., operating under-excited) produces a lagging current, that is, the machine is "seen" as a reactor (inductor) by the ac system.
- Under either operating condition a small amount of real power of course flows from the ac system to the machine to supply its mechanical and electrical losses.
- Note that if the excitation of the machine is controlled so that the corresponding reactive output maintains or varies a specific parameter of the ac system (e.g., bus voltage), then the machine (rotating var generator) functions as a rotating synchronous compensator (condenser).
- The basic voltage-sourced converter scheme for reactive power generation is shown in the form of a single-line diagram.
- From a dc input voltage source, provided by the charged capacitor C the converter produces a set of controllable three-phase output voltages with the frequency of the ac power system.
- Each output voltage is in phase with, and coupled to the corresponding ac system voltage via a relatively small (0.1-0.15 p.u.) tie reactance (which in practice is provided by the per phase leakage inductance of the coupling transformer).

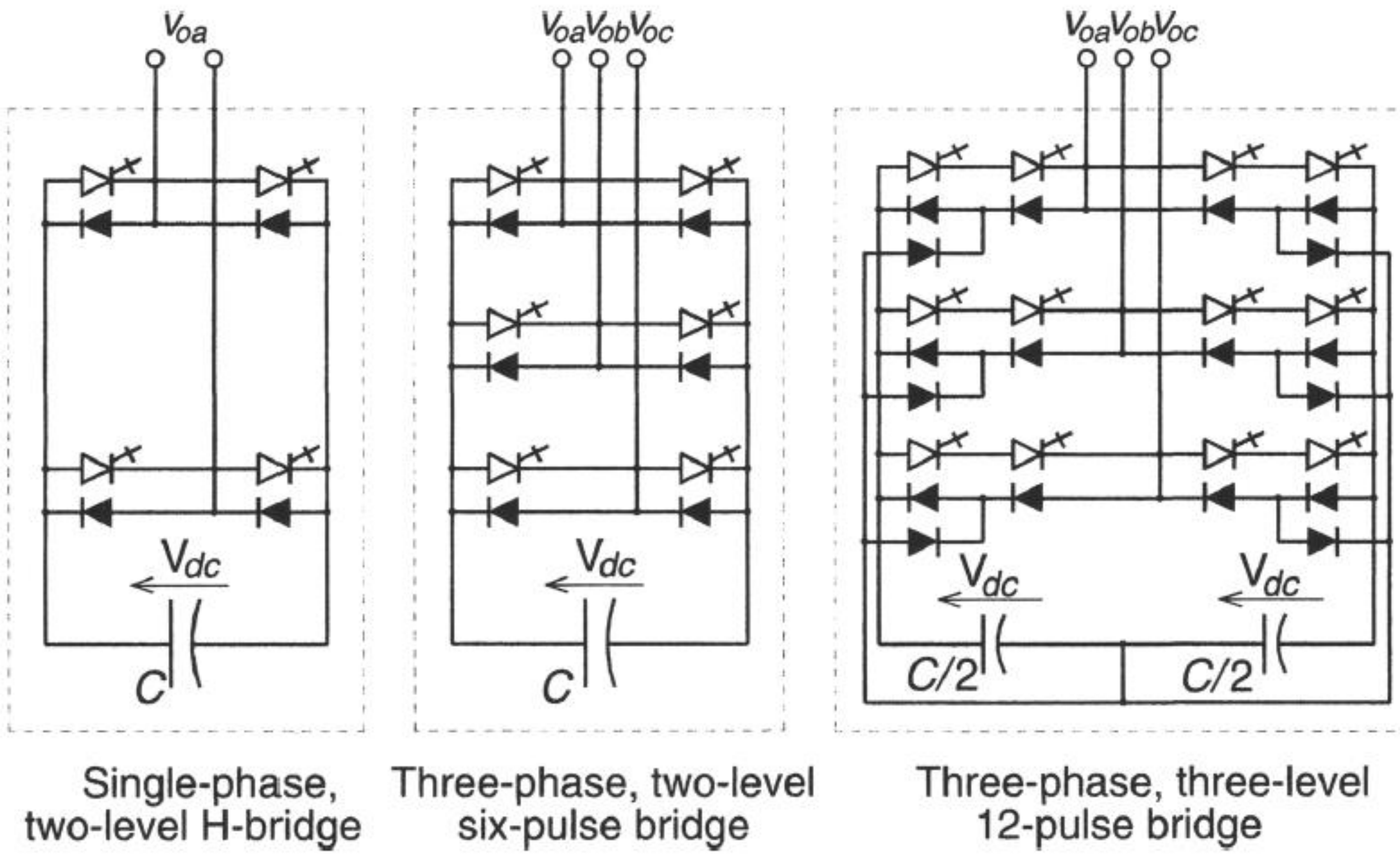


Figure Basic converter schemes used for reactive power generation

- By varying the amplitude of the output voltages produced, the reactive power exchange between the converter and the ac system can be controlled in a manner similar to that of the rotating synchronous machine.
- That is, if the amplitude of the output voltage is increased above that of the ac system voltage, then the current flows through the tie reactance from the converter to the ac system, and the converter generates reactive (capacitive) power for the ac system.
- If the amplitude of the output voltage is decreased below that of the ac system, then the reactive current flows from the ac system to the converter, and the converter absorbs reactive (inductive) power.
- If the amplitude of the output voltage is equal to that of the ac system voltage, the reactive power exchange is zero
- Since the converter supplies only reactive output power (its output voltages are controlled to be in phase with the ac system voltages), the real input power provided by the dC source (charged capacitor) must be zero (as the total instantaneous power on the ac side is also zero).
- Furthermore, since reactive power at zero frequency (at the dc capacitor) by definition is zero, the de capacitor plays no part in the reactive power generation.
- In other words, the converter simply interconnects the three ac terminals in such a way that the reactive output currents can flow freely between them.
- Viewing this from the terminals of the ac system, one could say that the converter establishes a circulating current flow among the phases with zero net instantaneous power exchange.

2. BASIC CONTROL APPROACHES

- A static (var) generator converter comprises a large number of gate controlled semiconductor power switches (GTO thyristors).
- The gating commands for these devices are generated by the internal converter control (which is part of the var generator proper) in response to the demand for reactive and/or real power reference signal(s).
- The reference signals are provided by the external or system control, from operator instructions and system variables, which determine the functional operation of the STATCOM.
- The internal control is an integral part of the converter. Its main function is to operate the converter power switches so as to generate a fundamental output voltage waveform with the demanded magnitude and phase angle in synchronism with the ac system.
- In this way the power converter with the internal control can be viewed as a sinusoidal, synchronous voltage source behind a tie reactor (provided by the leakage inductance of the coupling transformer), the amplitude and phase angle of which are controlled by the external (STATCOM system) control via appropriate reference signal(s).
- The main function of the internal control, as stated above, is to operate the converter power switches so as to produce a synchronous output voltage waveform that forces the reactive (and real) power exchange required for compensation

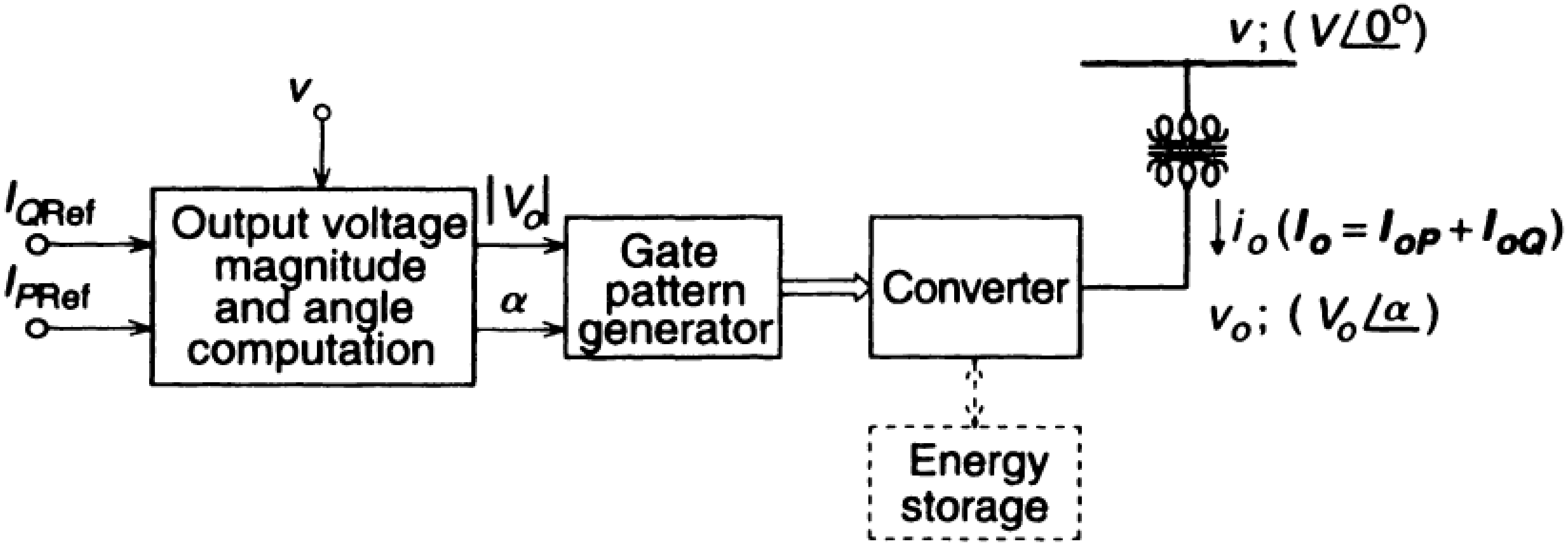
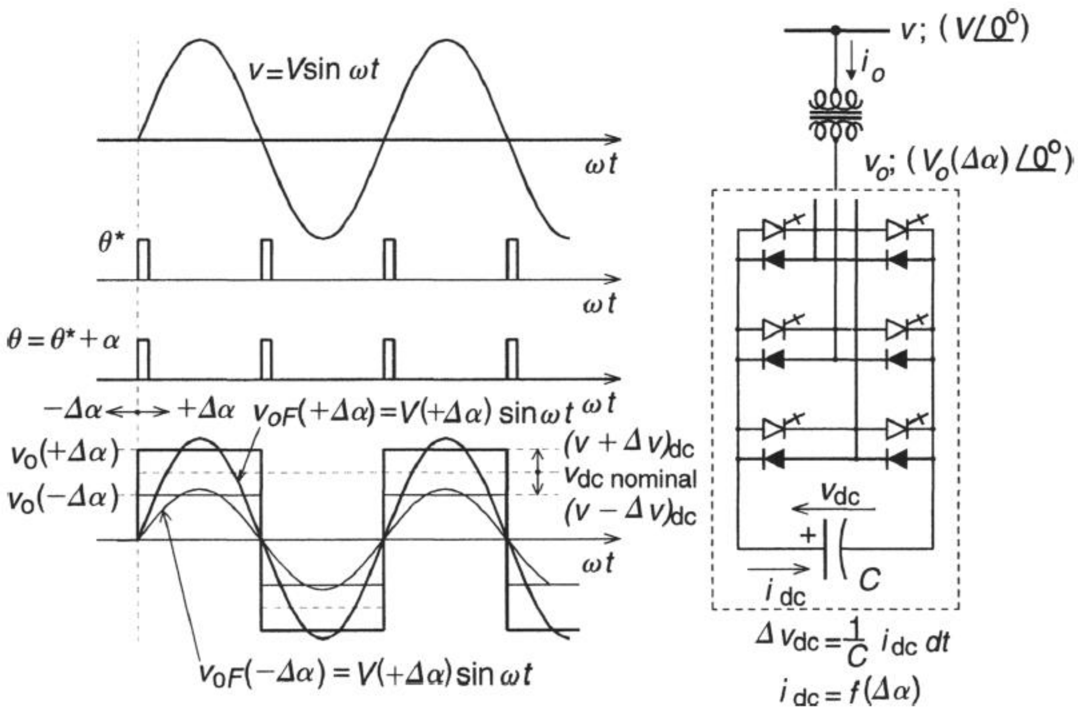


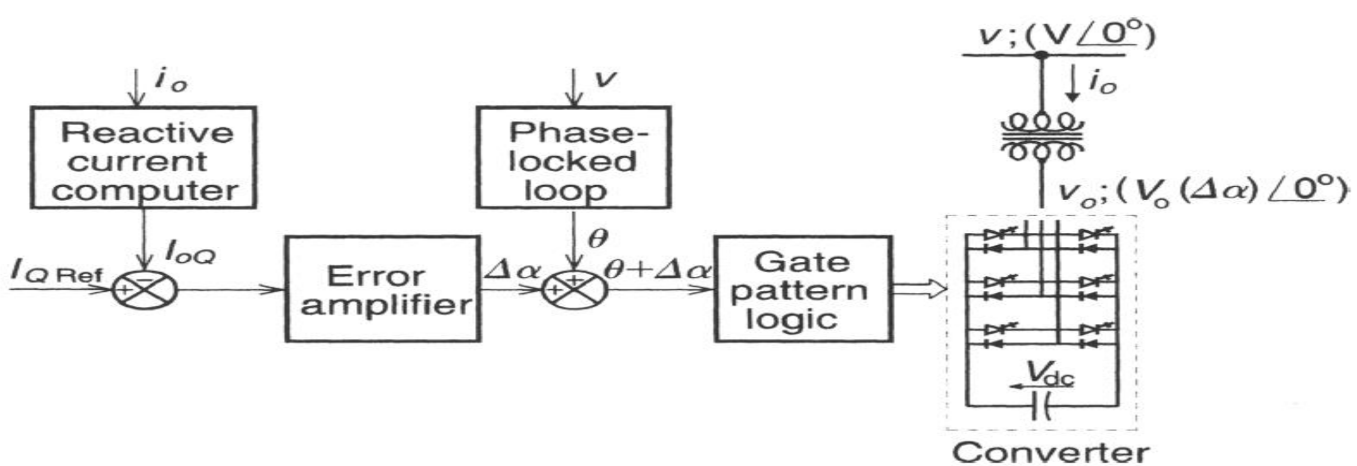
Figure 32 Main functions of the internal converter control

- The internal control achieves this by computing the magnitude and phase angle of the required output voltage from I_{QRef} and I_{PRef} provided by the external control and generating a set of coordinated timing waveforms ("gating pattern"), which determines the on and off periods of each switch in the converter corresponding to the wanted output voltage.
- These timing waveforms have a defined phase relationship between them, determined by the converter pulse number, the method used for constructing the output voltage waveform, and the required angular phase relationship between the three outputs (normally 120 degrees).

- The magnitude and angle of the output voltage are those internal parameters which determine the real and reactive current the converter draws from, and thereby the real and reactive power it exchanges with the ac system.
- If the converter is restricted for reactive power exchange, i.e., it is strictly operated as a static var generator, then the reference input to the internal control is the required reactive current.
- From this the internal control derives the necessary magnitude and angle for the converter output voltage to establish the required dc voltage on the dc capacitor since the magnitude of the ac output voltage is directly proportional to the dc capacitor voltage.
- Because of this proportionality, the reactive output current, as one approach, can be controlled indirectly via controlling the dc capacitor voltage (which in turn is controlled by the angle of the output voltage) or, as another approach, directly by the internal voltage control mechanism (e.g., PWM) of the converter in which case the de voltage is kept constant (by the control of the angle)
- There are two basic approaches to output voltage, and thus to var control
- 1. Indirect output voltage control
- 2. Direct" output voltage control

Block diagram of the internal control for purely reactive compensation, based on the indirect approach of dc capacitor voltage control:

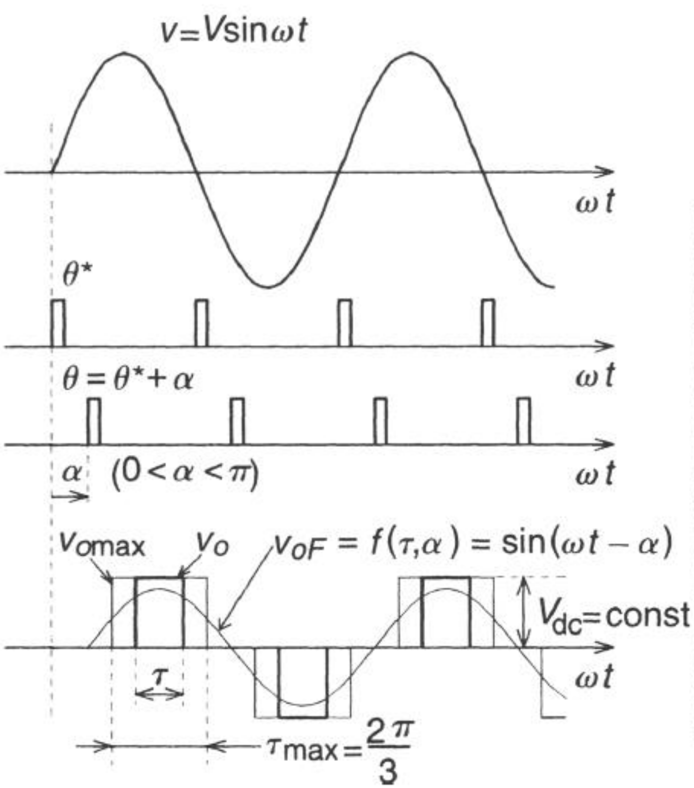


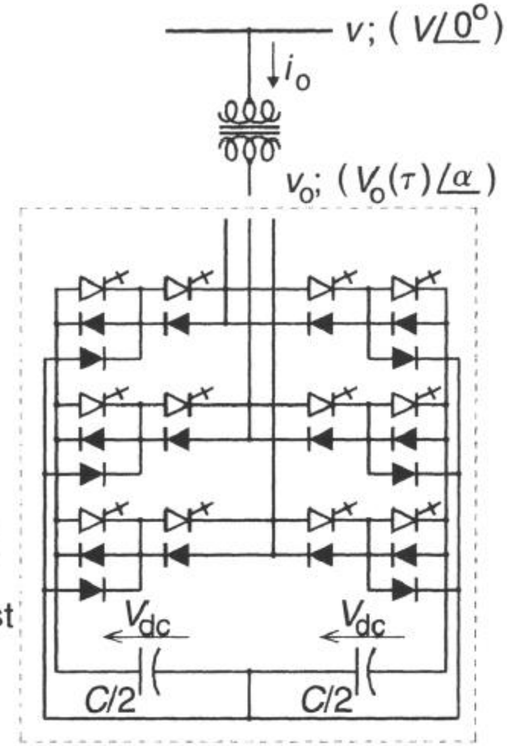


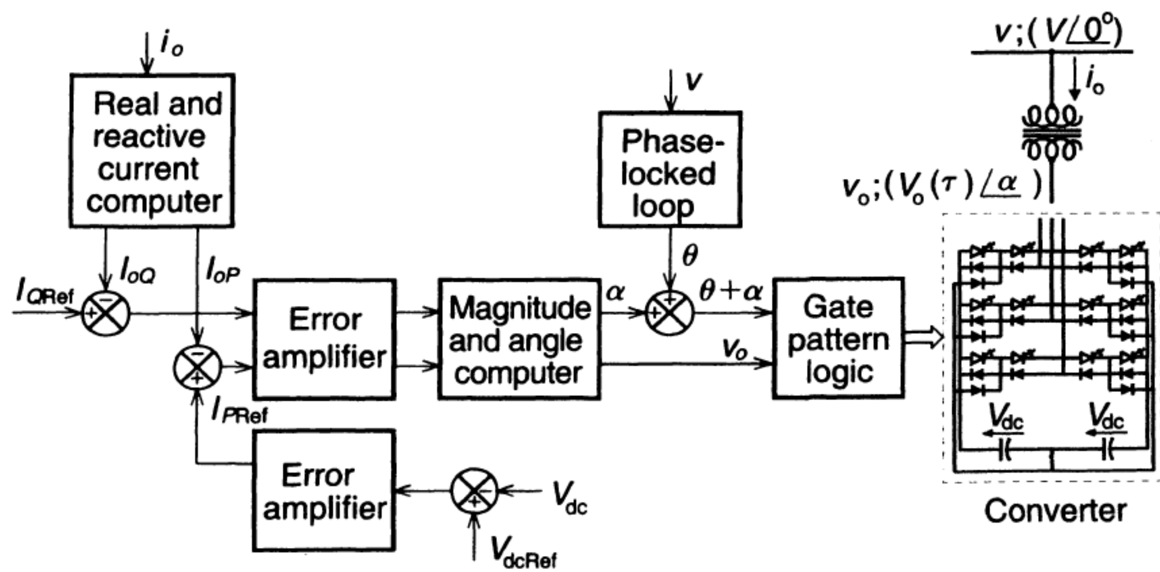
- The inputs to the internal control are: the ac system bus voltage v, the output current of the converter i0 reference, and the reactive current I_{QRef} .
- Voltage v operates a phase-locked loop that provides the basic synchronizing signal, angle θ.
- The output current, i0 ' is decomposed "into its reactive and real components, and the magnitude of the reactive current component, I_{0Q} to the reactive current reference, IQRef is compared.
- The error thus obtained provides, after suitable amplification, angle α, which defines the necessary phase shift between the output voltage of the converter and the ac system voltage needed for charging (or discharging) the storage capacitor to the dc voltage level required.
- Accordingly, angle α is summed to θ to provide angle θ + α, which represents the desired synchronizing signal for the converter to satisfy the reactive current reference.
- Angle θ + α operates the gate pattern logic (which may be a digital look-up table) that provides the individual gate drive logic signals to operate the converter power switches.

Block diagram of the internal control for a converter with direct internal voltage control capability, such as the three-level converter:

- The input signals are again the bus voltage, v, the converter output current, i0 , and the reactive current reference, IQRef, plus the dc voltage reference Vdc .
- This dc voltage reference determines the real power the converter must absorb from the ac system in order to supply its internal losses.
- The converter output current is decomposed into reactive and real current components.
- These components are compared to the external reactive current reference (determined from compensation requirements) and the internal real current reference derived from the dc voltage regulation loop.
- After suitable amplification, the real and reactive current error signals are converted into the magnitude and angle of the wanted converter output voltage, from which the appropriate gate drive signals, in proper relationship with the phase-locked loop provided phase reference, are derived.


$v = V\sin\omega t$
ωt
θ^*
ωt
$\theta = \theta^* + \alpha$
ωt
α $(0 < \alpha < \pi)$
ωt
v_{Omax}
v_O
$v_{OF} = f(\tau, \alpha) = \sin(\omega t - \alpha)$
V_{dc}=const
ωt
τ
$\tau_{max} = \frac{2\pi}{3}$


v; $(V\angle 0^o)$
i_o
v_o; $(V_o(\tau)\angle\alpha)$
V_{dc}
V_{dc}
$C/2$
$C/2$


i_o
Real and reactive current computer
I_{oQ}
I_{oP}
I_{QRef}
Error amplifier
Magnitude and angle computer
α
v
Phase-locked loop
θ
$\theta + \alpha$
V_o
Gate pattern logic
I_{PRef}
Error amplifier
V_{dc}
V_{dcRef}
v; $(V\angle 0^o)$
i_o
v_o; $(V_o(\tau)\angle\alpha)$
V_{dc}
V_{dc}
Converter

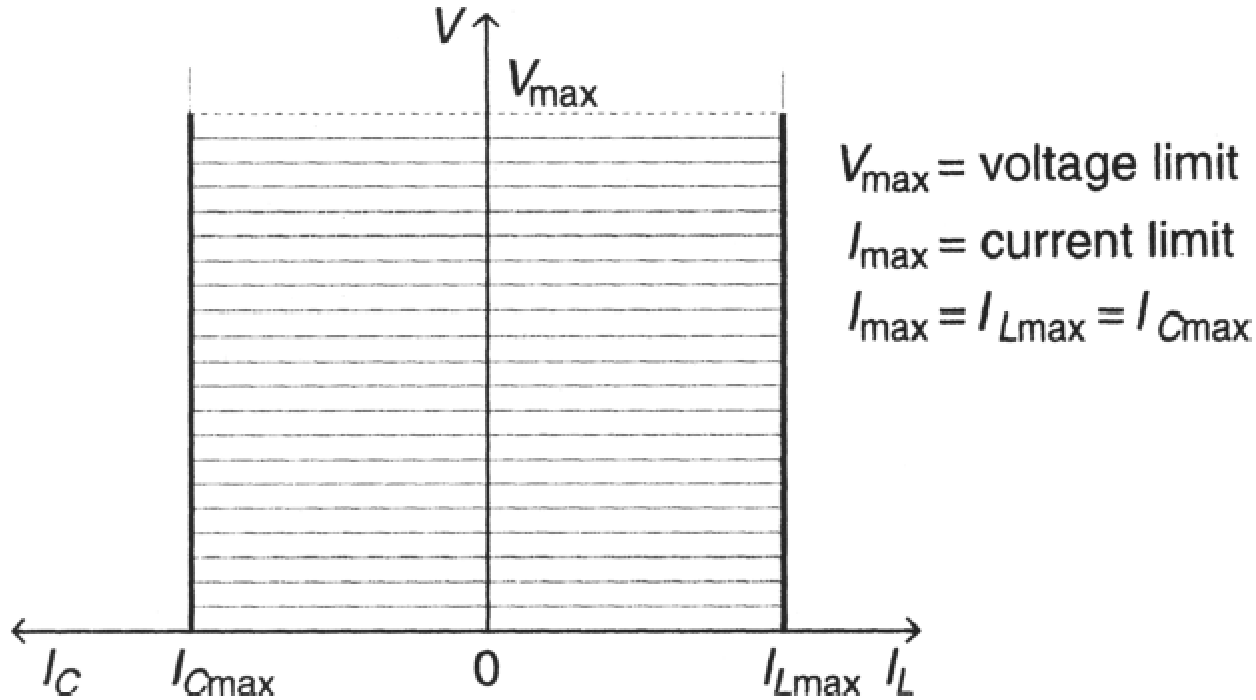


Figure 37 Operating V-I area of the voltage-sourced converter type var generator

- The *V-I* operating area of this var generator is limited only by the maximum voltage and current ratings of the converter, as illustrated in Figure 37.
- (Note that there would also be a low voltage-about 0.2 p.u.-limit at which the converter still would be able to absorb the necessary real power from the ac system to supply its operating losses.)

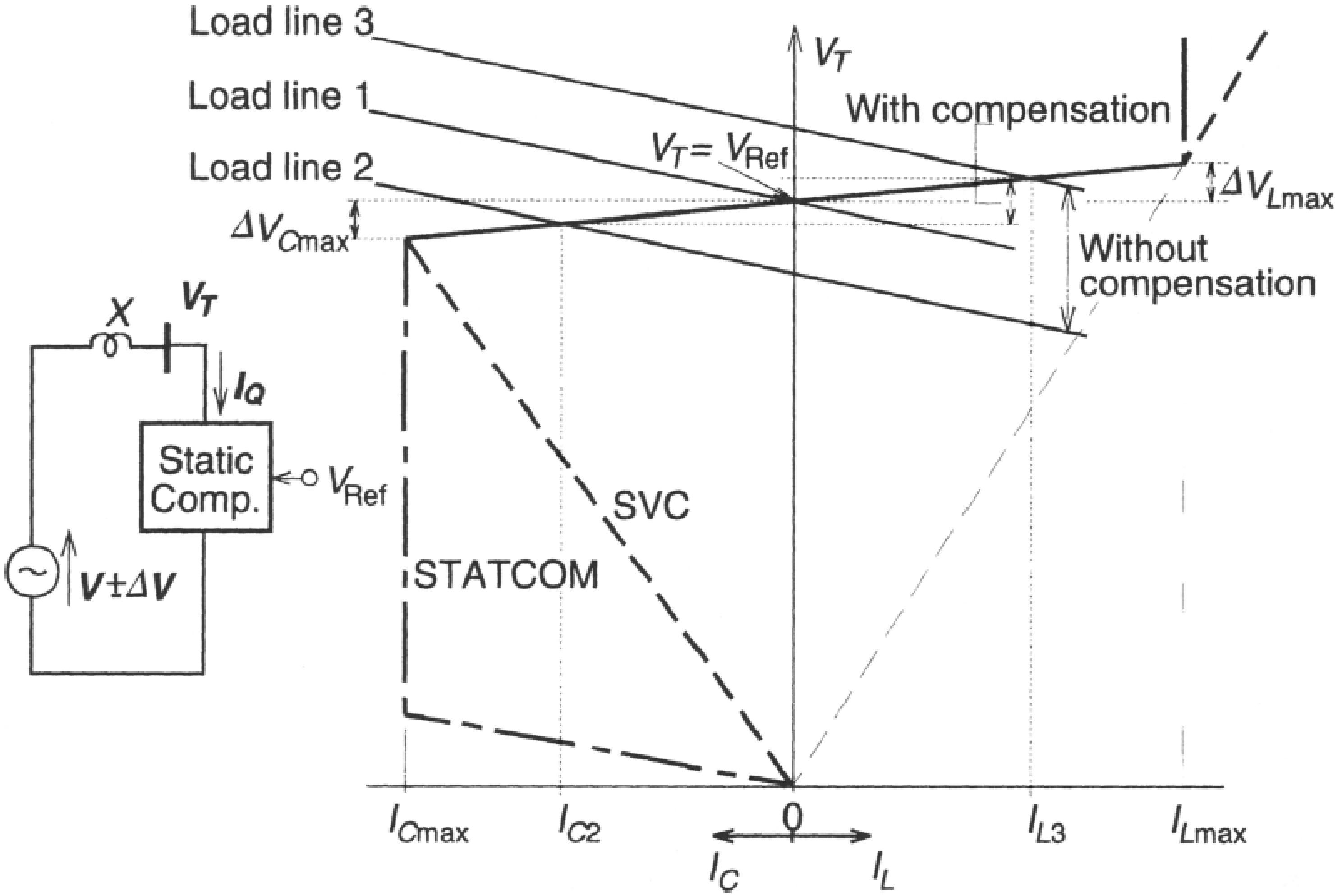
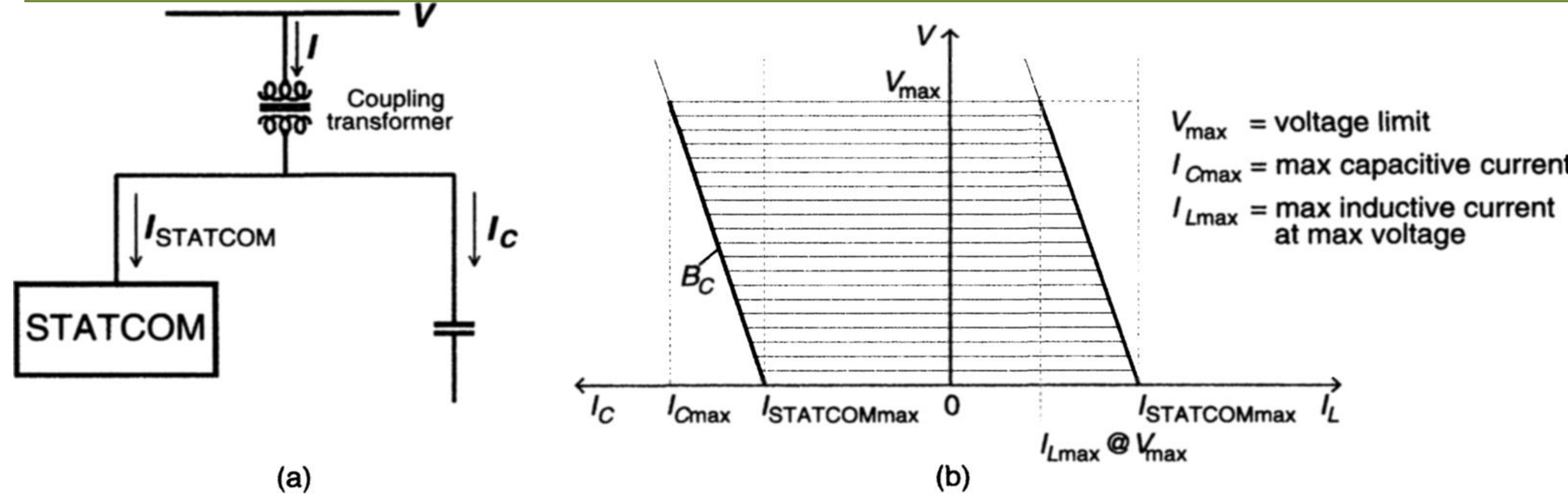


Figure V-I characteristic of the SVC and the STATCOM.

Summary of Static Var Generators



Combined converter-based and fixed capacitor type var generator (a), and associated operating V-I area (b).

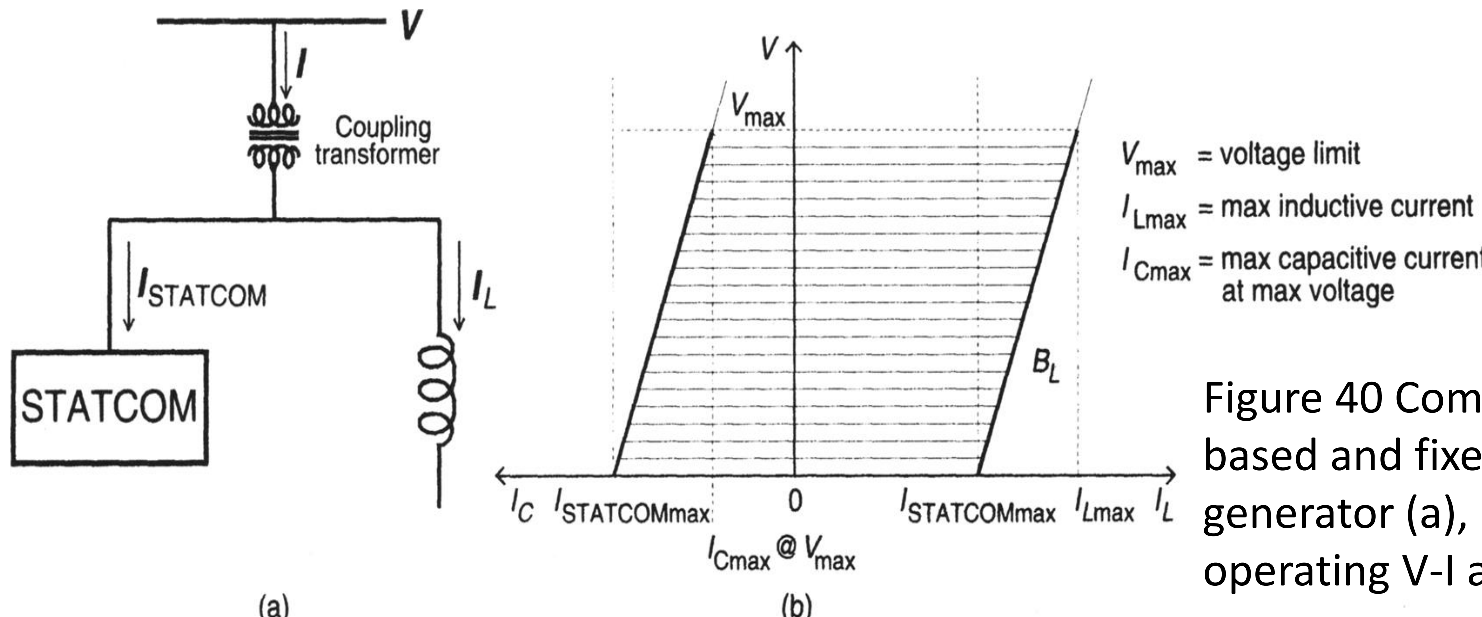


Figure 40 Combined converter-based and fixed reactor type var generator (a), and associated operating V-I area (b).

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Department of Electrical and Electronics Engineering

Subject Code & Name:	EE811PE & POWER QUALITY AND FACTS
UNIT- III Static Shunt Compensators	
Topic Name :	Comparison of Static Var Generators
Faculty Name :	Dr.K.Eswaramoorthy

Comparison of Static Var Generators

VAR generator	TCR-FC	TSC-(TSR)	TCR-TSC	Converter-based
Type	Controlled Impedance	Controlled Impedance	Controlled Impedance	Synch. Voltage Source
V-I and V-Q characteristics	Max comp. current is proportional to system voltage. Max. cap. var output decreases with the square of voltage decrease.	Max comp. current is proportional to system voltage. Max. cap. var output decreases with the square of voltage decrease.	Max comp. current is proportional to system voltage. Max. cap. var output decreases with the square of voltage decrease.	Max comp. current is maintained independent of system voltage. Max. cap. var output decreases linearly with voltage decrease.
Loss vs. var output	High losses at zero output. Losses decrease smoothly with cap. output, increase with inductive output.	Low losses at zero output. Losses increase step-like with cap. output.	Low losses at zero output. Losses increase step-like with cap. output, smoothly with ind. output.	Low losses at zero output. Losses increase smoothly with both cap. and inductive output.
Harmonic generation	Internally high (large p.u. TCR). Requires significant filtering.	Internally very low. Resonances (and current limitation) may necessitate tuning reactors.	Internally low (small p.u. TCR). Requires filtering.	Can be internally very low (multipulse, multilevel converters). May require no filtering.
Max. theoret. delay	Half-cycle	One cycle	One cycle	Negligible
Transient behavior under system voltage disturbances	Poor. (FC causes transient over-voltages in response to step disturbances.)	Can be neutral. (Capacitors can be switched out to minimize transient over-voltages.)	Can be neutral. (Capacitors can be switched out to minimize transient over-voltages.)	Trends to damp transients. (Low impedance voltage source.)

Department of Electrical and Electronics Engineering

Subject Code & Name:	EE811PE & POWER QUALITY AND FACTS
UNIT- IV Static Series Compensators	
Faculty Name :	Dr.K.Eswaramoorthy

UNIT- IV
Static Series Compensators:

- Objectives of series compensator, variable impedance type of series compensators, TCSC, TSSC-operating principles and control schemes, SSSC, Power Angle characteristics, Control range and VAR rating, Capability to provide reactive power compensation, external control

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Department of Electrical and Electronics Engineering

Subject Code & Name:	EE811PE & POWER QUALITY AND FACTS
UNIT- IV Static Series Compensators	
Topic Name :	OBJECTIVES OF SERIES COMPENSATION
Faculty Name :	Dr.K.Eswaramoorthy

OBJECTIVES OF SERIES COMPENSATION

- The reactive shunt compensation, when applied at sufficiently close intervals along the line, could theoretically make it possible to transmit power up to thermal limit of the line, if a large enough angle between the two end voltages could be established.
- However, shunt compensation is ineffective in controlling the actual transmitted power which, at a defined transmission voltage, is ultimately determined by the series line impedance and the angle between the end voltages of line.
- It was always recognized that ac power transmission over long lines was primarily limited by the series reactive impedance of the line.
- Series capacitive compensation was introduced decades ago to cancel a portion of the reactive line impedance and thereby increase the transmittable power.
- Subsequently, within the FACTS initiative, it has been demonstrated that variable series compensation is highly effective in both controlling power flow in the line and in improving stability.
- It can be applied to achieve full utilization of transmission assets by **controlling the power flow in the lines, preventing loop flows and, with the use of fast controls, minimizing the effect of system disturbances, thereby reducing traditional stability margin requirements.**

- The effect of series compensation on the basic factors, determining attainable
  - MAXIMAL POWER TRANSMISSION,
  - STEADY-STATE POWER TRANSMISSION
  - LIMIT, TRANSIENT STABILITY,
  - VOLTAGE STABILITY
  - POWER OSCILLATION DAMPING
- We are going to deal the following subheadings
  1. Concept of Series Capacitive Compensation
  2. Voltage Stability
  3. Improvement of Transient Stability
  4. Power Oscillation Damping
  5. Subsynchronous Oscillation Damping
  6. Summary of Functional Requirements

1.CONCEPT OF SERIES CAPACITIVE COMPENSATION

- The basic idea behind series capacitive compensation is to decrease the overall effective series transmission impedance from the sending end to the receiving end, i.e., X in the P = (V_2/X) sin δ relationship characterizing the power transmission over a single line.
- Consider the simple two-machine model, with a series capacitor compensated line, which, for convenience, is assumed to be composed of two identical segments.
- Note that for the same end voltages the magnitude of the total voltage across the series line inductance, $V_X = 2V_{X/2}$ is increased by the magnitude of the opposite voltage, Vc developed across the series capacitor and this results from an increase in the line current.
- Effective transmission impedance with the series capacitive compensation is $X_{eff} = X - X_c$
- $X_{eff} = (1 - K)X$

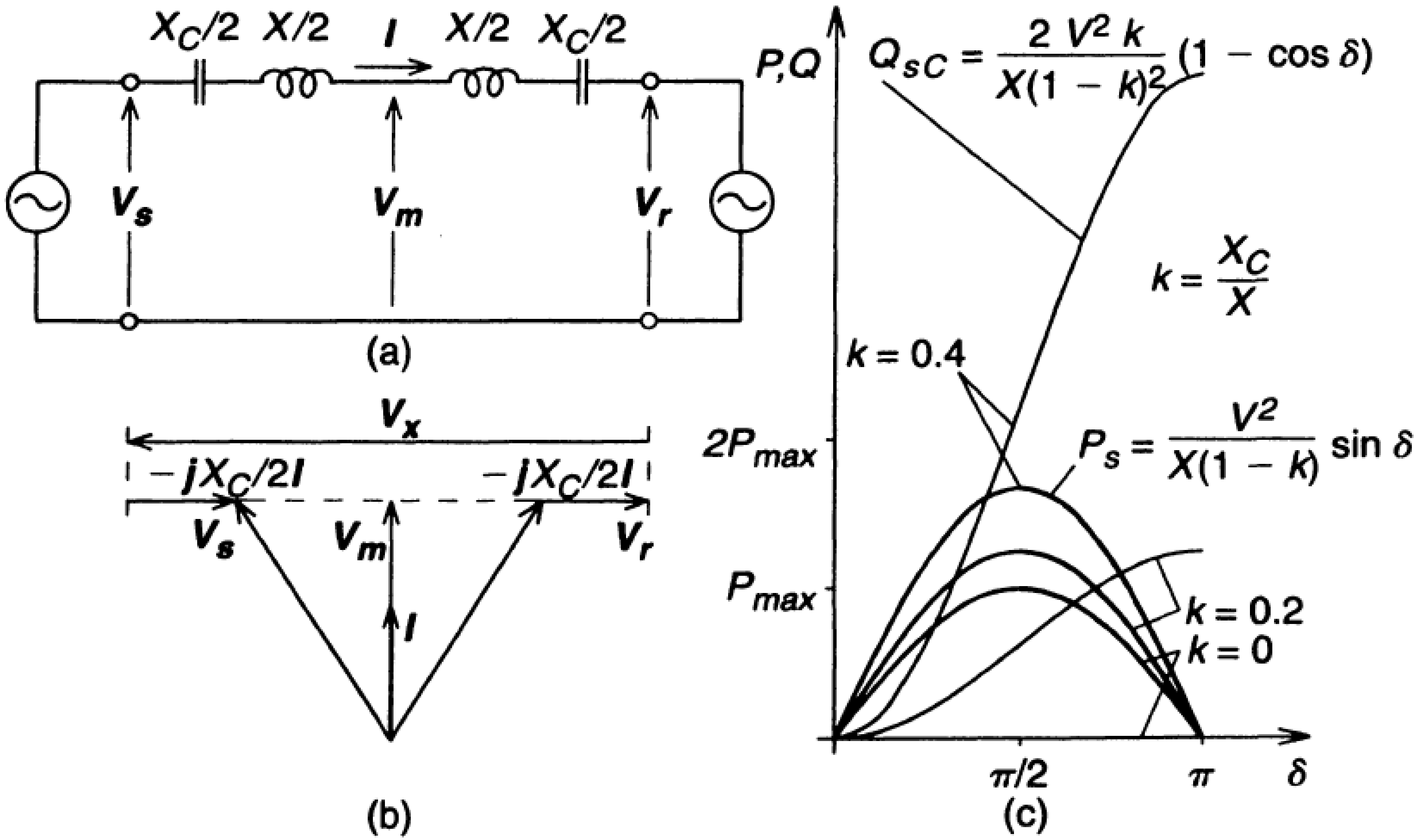


Figure 1 Two-machine power system with series capacitive compensation (a), corresponding phasor diagram (b), real power and series capacitor reactive power vs. angle characteristics (c).

where K is the degree of series compensation,

$$K = \frac{X_C}{X}$$

Assuming the voltages $V_S = V_r = V$

The current in the compensated line is

$$I = \frac{2V}{(1-K)X}\sin\frac{\delta}{2}$$

Real Power Transmitted is

$$P = V_m I = \frac{V^2}{(1-K)X}\sin\delta$$

Reactive power supplied by the series capacitor is

$$Q_C = I^2 X_C = \frac{2V^2}{(1-K)^2 X}\,(1-\cos\delta)$$

- The relationship between the real power P, series capacitor reactive power Qc, and angle δ is shown plotted at various values of the degree of series compensation k in Figure 1(c).
- It can be observed that, as expected, the transmittable power rapidly increases with the degree of series compensation k.
- Similarly, the reactive power supplied by the series capacitor also increases sharply with k and varies with angle B in a similar manner as the line reactive power.
- The conventional explanation is that the impedance of the series compensating capacitor cancels a portion of the actual line reactance and thereby the effective transmission impedance, per (1), is reduced as if the line was physically shortened.
- An equally valid physical explanation, which will be helpful to the understanding of converter based power flow controllers, is that in order to increase the current in the given series impedance of the actual physical line (and thereby the corresponding transmitted power), the voltage across this impedance must be increased.
- This can be accomplished by an appropriate series connected circuit element, such as a capacitor, the impedance of which produces a voltage opposite to the prevailing voltage across the series line reactance and, as the phasor diagram in Figure 1(c) illustrates, thereby causes this latter voltage to increase.
- It is easy to see that within this second explanation the physical nature of the series circuit element is irrelevant as long as it produces the desired compensating voltage.
- Thus, an alternate compensating circuit element may be envisioned as an ac voltage source which directly injects the desired compensating voltage in series with the line.
- As will be seen, the switching power converter used in the shunt-connected STATCOM, applied as a voltage source in series with the line, serves the functional capabilities of series capacitive compensation and also provides additional options for power flow control.

2. Voltage Stability

- Series capacitive compensation can also be used to reduce the series reactive impedance to minimize the receiving-end voltage variation and the possibility of voltage collapse.
- A simple radial system with feeder line reactance X, series compensating reactance Xc, and load impedance Z is shown .
- The "nose point" at each plot given for a specific compensation level represents the corresponding voltage instability where the same radial system with a reactive shunt compensator, supporting the end voltage, is shown fig 2.
- Clearly, both shunt and series capacitive compensation can effectively increase the voltage stability limit. Shunt compensation does it by supplying the reactive load demand and regulating the terminal voltage.
- Series capacitive compensation does it by canceling a portion of the line reactance and thereby, in effect, providing a "stiff“ voltage source for the load.
- For increasing the voltage stability limit of overhead transmission, series compensation is much more effective than shunt compensation of the same MVA rating.

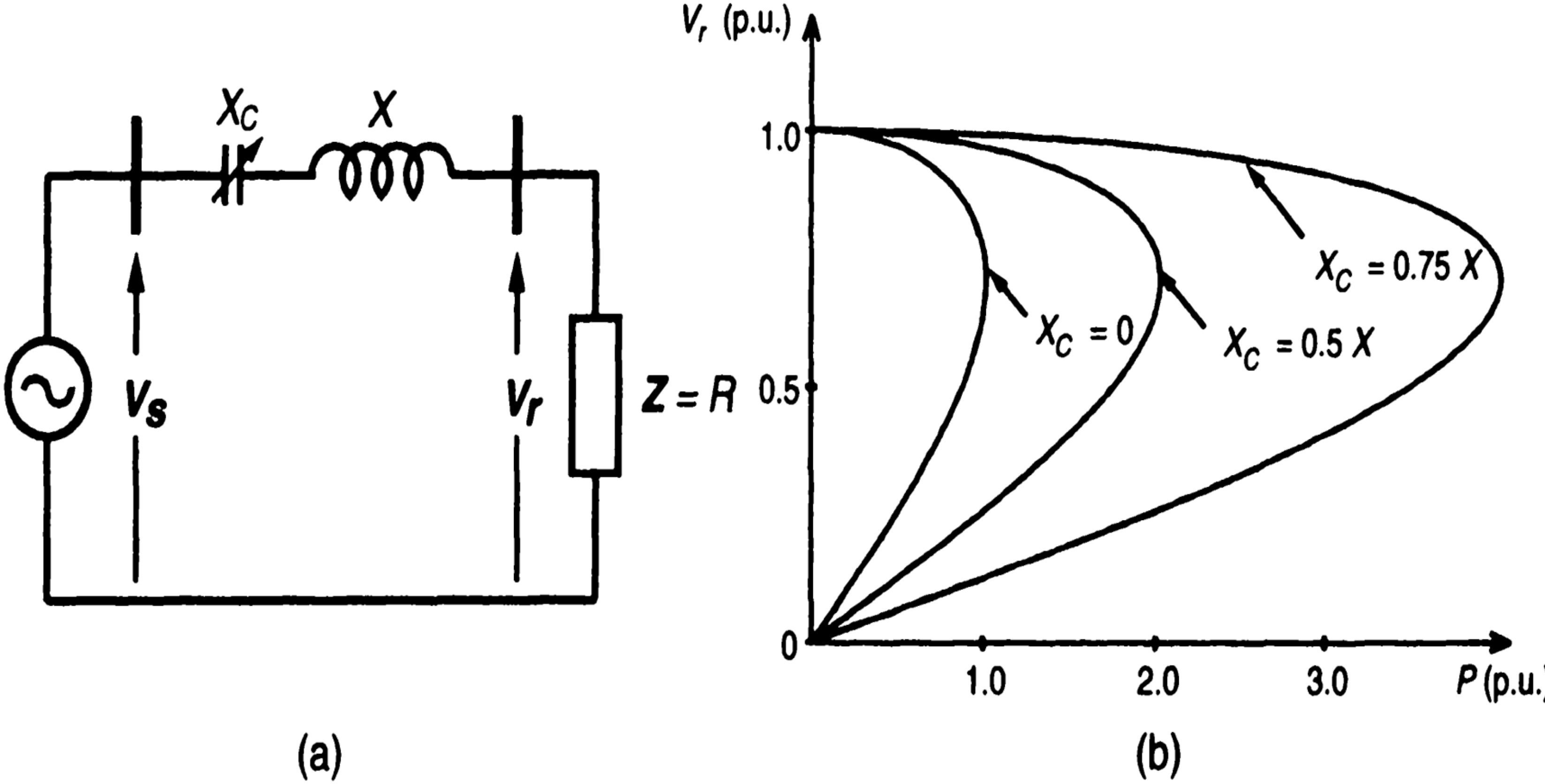
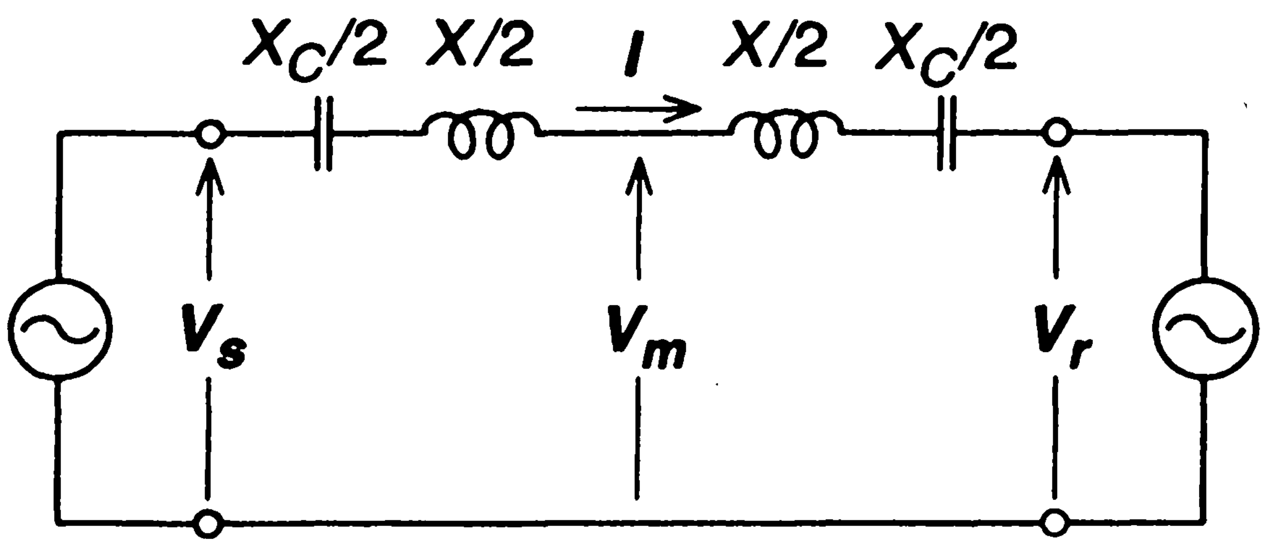


Figure 2 Transmittable power and voltage stability limit of a radial transmission line as function of series capacitive compensation

3.Improvement of Transient Stability

- The powerful capability of series line compensation to control the transmitted power can be utilized much more effectively to increase the transient stability limit and to provide power oscillation damping.
- The equal area criterion, to investigate the capability of the ideal shunt compensator to improve the transient stability, is used again here to assess the relative increase of the transient stability margin attainable by series capacitive compensation.
- Consider the simple system with the series compensated line shown.
- As for the shunt compensated system shown, it is, for convenience, also assumed for the series compensated case that the pre-fault and post-fault systems remain the same.
- Suppose that the system, with and without series capacitive compensation, transmits the same power Pm.
- Assume that both the uncompensated and the series compensated systems are subjected to the same fault for the same period of time.

- The dynamic behavior of these systems is illustrated in as seen, prior to the fault both of them transmit power Pm at angles δ1 and δs1, respectively.
- During the fault, the transmitted electric power becomes zero While the mechanical input power to the generators remains constant, Pm.
- Therefore, the sending-end generator accelerates from the steady-state angles δ1 and δs1 to δ2 and δs2 respectively, when the fault clears.
- The accelerating energies are represented by areas A1 and As1 After fault clearing, the transmitted electric power exceeds the mechanical input power and therefore the sending-end machine decelerates.
- However, the accumulated kinetic energy further increases until a balance between the accelerating and decelerating energies, represented by areas A1 , As1 and A2 , As2 respectively is reached at the maximum angular swings, δ3 and δs3



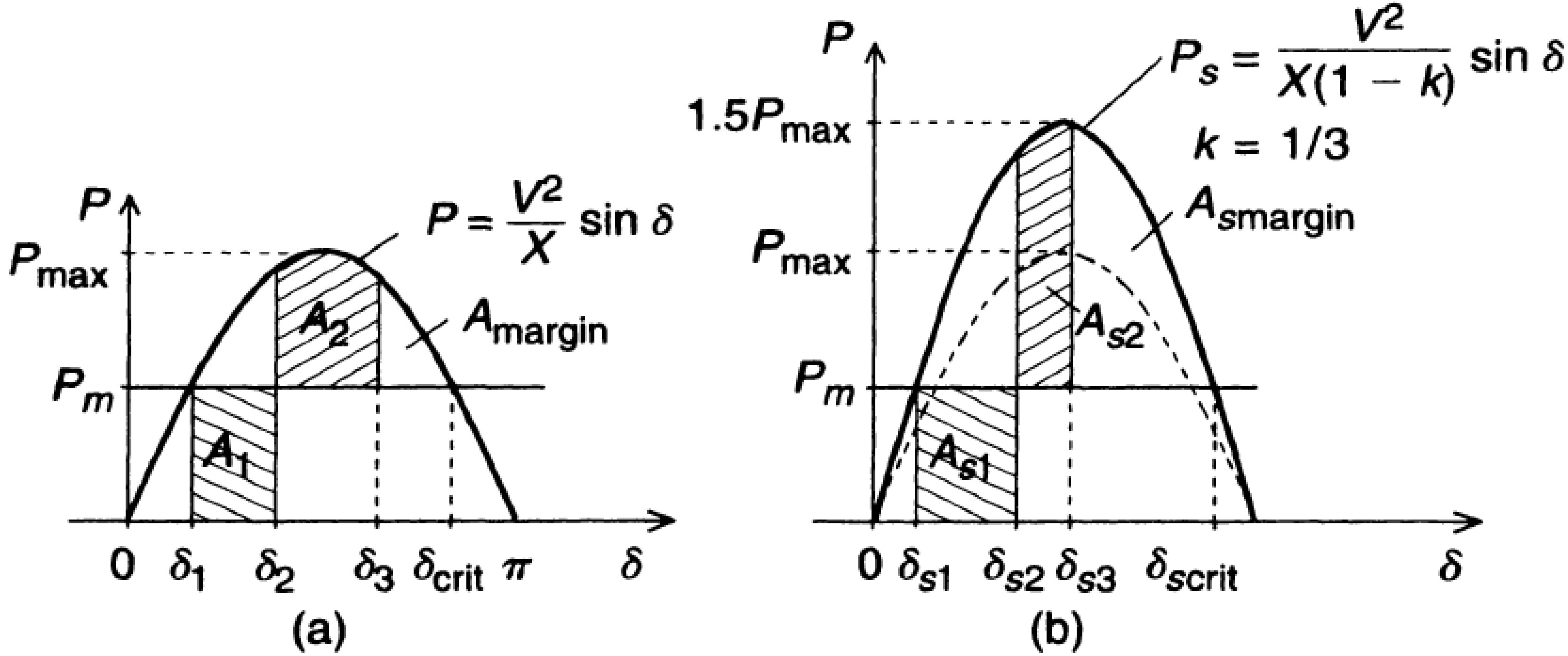


Figure 3 Equal area criterion to illustrate the transient stability margin for a simple two-machine system, (a) without compensation, and (b) with a series capacitor

- The areas between the P and δ curve and the constant Pm line over the interval defined by the angles δ3 and δcritical and δs3 and δscritical respectively.
- Transient margin stability represented by Amargin and Asmargin.
- Comparison clearly shows a substantial increase in the transient stability margin the series capacitive compensation can provide by partial cancellation of the series impedance of the transmission line.
- The increase of transient stability margin is proportional to the degree of series compensation.
- Theoretically this increase becomes unlimited for an ideal reactive line as the compensation approaches 100%.
- However, practical series capacitive compensation does not usually exceed 75% for a number of reasons, including load balancing with parallel paths, high fault current, and the possible difficulties of power flow control. Often the compensation is limited to less than 30% due to subsynchronous concerns

4.POWER OSCILLATION DAMPING

- Controlled series compensation can be applied effectively to damp power oscillations, for power oscillation damping it is necessary to vary the applied compensation so as to counteract the accelerating and decelerating swings of the disturbed machine(s).
- That is, when the rotationally oscillating generator accelerates and angle δ increases ($d\delta/dt > 0$), the electric power transmitted must be increased to compensate for the excess mechanical input power.
- Conversely, when the generator decelerates and angle δ decreases ($d\delta/dt < 0$), the electric power must be decreased to balance the insufficient mechanical input power.
- As seen, k is maximum when $d\delta/dt > 0$, and it is zero when $d\delta/dt < 0$. With maximum k, the effective line impedance is minimum (or, alternatively, the voltage across the actual line impedance is maximum) and consequently, the electric power transmitted over the line is maximum.
- When k is zero, the effective line impedance is maximum (or, alternatively, the voltage across the actual line impedance is minimum) and the power transmitted is minimum.
- The illustration shows that k is controlled in a "bang-bang" manner (output of the series compensator is varied between the minimum and maximum values).
- Indeed, this type of control is the most effective for damping large oscillations.
- However, damping relatively small power oscillations, particularly with a relatively large series compensator, continuous variation of k, in sympathy with the generator angle or power, may be a better alternative.

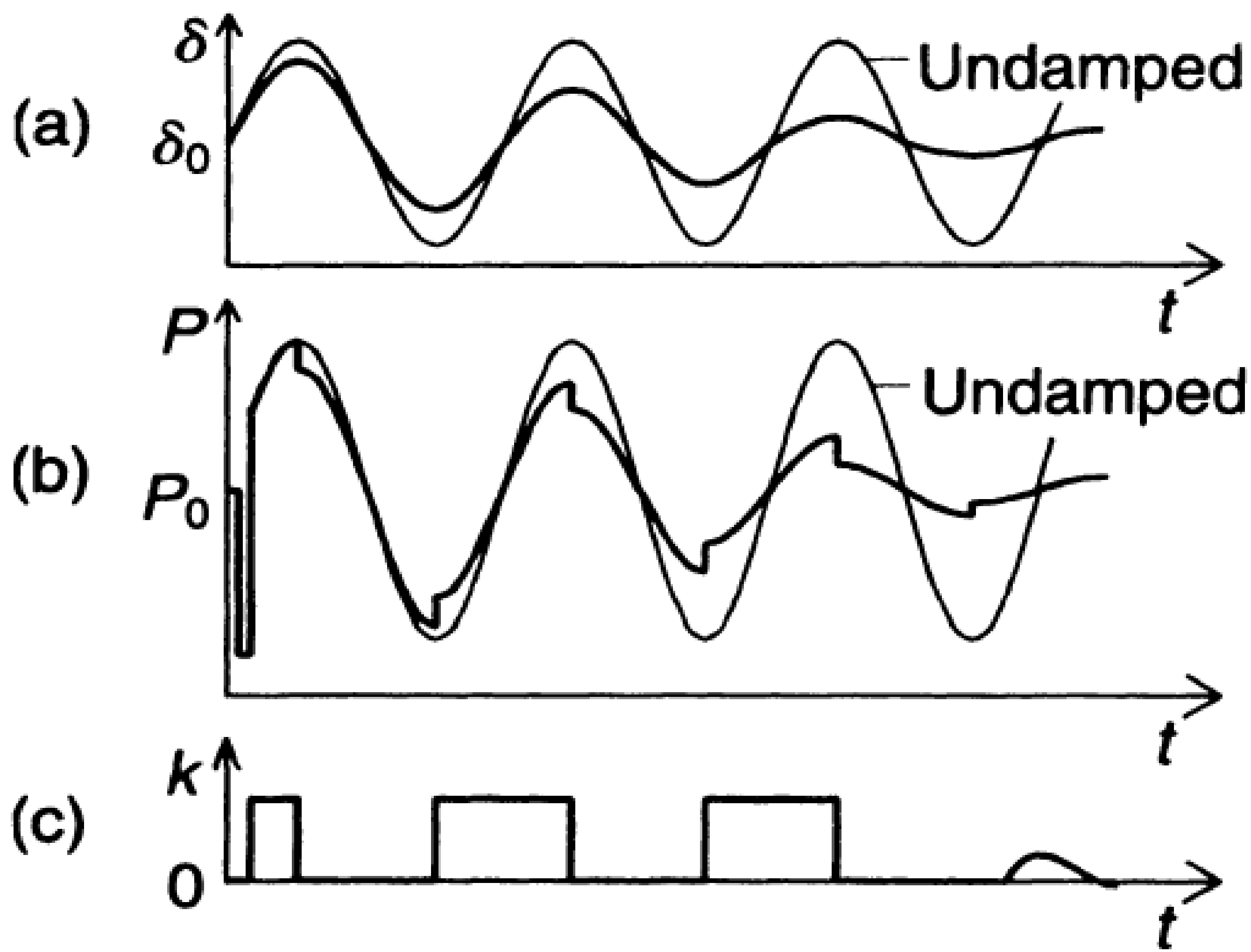


Figure 4 Waveforms illustrating power oscillation damping by controllable series compensation: (a) generator angle, (b) transmitted power, and (c) degree of series compensation.

5. SUBSYNCHRONOUS OSCILLATION DAMPING

- Sustained oscillation below the fundamental system frequency can be caused by series capacitive compensation.
- The phenomenon, referred to as SUBSYNCHRONOUS RESONANCE (SSR), was observed as early as 1937, but it received serious attention only in the 1970s, after two turbine-generator shaft failures occurred at the Mojave Generating Station in southern Nevada.
- Theoretical investigations showed that interaction between a series capacitor-compensated transmission line, oscillating at the natural (subharmonic) resonant frequency, and the mechanical system of a turbine-generator set in torsional mechanical oscillation can result in negative damping with the consequent mutual reinforcement of the electrical and mechanical oscillations.
- The phenomenon of subsynchronous resonance can be briefly described as follows: A capacitor in series with the total circuit inductance of the transmission line (including the appropriate generator and transformer leakage inductive) forms a series resonant circuit with the natural frequency of

$$f_e = \frac{1}{2\pi\sqrt{LC}} = f\sqrt{\frac{X_C}{X}}$$

- where Xc is the reactance of the series capacitor and X is the total reactance of the line at the fundamental power system frequency f.
- Since the degree of series compensation k = Xc/X is usually in the 25 to 75% range, the electrical resonant frequency fe; is less than the power frequency f, i.e., fe is a sub harmonic frequency.
- If the electrical circuit is brought into oscillation (by some network disturbance) then the sub harmonic component of the line current results in a corresponding sub harmonic field in the machine which, as it rotates backwards relative to the main field (since t. < f), produces an alternating torque on the rotor at the difference frequency of f - fe.
- If this difference frequency coincides with one of the torsional resonances of the turbine-generator set, mechanical torsional oscillation is excited, which, in turn, further excites the electrical resonance.
- This condition is defined as subsynchronous resonance. (Of course, this process could also start in the reverse sense: a shock could start a torsional oscillation which, under the condition of subsynchronous resonance, would be reinforced by the response of the electrical network.)

6.Summary of Functional Requirements

- The series compensator is primarily applied to solve power flow problems.. These problems may be related to the length of the line or the structure of the transmission network. The electric length of the line can be shortened to meet power transmission requirements by fixed (percent) compensation of the line .. Network structure related problems, which typically result in power flow unbalance, as well as parallel and loop power flows, may require controlled series compensation, particularly if contingency or planned network changes are anticipated.
- Fixed or controlled series capacitive compensation can also be used to minimize the end-voltage variation of radial lines and prevent voltage collapse.
- Series compensation, appropriately controlled to counteract prevailing machine swings, can provide significant transient stability improvement for post-fault systems and can be highly effective in power oscillation damping.

- Appropriately structured and controlled series compensation can be applied without the danger of subsynchronous resonance to achieve full utilization of transmission lines.
- In future Flexible AC Transmission Systems various controlled series compensators will playa key part in maintaining power flow over predefined paths, establishing alternative flow paths under contingency conditions, managing line loading, and generally ensuring the optimal use of the transmission network.
- It will be seen that, analogously to shunt compensation, controlled series compensation to meet the above functional requirements can be accomplished by both thyristor controlled impedance type and converter-based, voltage-source type compensators.
- However, the operating and performance characteristics of the two types of series compensator are considerably different

7. Approaches to Controllable Series Compensation

- there are two basic approaches to modern, power electronics- based shunt compensators:
  1. which employs thyristor-switched capacitors thyristor-controlled reactors to realize a variable reactive admittance
  2. which employs a switching power converter to realize a controllable synchronous voltage source.
- The series compensator is a reciprocal of the shunt compensator. The shunt compensator is functionally a controlled reactive current source which is connected in parallel with the transmission line to control its voltage.
- The series compensator is functionally a controlled voltage source which is connected in series with the transmission line to control its current.
- This reciprocity suggests that both the admittance and voltage source type shunt compensators have a corresponding series compensator.
- Because of this duality between the shunt and series compensators, manyof the concepts, and circuit and control approaches

VARIABLE IMPEDANCE TYPE SERIES COMPENSATORS

- variable impedance type series compensators are composed of thyristor- switched/controlled-capacitors or thyristor-controlled reactors with fixed capacitors.
- <u>METHODS OF CONTROLLABLE VAR GENERATION</u>
- **VARIABLE IMPEDANCE TYPE STATIC VAR GENERATORS:**
  - **GTO THYRISTOR-CONTROLLED SERIES CAPACITOR (GCSC)**
  - **THYRISTOR-CONTROLLED SERIES CAPACITOR (TCSC)**
  - **THYRISTOR-SWITCHED SERIES CAPACITOR (TSSC)**
- **SWITCHING CONVERTER TYPE VAR GENERATORS**
  - **STATIC SYNCHRONOUS SERIES COMPENSATOR (SSSC)**

GTO THYRISTOR-CONTROLLED SERIES CAPACITOR (GCSC):

- An elementary GTO Thyristor-Controlled Series Capacitor, proposed by Karady with others in 1992, is shown.
- It consists of a fixed capacitor in parallel with a GTO thyristor (or equivalent) valve (or switch) that has the capability to turn on and off upon command.
- The objective of the GCSC scheme shown is to control the ac voltage Vc across the capacitor at a given line current i.
- Evidently, when the GTO valve, SW, is closed, the voltage across the capacitor .is zero, and when the valve is open, it is maximum.
- For controlling the capacitor voltage, the closing and opening of the valve is carried out in each half-cycle in synchronism with the ac system frequency.
- The GTO valve is stipulated to close automatically (through appropriate control action) whenever the capacitor voltage crosses zero. (Recall that the thyristor valve of the TCR opens automatically whenever the current crosses zero.)
- However, the turn-off instant of the valve in each half-cycle is controlled by a (turn-off) delay angle γ ($0 \leq \gamma \leq \pi/2$), with respect to the peak of the line current. where the line current i, and the capacitor voltage VC(γ) are shown at $\gamma = 0$ (valve open) and at an arbitrary turn-off delay angle γ for a positive and a negative half-cycle.

- When the valve sw is opened at the crest of the (constant) line current ($\gamma = 0$), the resultant capacitor voltage Vc will be the same as that obtained in steady state with a permanently open switch.
- When the opening of the valve is delayed by the angle γ with respect to the crest of the line current, the capacitor voltage can be expressed with a defined line current, as follows

$$i(t) = I\cos\omega t$$

$$V_C(t) = \frac{1}{C}\int_{\gamma}^{\omega t} i(t)dt = \frac{I}{\omega C}(\sin\omega t - \sin\gamma)$$

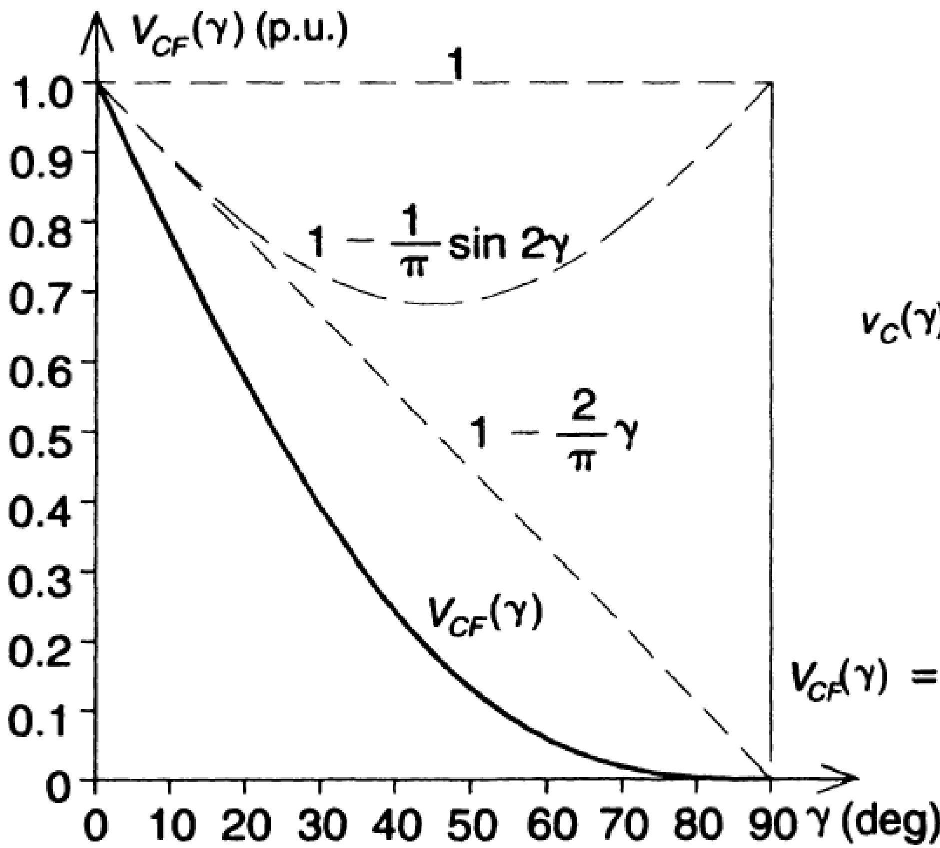
- Since the valve opens at γ and stipulated to close at the first voltage zero, is valid for the interval $\gamma \leq \omega t \leq \pi - \gamma$.
- For subsequent positive half-cycle intervals the same expression remains valid. For subsequent negative half-cycle intervals, the sign of the terms becomes opposite.
- It is evident that the magnitude of the capacitor voltage can be varied continuously by this method of turn-off delay angle control from maximum ($\gamma = 0$) to zero ($\gamma = \pi/2$) , where the capacitor voltage Vc(γ), together with its fundamental component VCF(γ), are shown at, various tum-off delay angles, /'. Note, however, that the adjustment of the capacitor voltage, similar to the adjustment of the TCR current, is discrete and can take place only once in each half-cycle.
- The amplitude of the capacitor voltage is given by

$$V_{CF}(\gamma) = \frac{I}{\omega C}\left(1 - \frac{2\gamma}{\pi} - \frac{1}{\pi}\sin 2\gamma\right)$$

- where I is the amplitude of the line current, C is the capacitance of the GTO thyristor controlled capacitor, and ω is the angular frequency of the ac system.

- On the basis of the GCSC, varying the fundamental capacitor voltage at a fixed line current, could be considered as a variable capacitive impedance.
- Indeed, an effective capacitive impedance can be found for a given value of angle γ Of, in other words, an effective capacitive impedance, Xc, as a function of γ, for the GCSC can be defined.

$$X_C(\gamma) = \frac{1}{\omega C}\left(1 - \frac{2\gamma}{\pi} - \frac{1}{\pi}\sin 2\gamma\right)$$



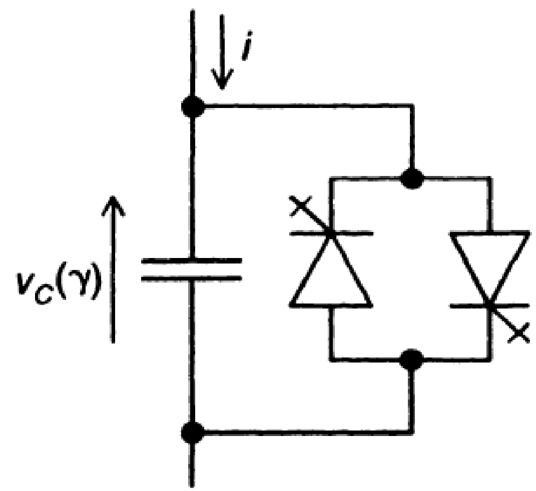


Figure 6 Fundamental component of the series capacitor voltage vs. the turn-off delay angle 'Y.

- In the voltage compensation mode, the GCSC is to maintain the rated compensating voltage in face of decreasing line current over a defined interval [$I_{min} \leq I \leq I_{max}$, as illustrated in Figure 7(a1).

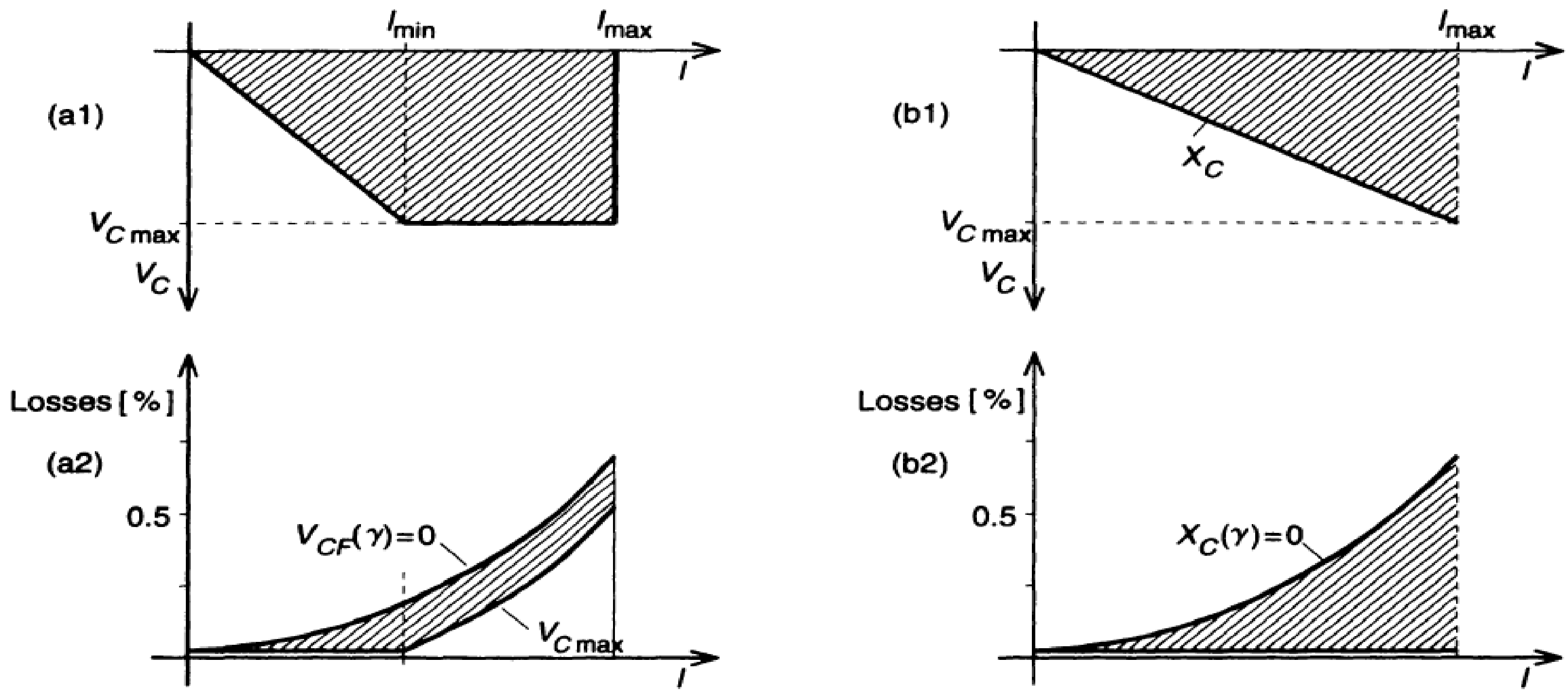


Figure 7 Attainable V-I (compensating voltage vs. line current) characteristics of the GCSC when operated in voltage control (a 1) and reactance control (bl) modes, and the associated loss vs. line current characteristics (a2 and b2, respectively).

- The loss, as percent of the rated var output, versus line current characteristic of the GCSC operated in the voltage compensation mode is shown in Figure 7(a2) for zero voltage injection [the capacitor is bypassed by the GTO valve to yield $V_{CF}(\gamma) = 0$] and for maximum rated voltage injection [$V_{CF}(\gamma) = V_{CmAX}$].
- In the impedance compensation mode, the GCSC is to maintain the maximum rated compensating reactance at any line current up to the rated maximum, as illustrated in Figure 7(bl).
- The loss versus line current characteristic of the GCSC for this operating mode is shown in Figure 6.7(b2) for zero compensating impedance (capacitor is bypassed by the GTO valve) and for maximum compensating impedance (the GTO valve is open and the capacitor is fully inserted).
- The turn-off delay angle control of the GCSC, just like the turn-on delay angle control of the TCR, generates harmonics. For identical positive and negative voltage half-cycles, only odd harmonics are generated. The amplitudes of these are a function of angle γ and, can be expressed in the following form:

$$V_{Cn}(\gamma) = \frac{I}{\omega C}\frac{4}{\pi}\left\{\frac{\sin\gamma\cos(n\gamma) - n\cos\gamma\sin(n\gamma)}{n(n^2-1)}\right\}$$

where $n = 2k + 1$, $k = 1, 2, 3, \ldots$

- The amplitude variation of the harmonics, expressed as a percentage of the maximum fundamental capacitor voltage, is shown plotted against γ in Figure 8.
- However, if necessary, the magnitudes of the harmonics generated by GCSC can be attenuated effectively by the complementary application of the method of "sequential control" introduced for the reduction of TCR generated harmonics
- The reactors are "sequentially" controlled; that is, only one of the n reactors is delay angle controlled, and each of the remaining m - 1 reactors is either fully "on" or fully "off.“

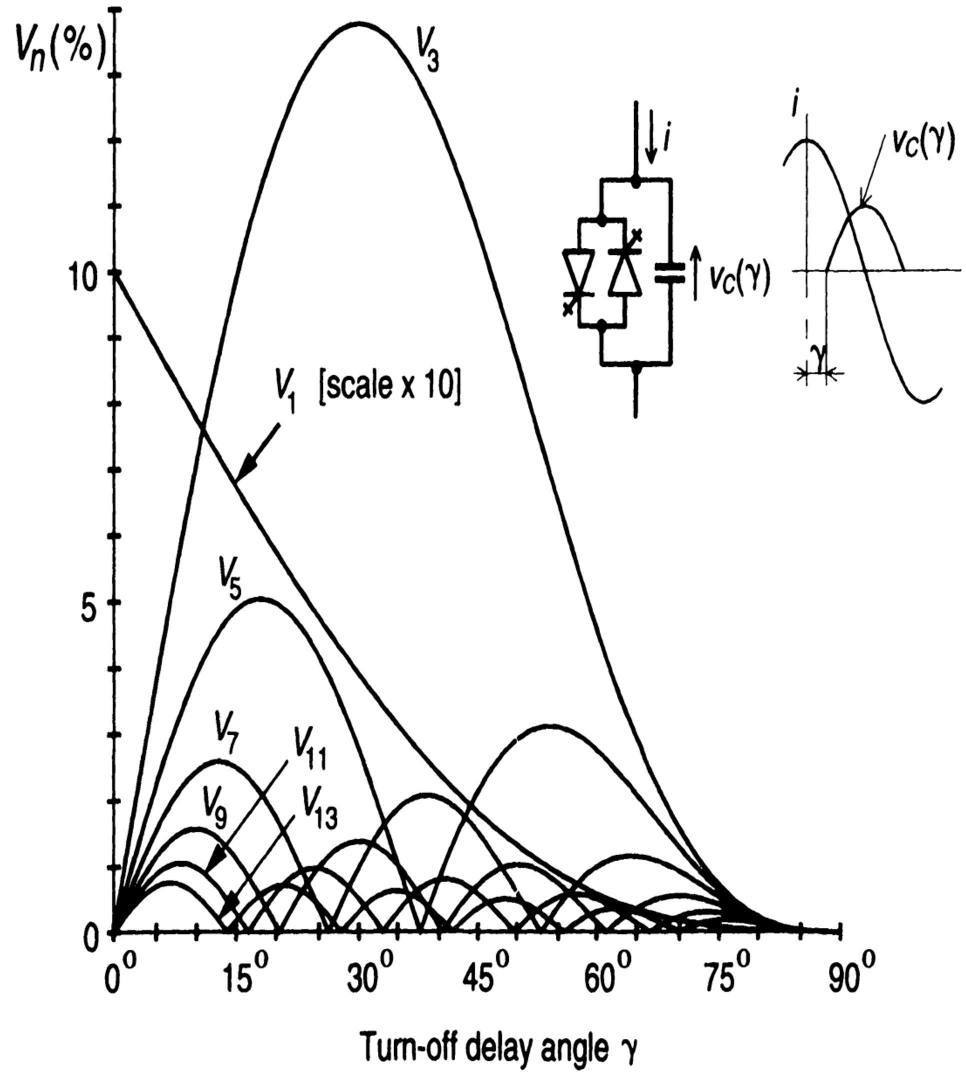


Fig 8 The amplitudes of the harmonic voltages, expressed as percents of the maximum fundamental capacitor voltage vs. the turn-off delay angle γ.

- The method of sequential control eminently suits the GCSC. It follows from its duality with the TCR that it requires the use of m (m ≥ 2) series connected GCSCs, each with 11m of the total (voltage) rating required. As illustrated in Figure 9, all but one of m capacitors are "sequentially" controlled to be inserted (valve is off) or bypassed (valve is on).
- Note that, in contrast to the TCR arrangement, where for economic reasons only a relatively small number (usually no more than two) of parallel branches would be applied, there is no significant economic disadvantage, and may be a technical preference, to break a single high-voltage valve into four or more series connected modules to realize a practical GCSC.
- The losses of the sequentially controlled GCSC are inversely proportional to the var output Irated^2 X XGcsc.
- The losses are maximum (about 0.7% of the rated var output) when all capacitors of the sequentially controlled GCSC are bypassed (GTO valves are fully on); they are negligible when all capacitors are fully inserted (all GTO valves are off).
- **why not replace the GTO valves in the m - 1 modules with the less expensive conventional thyristor modules?**
- The answer is that with conventional thyristor valves the operation of the total valve would become different. In other words, the conventional thyristor valve cannot imitate GTO valve operation even for full conduction capacitor switching.
- The conventional thyristor valve could be turned on at the required instant of voltage zero, but it would only turn off at a current zero, which occurs either a quarter cycle before or a quarter cycle after the voltage zero where the proper turn-off should take place.

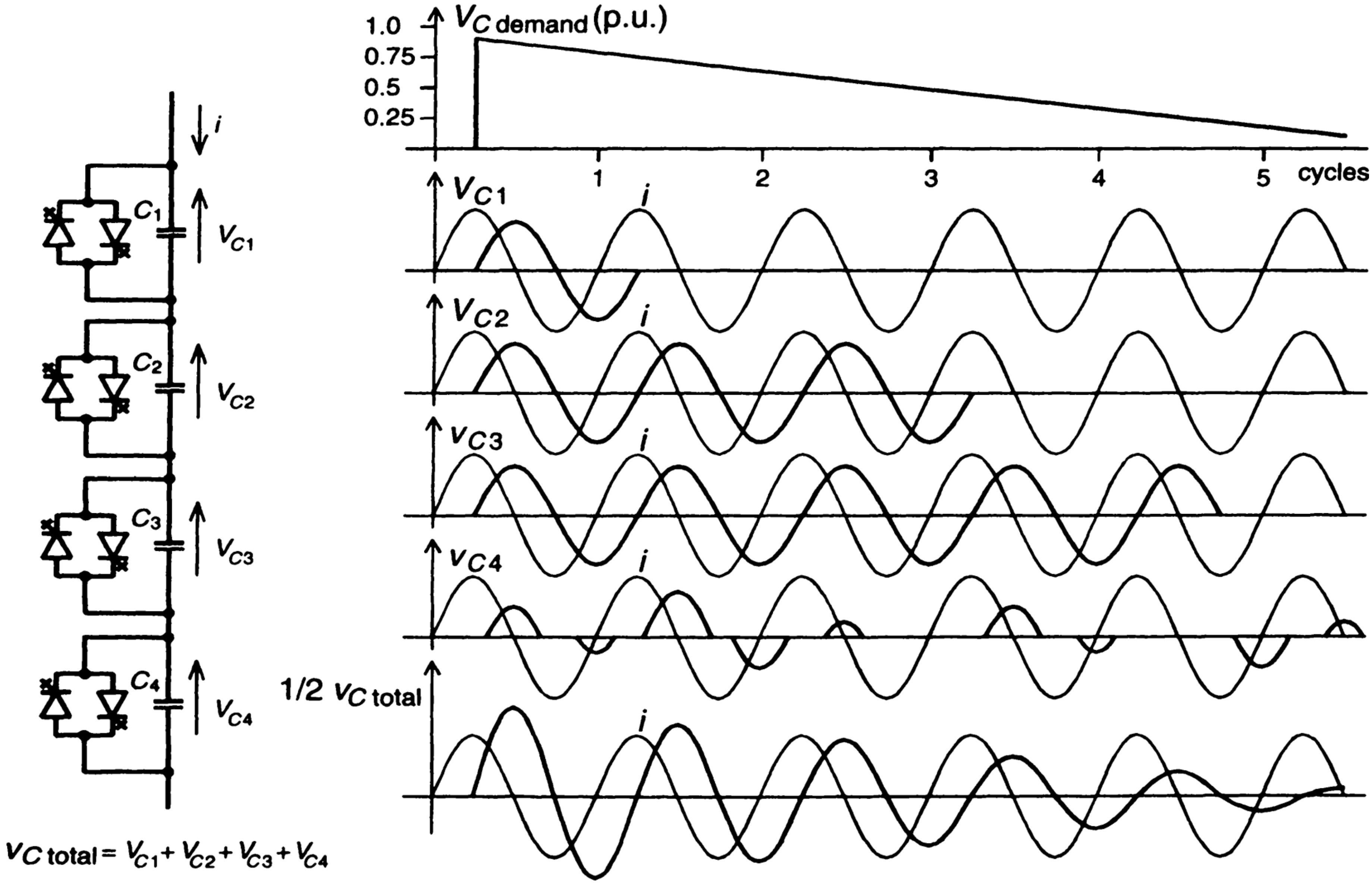


Figure 9 Waveforms illustrating the method of controlling four series-connected GCSC banks "sequentially" to achieve harmonic reduction.

2. Thyristor-Switched Series Capacitor (TSSC)

- The basic circuit arrangement of the thyristor-switched series capacitor is shown.
- It consists of a number of capacitors, each shunted by an appropriately rated bypass valve composed of a string of reverse parallel connected thyristors, in series.
- Its operation is different due to the imposed switching restrictions of the conventional thyristor valve.
- The operating principle of the TSSC is straightforward: the degree of series compensation is controlled in a step-like manner by increasing or decreasing the number of series capacitors inserted.
- A capacitor is inserted by turning off, and it is bypassed by turning on the corresponding thyristor valve.
- A thyristor valve commutates "naturally," that is, it turns off when the current crosses zero.
- Thus a capacitor can be inserted into the line by the thyristor valve only at the zero crossings of the line current.

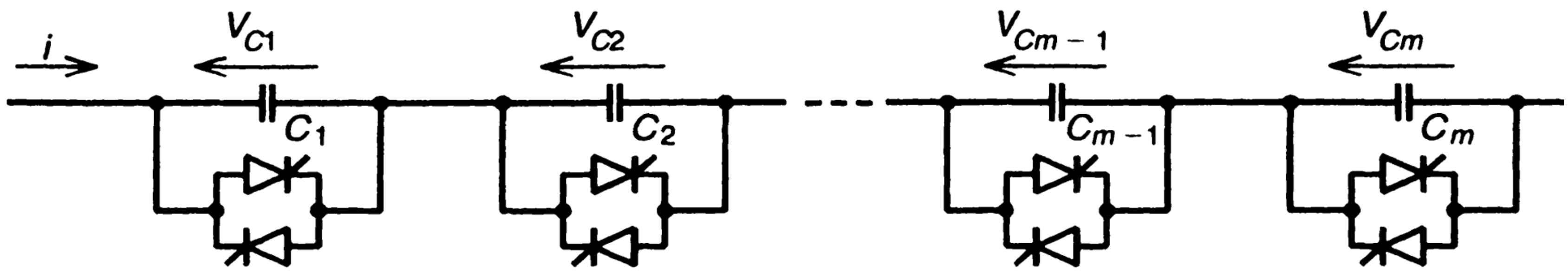
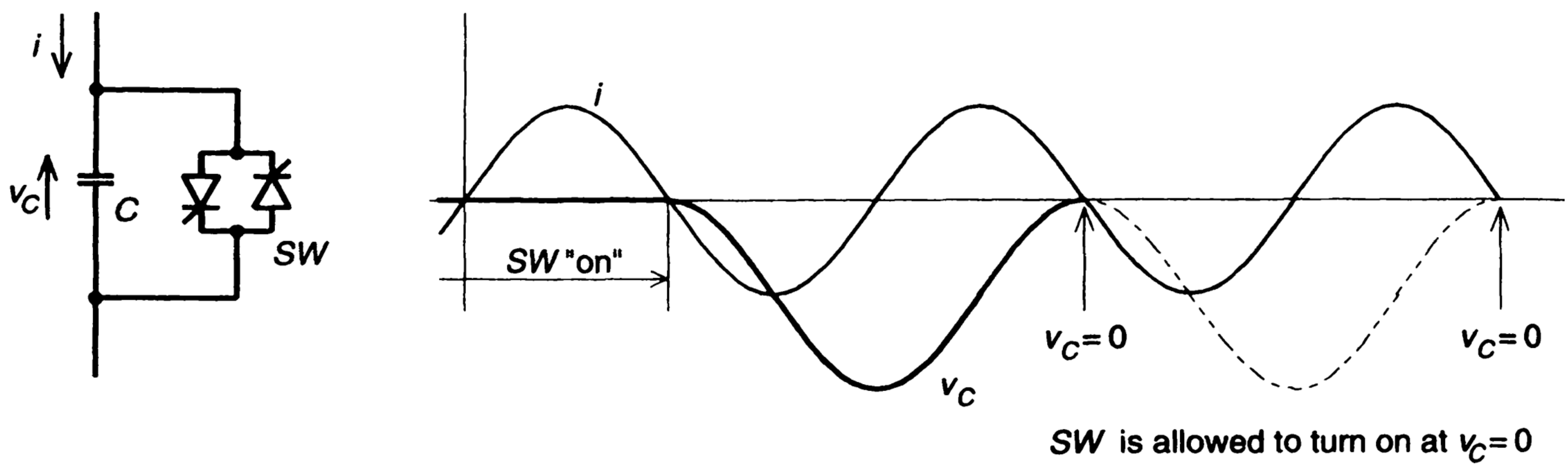


Figure 10 Basic Thyristor-Switched Series Capacitor scheme



Flgure 11 Illustration of capacitor offset voltage resulting from the restriction of inserting at zero line current

- Since the insertion takes place at line current zero, a full half-cycle of the line current will charge the capacitor from zero to maximum and the successive, opposite polarity half-cycle of the line current will discharge it from this maximum to zero, as.
- The capacitor insertion at line current zero, necessitated by the switching limitation of the thyristor valve, results in a de offset voltage which is equal to the amplitude of the ac capacitor voltage.
- In order to minimize the initial surge current in the valve, and the corresponding circuit transient, the thyristor valve should be turned on for bypass only when the capacitor voltage is zero.
- With the prevailing de offset, this requirement can cause a delay of up to one full cycle, which would set the theoretical limit for the attainable response time of the TSSC.
- The basic V-I characteristic of the TSSC with four series connected compensator modules operated to control the compensating voltage is shown.
- For this compensating mode the reactance of the capacitor banks is chosen so as to produce, on the average, the rated compensating voltage, $V_{Cmax} = 4X_C I_{min}$ in the face of decreasing line current over a defined interval $I_{min} \leq I \leq I_{max}$.
- As the current Imin is increased toward Imax the capacitor banks are progressively bypassed by the related thyristor valves to reduce the overall capacitive reactance in a step-like manner and thereby maintain the compensating voltage with increasing line current.

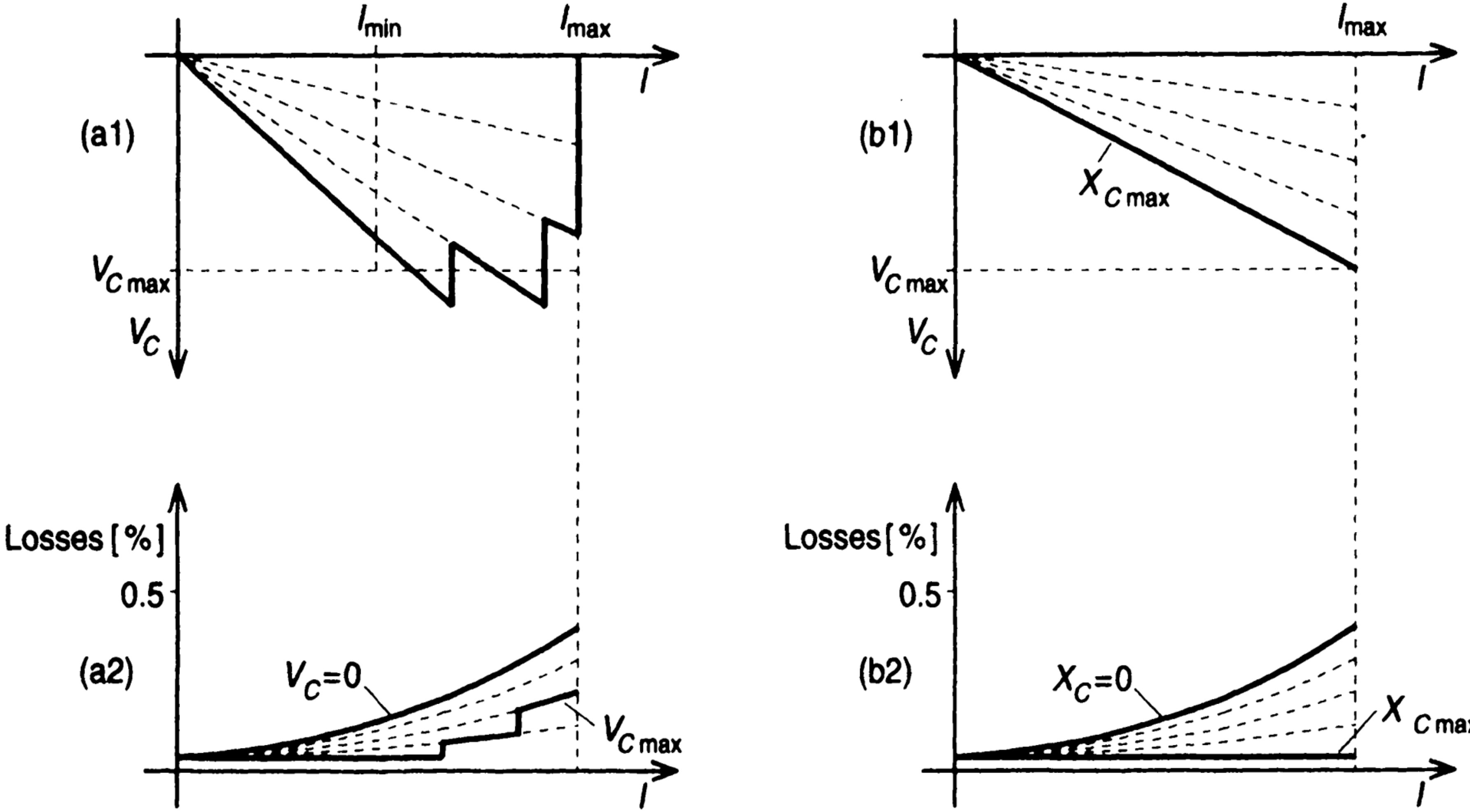


Figure 12 Attainable *V-I* (compensating voltage vs, line current) characteristics of the TSSC when operated in voltage control (a1) and reactance control (b1) modes, and the associated loss vs. line current characteristics (a2 and b2, respectively).

- In the impedance compensation mode, the TSSC is applied to maintain the maximum rated compensating reactance at any line current up to the rated maximum.
- In this compensation mode the capacitive impedance is chosen so as to provide the maximum series compensation at rated current, $4X_C = V_{Cmax}/I_{max}$, that the TSSC can vary in a step-like manner by bypassing one or more capacitor banks.
- The loss versus line current characteristic for this compensation mode is shown for zero compensating impedance (all capacitor banks are bypassed by the thyristor valves) and for maximum compensating impedance (all thyristor valves are off and all capacitors are inserted).
- The TSSC may also have transient ratings, usually defined as a function of time.
- Outside the defined ratings the TSSC would be protected against excessive current and voltage surges either by external protection across the capacitor and the parallel valve or, with sufficient rating, by the valve itself in bypass operation.
- Constraints imposed by physical device limitation on the turn-on conditions of thyristors (such as di/dt and surge current magnitude) would necessitate in practice the use of a current limiting reactor in series with the TSSC valve to handle bypass operation, or possible misfirings, which could turn on the valve into a fully charged capacitor of over 2.0 p.u. voltage.

Thyristor-Controlled Series Capacitor (TCSC)

- The basic Thyristor-Controlled Series Capacitor scheme, proposed in 1986 by Vithayathil with others as a method of "rapid adjustment of network impedance," is shown in Figure 13.
- It consists of the series compensating capacitor shunted by a Thyristor-Controlled Reactor.
- This arrangement is similar in structure to the TSSC and, if the impedance of the reactor, XL, is sufficiently smaller than that of the capacitor, Xc, it can be operated in an on/off manner like the TSSC.
- However, the basic idea behind the TCSC scheme is to provide a continuously variable capacitor by means of partially canceling the effective compensating capacitance by the TCR.
- The controllable by delay angle a, the steady-state impedance of the TCSC is that of a parallel LC circuit, consisting of a fixed capacitive impedance, Xc, and a variable inductive impedance, XL(a), that is,

$$X_{TCSC}(\alpha) = \frac{X_C X_L(\alpha)}{X_L(\alpha) - X_C}$$

$$X_L(\alpha) = X_L \frac{\pi}{\pi - 2\alpha - \sin\alpha}, X_L \leq X_L(\alpha) \leq \infty,$$

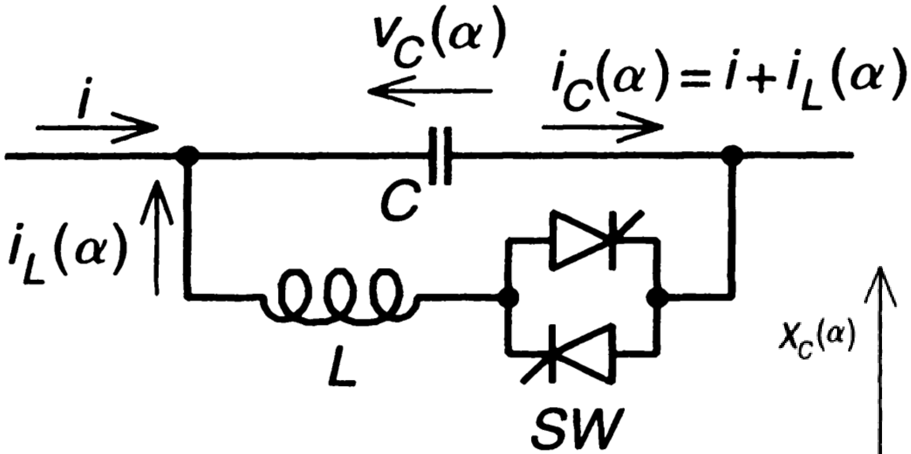


Figure 13 Basic Thyristor-Controlled Series Capacitor scheme.

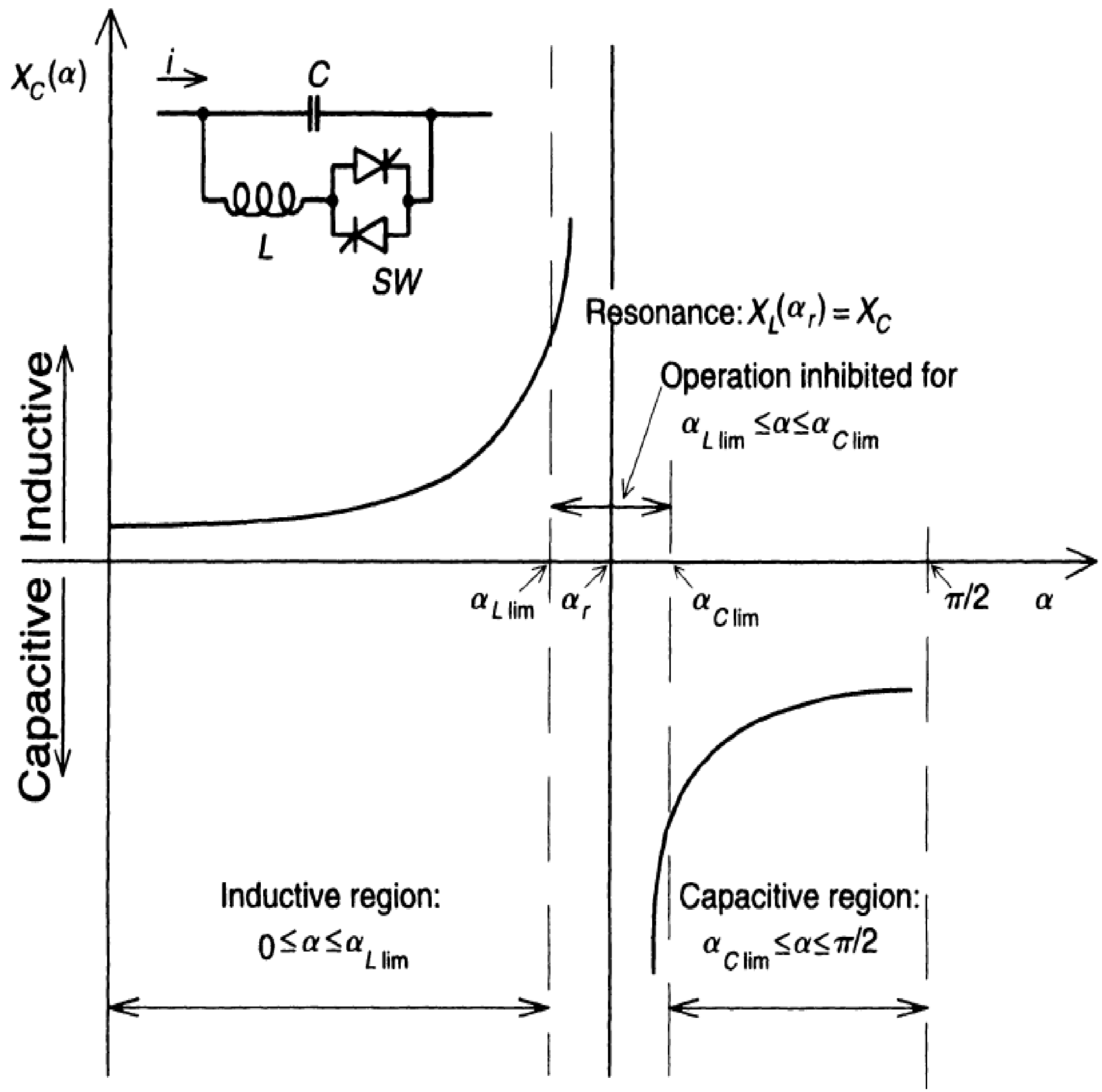


Figure 14 The impedance vs. delay angle ex characteristic of the TCSC.

- $X_L = \omega L$, and a is the delay angle measured from the crest of the capacitor voltage (or, equivalently, the zero crossing of the line current).
- As the impedance of the controlled reactor, XL(a), is varied from its maximum (infinity) toward its minimum (ωL), the TCSC increases its minimum capacitive impedance, X_{TCSC}.min = Xc = 1/ωC, (and thereby the degree of series capacitive compensation) until parallel resonance at Xc = XL(a) is established and XTCSC.max theoretically becomes infinite. Decreasing XL(a) further, the impedance of the TCSC, XTCSC(a) becomes inductive, reaching its minimum value of XLXc/(XL - Xc) at a = 0, where the capacitor is in effect bypassed by the TCR.
- Therefore, with the usual TCSC arrangement in which the impedance of the TCR reactor, X_L, is smaller than that of the capacitor, Xc, the TCSC has two operating ranges around its internal circuit resonance: one is the $\alpha_{Clim} \leq \alpha \leq \pi/2$ range, where Xrcsc(α) is capacitive, and the other is the $0 \leq \alpha \leq \alpha_{Llim}$ range, where Xrcsc(α) is inductive, as illustrated Fig14.

- Assume that the thyristor valve, *SW,* is initially open and the prevailing line current *i* produces voltage *Vco* across the fixed series compensating capacitor, as illustrated in Figure 15(a).
- Suppose that the TCR is to be turned on at *a,* measured from the negative peak of the capacitor voltage.
- As seen, at this instant of turn-on, the capacitor voltage is negative, the line current is positive and thus charging the capacitor in the positive direction.
- During this first half-cycle (and all similar subsequent half-cycles) of TCR operation, the thyristor valve can be viewed as an ideal switch, closing at *α,* in series with a diode of appropriate polarity to stop the conduction as the current crosses zero, as shown at the bottom of Figure 15(b).
- At the instant of closing switch SW, two substantially independent events will take place: One is that the line current, being a constant current source, continues to (dis)charge the capacitor. The other is that the charge of the capacitor will be reversed during the resonant half-cycle of the LC circuit formed by the switch closing. (This second event assumes, as stipulated, that XL < Xc.) The resonant charge reversal produces a de offset for the next (positive) half-cycle of the capacitor voltage, as illustrated in Figure 15(c).

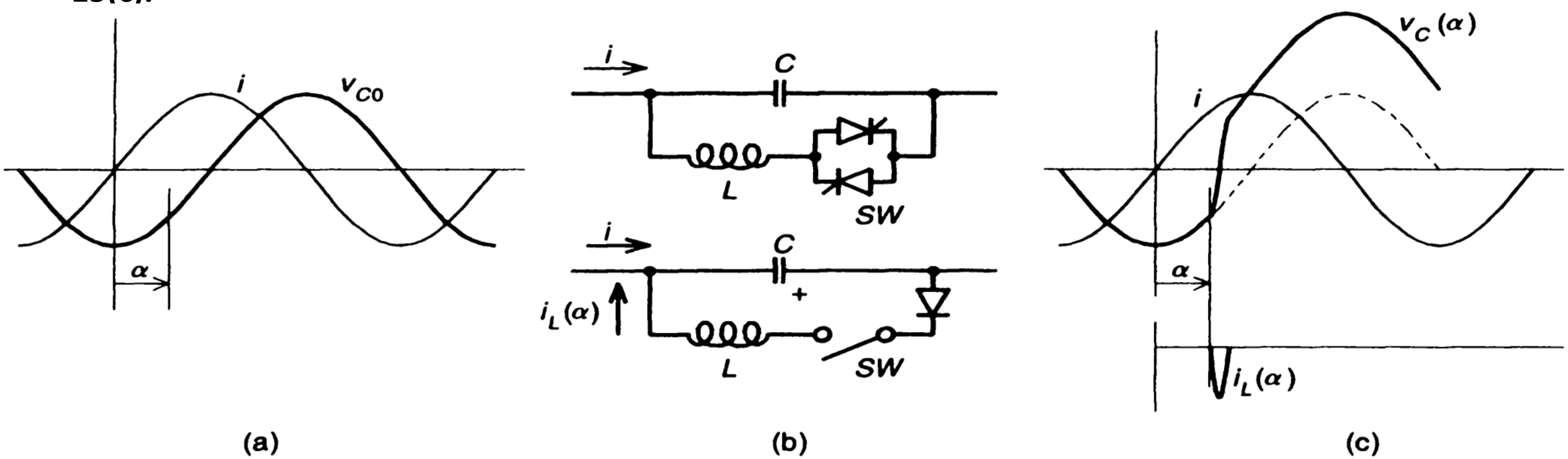
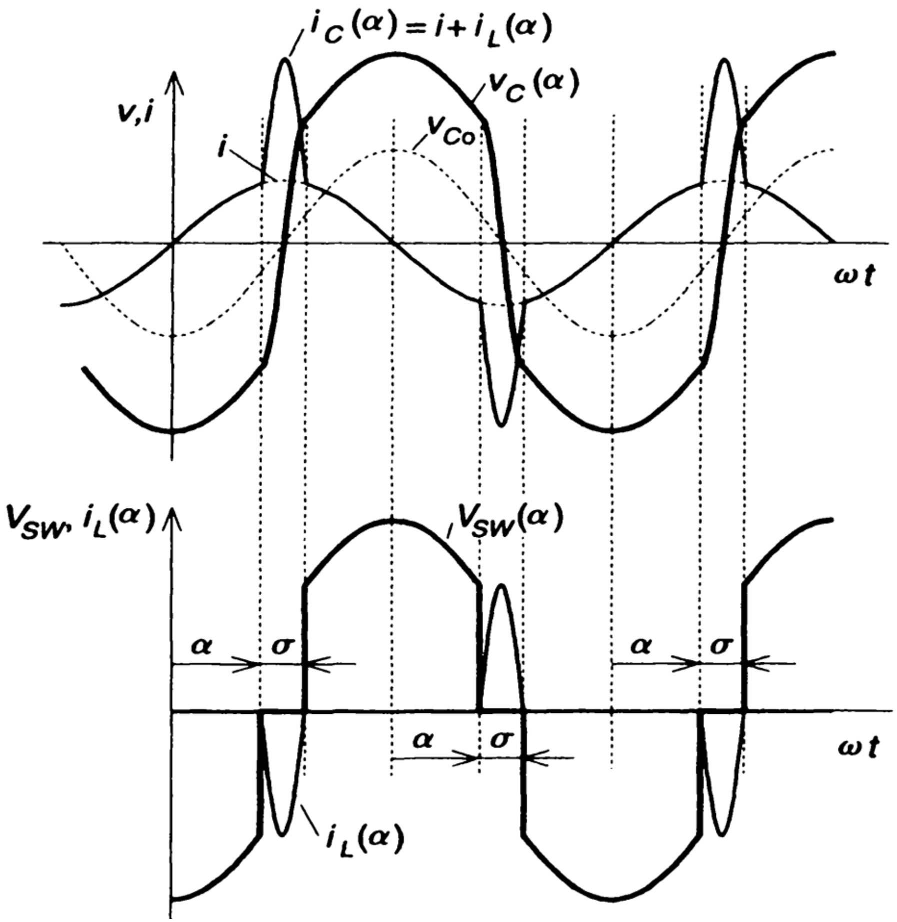


Figure 6.15 Illustration of capacitor voltage reversal by TCR: (a) line current and corresponding capacitor voltage, (b) equivalent circuit of the TCSC at the firing instant *a,* and (c) the resulting capacitor voltage and related TCR current.

- In the subsequent (negative) half-cycle, this de offset can be reversed by maintaining the same a, and thus a voltage waveform symmetrical to the zero axis can be produced, as illustrated in Figure 16, where the relevant current and voltage waveforms of the TCSC operated in the capacitive region are shown.
- Similar waveforms are shown for the inductive operating range, where the overall impedance of the TCSC is inductive, in Figure 17.
- The reversal of the capacitor voltage is clearly the key to the control of the TCSC.
- The time duration of the voltage reversal is dependent primarily on XL/Xc ratio, but also on the magnitude of the line current.
- If XL $\leq$ Xc, then the reversal is almost instantaneous, and the periodic voltage reversal produces a square wave across the capacitor that is added to the sine wave produced by the line current.
- Thus, as illustrated in Figure 18, the steady-state compensating voltage across the series capacitor comprises an uncontrolled and a controlled component:
- The uncontrolled component is Vco, a sine wave whose amplitude is directly proportional to the amplitude of the prevailing line current, and the controlled component is V_{CTCR}, substantially a square wave whose magnitude is controlled through charge reversal by the TCR.

Figure 16 Capacitor voltage and current waveforms, together with TCR voltage and current waveforms, characterizing the TCSC in the capacitive region under steady-state operation.



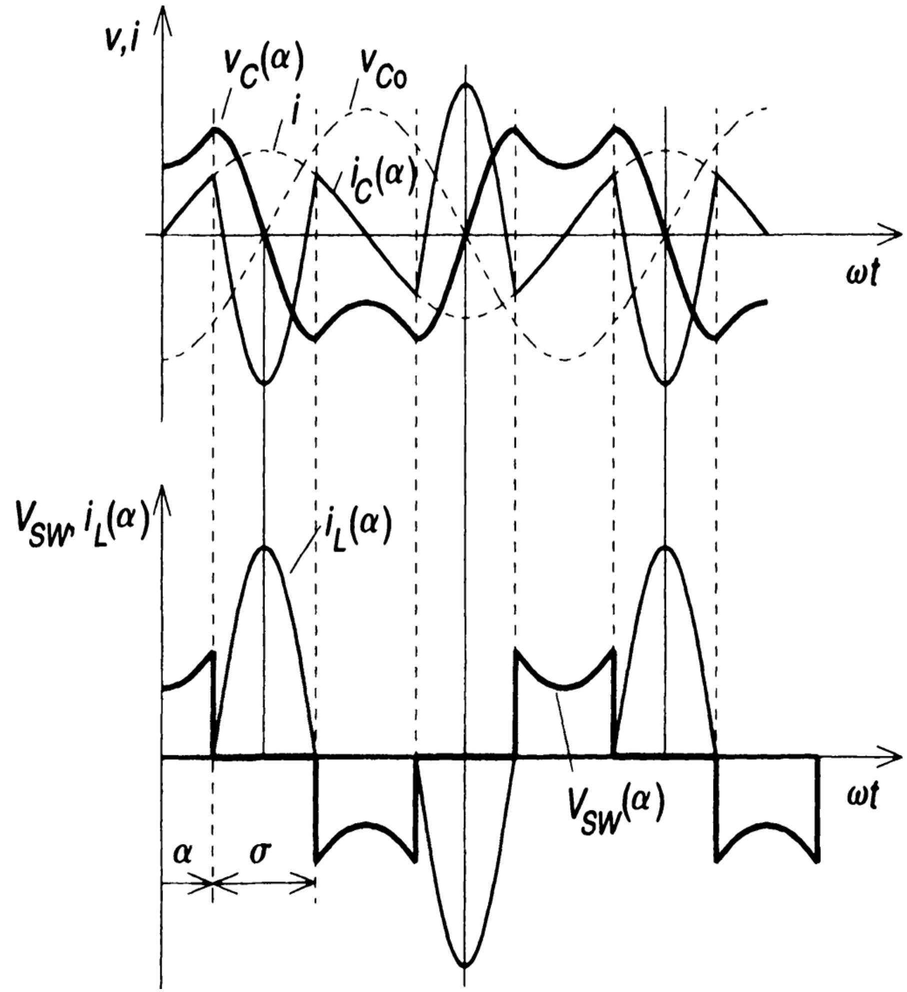
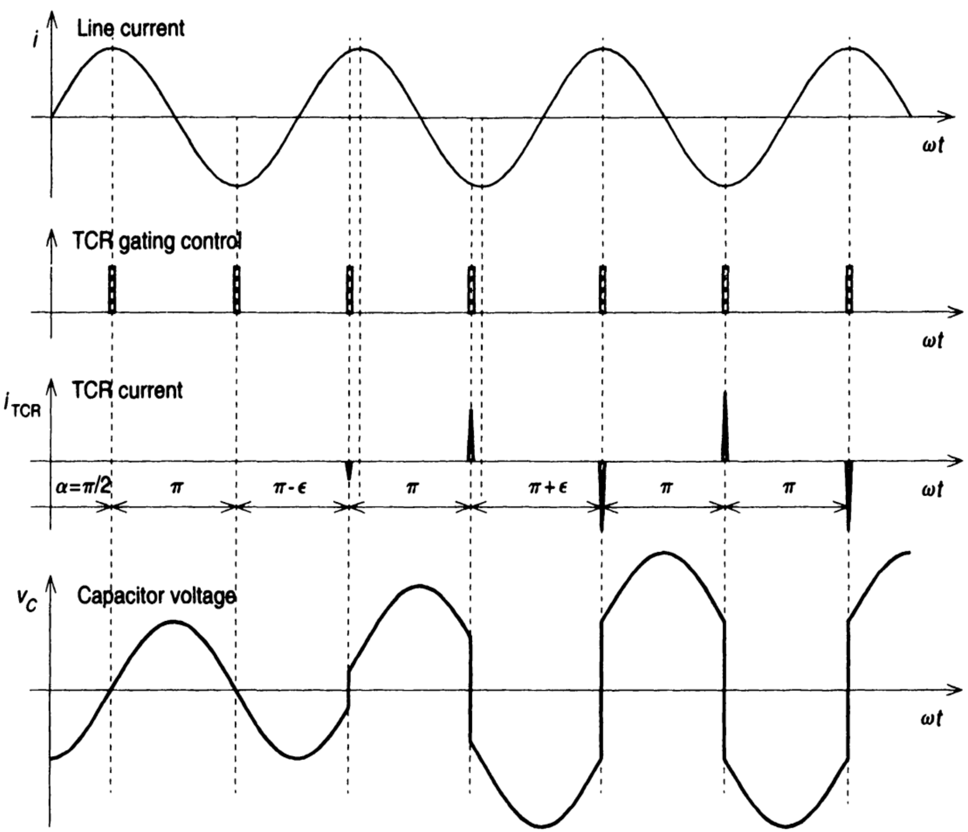
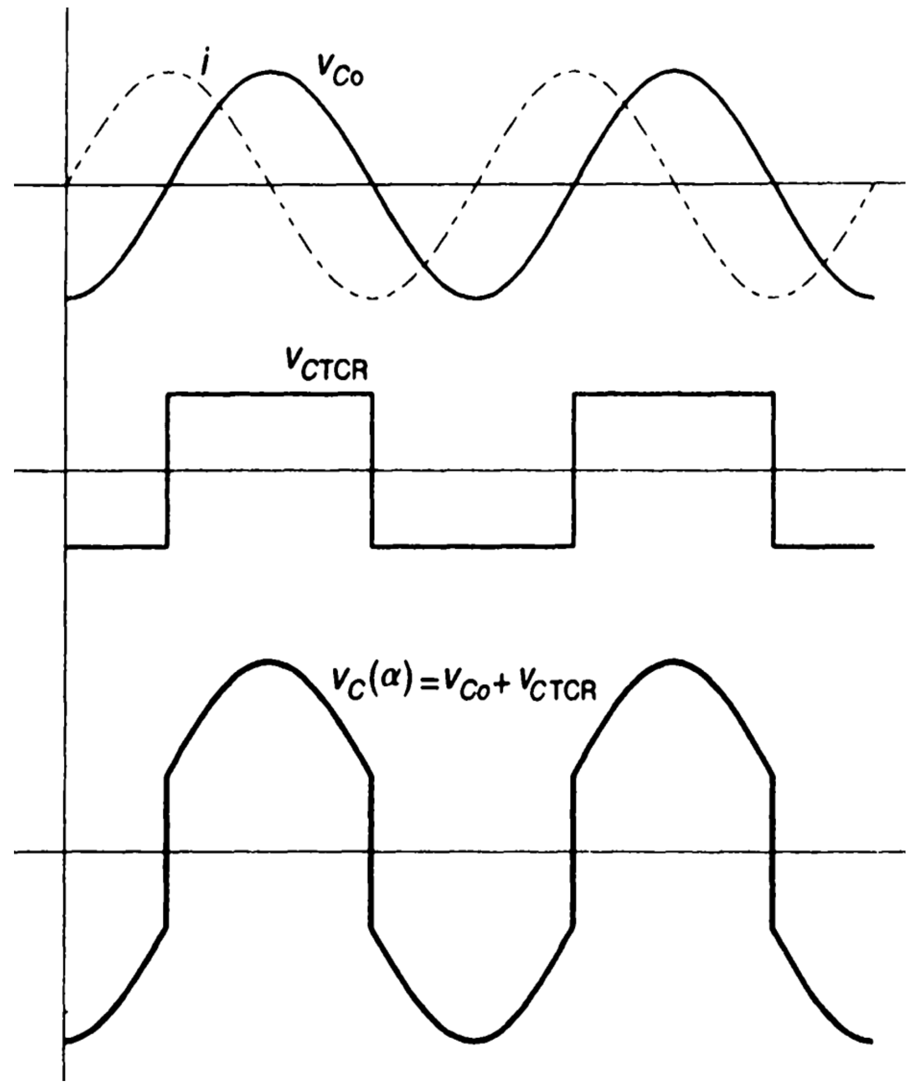


Figure 17 Capacitor voltage and current waveforms, together with TCR voltage and current waveforms, characterizing the TCSC in the inductive region under steady-state operation.

Figure 18 Composition of the idealized TCSC compensating voltage waveform from the line current produced (sinusoidal) capacitor voltage and the square wave voltage generated by capacitor voltage reversal.





- For a finite, but still relatively small, *XL,* the time duration of the charge reversal is not instantaneous but is quite well defined by the natural resonant frequency, *f* = $^1/_{2\pi\sqrt{LC}}$;, of the TCSC circuit, since the TCR conduction time is approximately equal to the half-period corresponding to this frequency: *T/2* = 1/2 *f* = $\pi\sqrt{LC}$.
- However, as *XL* is increased relative to *Xc,* the conduction period of the TCR increases and the zero crossings of the capacitor voltage become increasingly dependent on the prevailing line current.
- The mechanism of controlling the de offset by charge reversal is illustrated for the increase and decrease of the capacitor voltage in Figures 19(a) and (b), respectively.
- For the clarity of illustration, the theoretically ideal case of instantaneous voltage reversal is assumed (with an infinitesimal XL).
- In Figure 19(a), initially the TCR is gated on at α= π /2, at which the TCR current is zero and the capacitor voltage is entirely due to the line current. To produce a de offset, the periodically repeated
- gating in the second cycle is advanced by a small angle B, i.e., the prevailing halfperiod is reduced by ε to π - ε.

Figure 19b Decrease of the capacitor voltage by retarding the voltage reversal from α = π 'to a = ε + π .

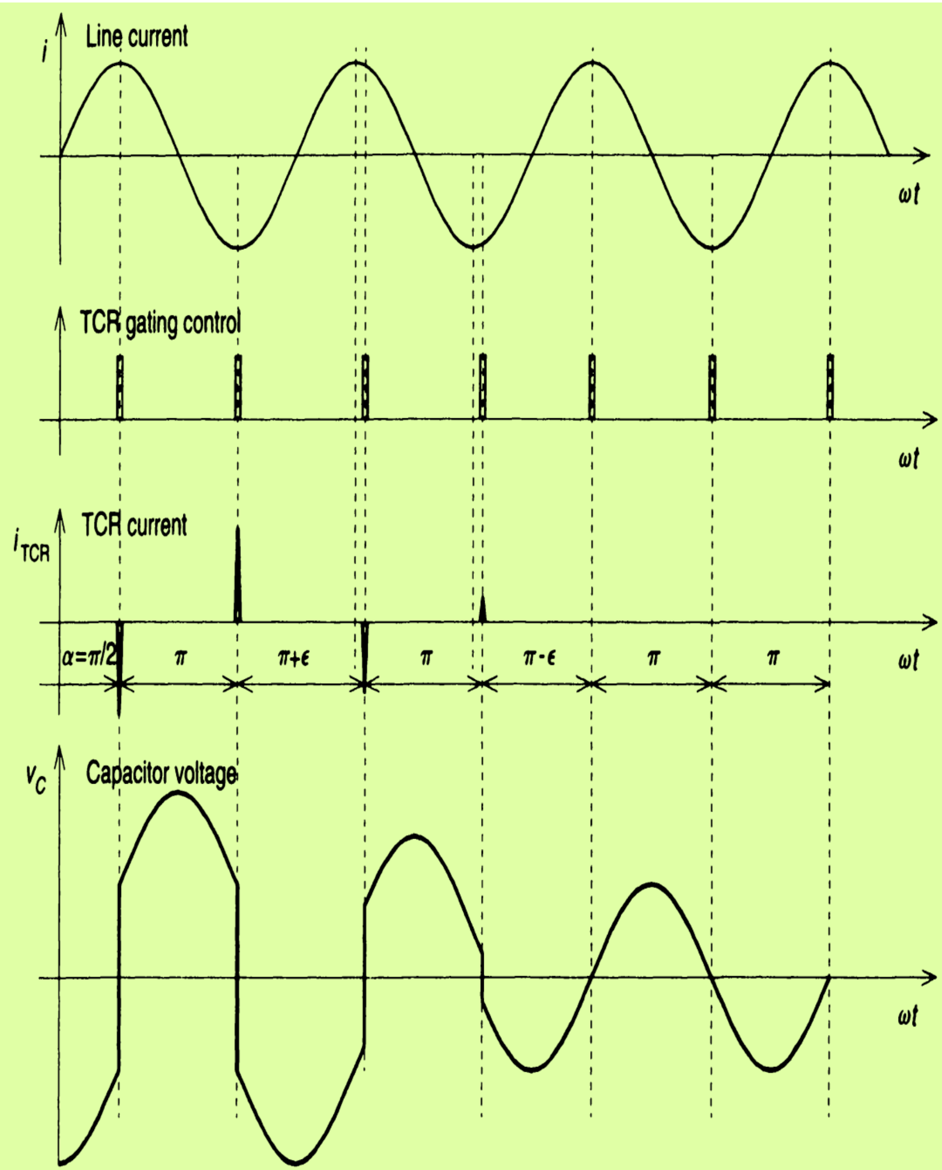
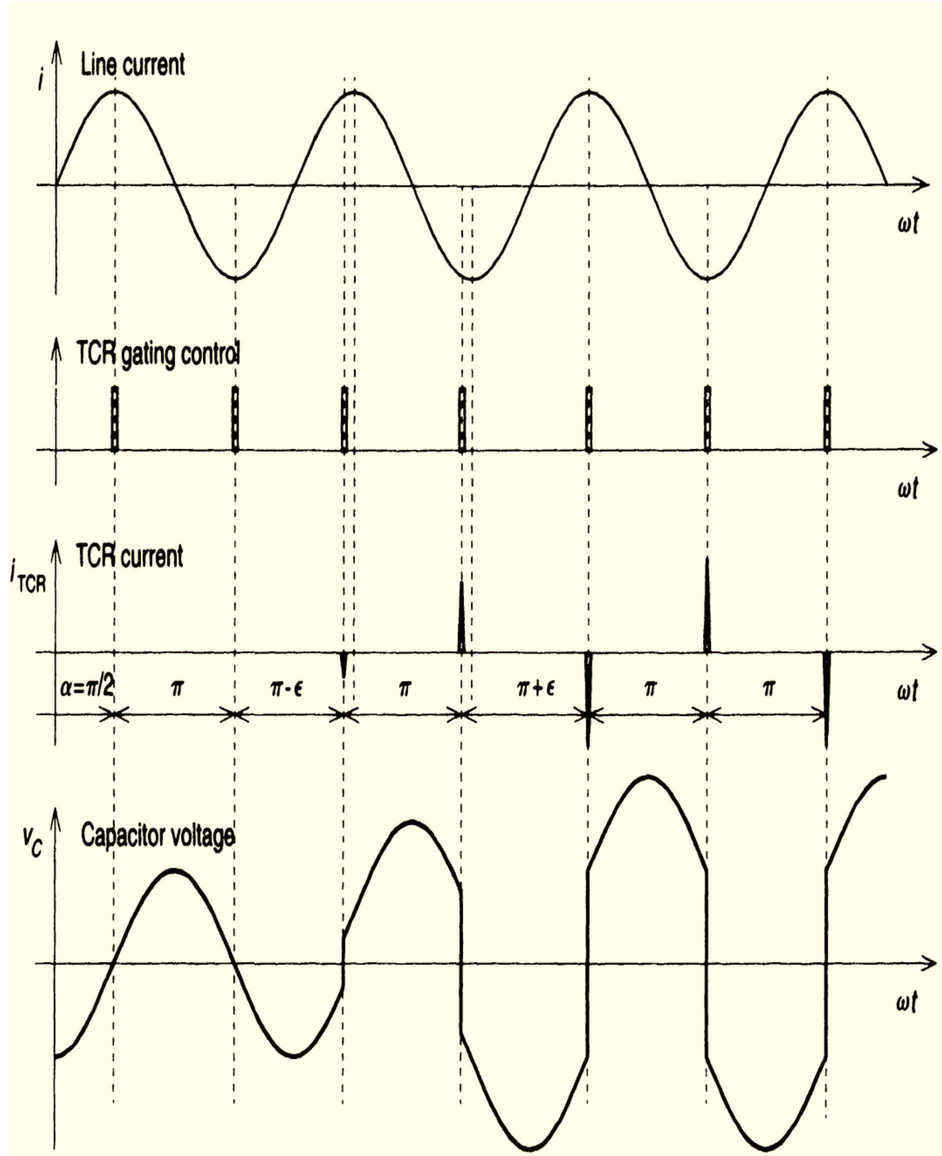


Figure 19.a Increase of the capacitor voltage b advancing the voltage reversal from *a* = 11 to *a* = 11 - *e.*



- The compensating voltage versus line current (V-I) characteristic of a basic TCSC is shown in Figure 20(a1).
- As illustrated, in the capacitive region the minimum delay angle, α_{Clim}, sets the limit for the maximum compensating voltage up to a value of line current (Imin) at which the maximum rated voltage, V_{cmax} constrains the operation until the rated maximum current, Imax, is reached.
- In the inductive region, the maximum delay angle, α_{Llim}, limits the voltage at low line currents and the maximum rated thyristor current at high line currents.
- The loss, as a percent of the rated var output, versus line current for voltage compensation mode in the capacitive operating region is shown in Figure 20(a2) for maximum and minimum compensating voltage, as well as for bypass operation (thyristor valve is fully on).
- The losses are almost entirely due to the TCR, which include the conduction and switching losses of the thyristor valve and the I^2R losses of the reactor.
- Note that the loss characteristic of the TCSC shown in Figure 20(a2) correlates with its voltage compensation characteristic shown in Figure 20(a1).
- In the impedance compensation mode, the TCSC is applied to maintain the maximum rated compensating reactance at any line current up to the rated maximum.
- For this operating mode the TCSC capacitor and thyristor-controlled reactor are chosen so that at α_{Clim} the maximum capacitive reactance can be maintained at and below the maximum rated line current, as illustrated in Figure 20(b1).
- The minimum capacitive compensating impedance the TCSC can provide is, of course, the impedance of the capacitor itself, theoretically obtained at α= 90° (with nonconducting thyristor valve).
- The loss versus line current characteristic for this operating mode is shown in Figure 20(b2) for maximum and minimum capacitive compensating reactances.

Figure 20 Attainable *V-I* (compensating voltage vs. line current) characteristics of the TCSC when operated in voltage control (a1) and reactance control (b 1) modes, and the associated loss vs. line current characteristics (a2 and b2, respectively).

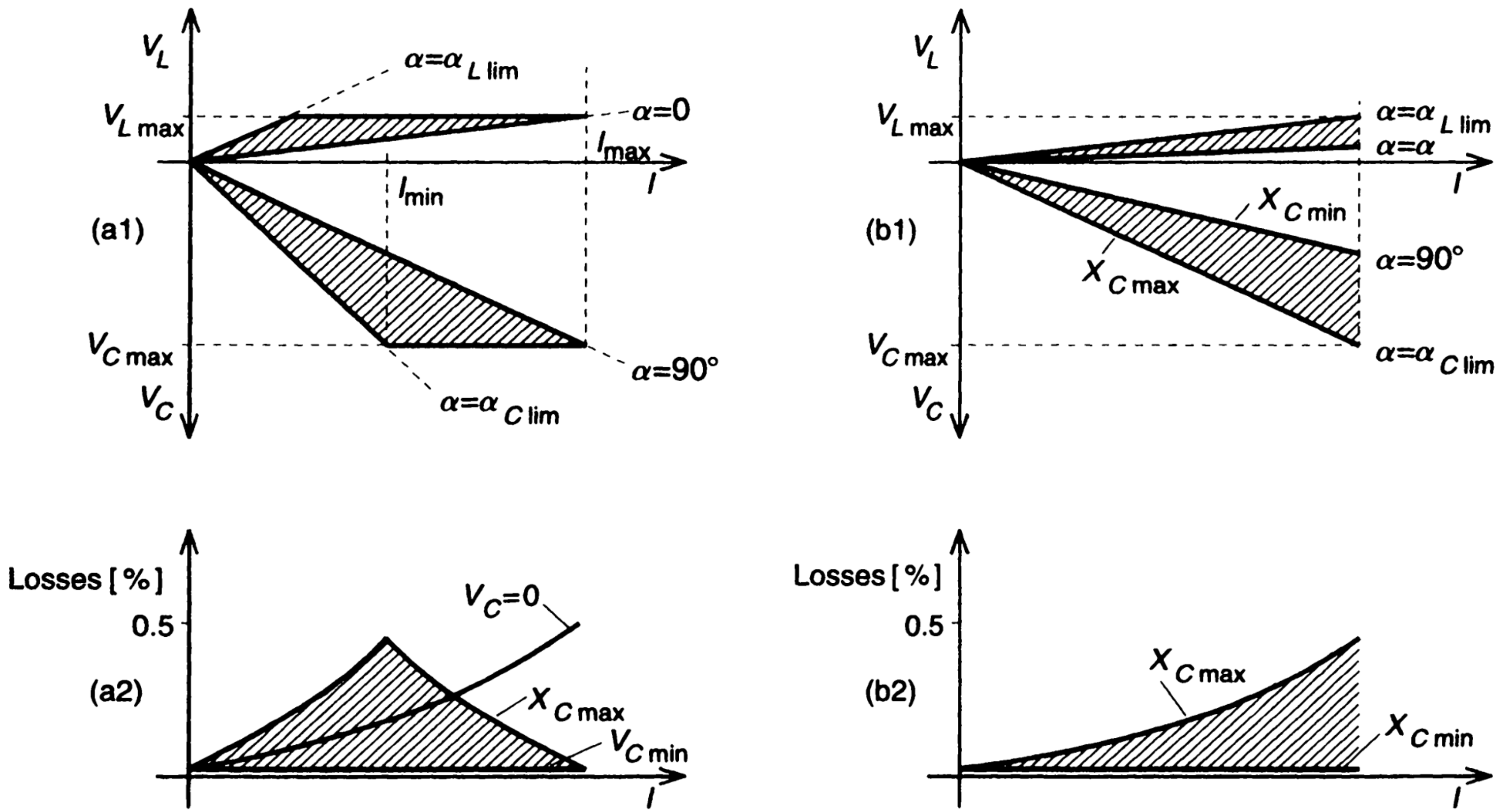
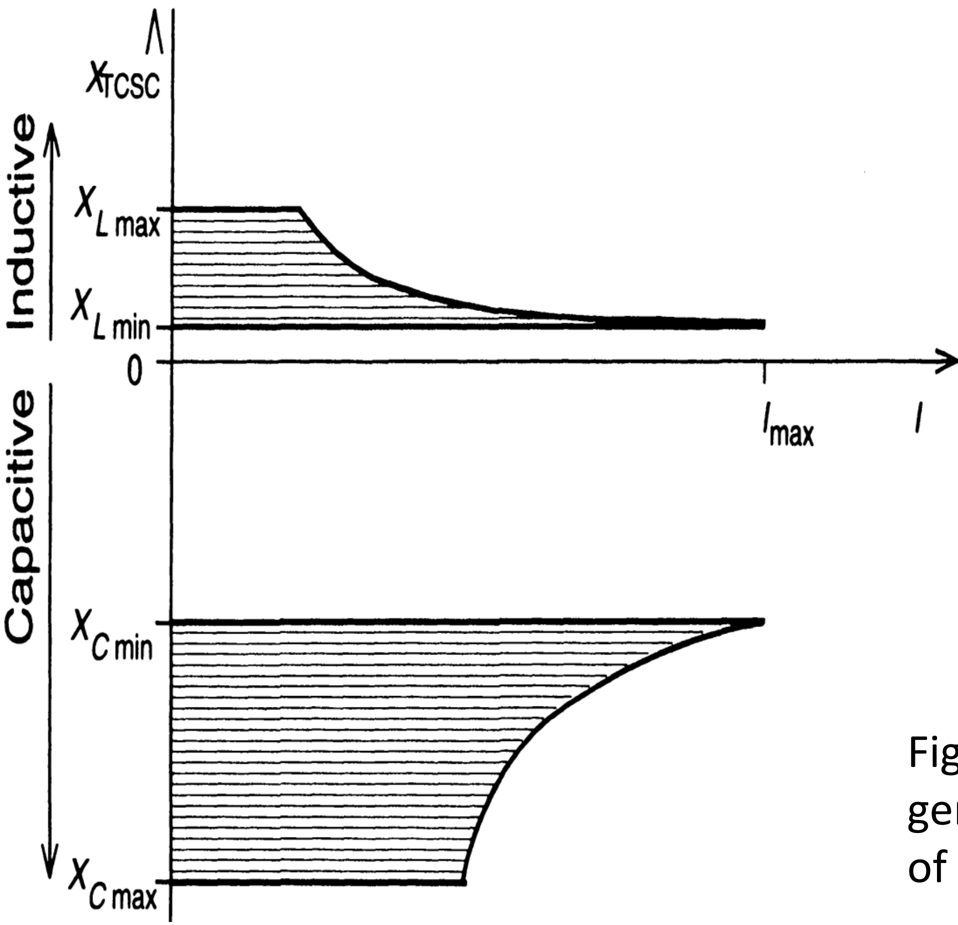


Figure 21 The attainable compensating reactance vs. line current characteristic of the TCSC corresponding to the voltage compensation mode V-I characteristic shown in Figure 20(a 1).



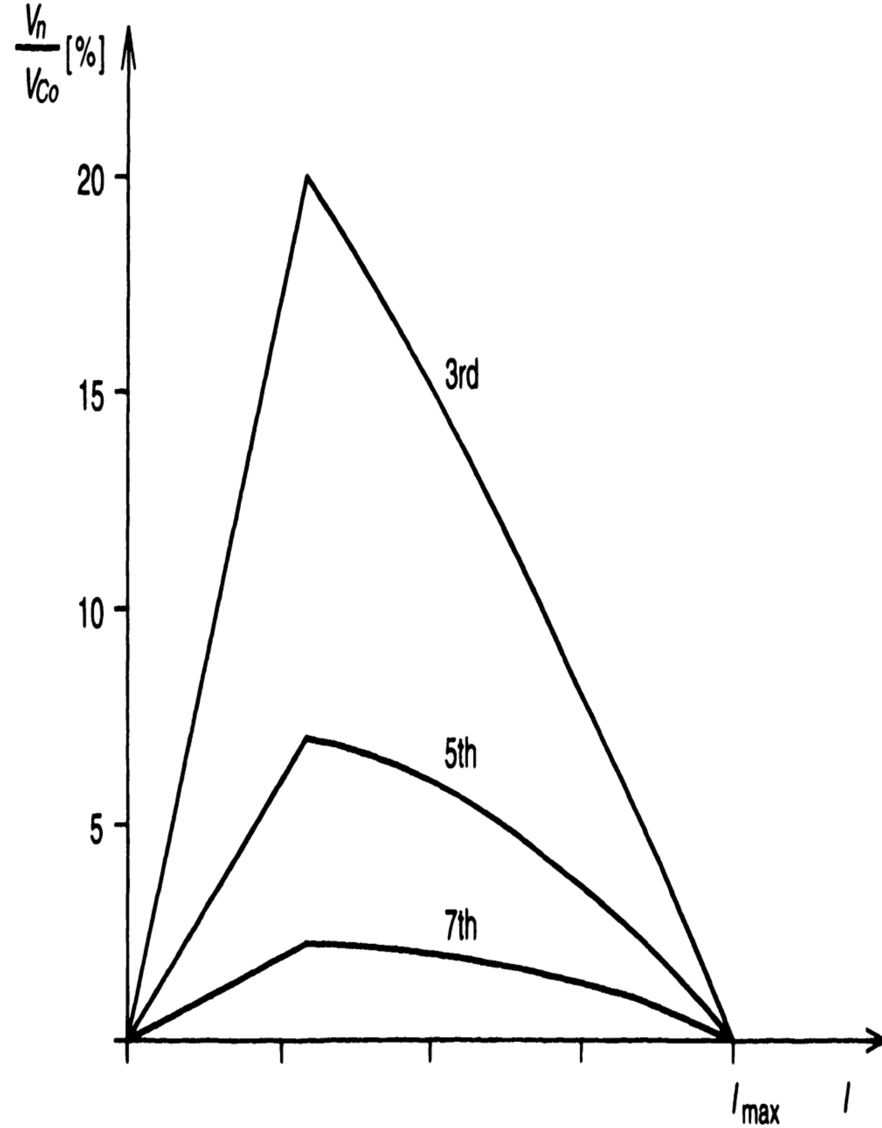


Figure 22 Dominant harmonic voltages generated by the TCSC at an *XL/XC* ratio of 0.133.

- For example, the compensating voltage versus line current characteristic shown in Figure 20(a1) can be transformed into the compensating reactance versus line current characteristic shown in Figure 21.
- It can be observed in these figures that constant compensating voltage necessarily results in varying compensating impedance and, vice versa, constant impedance produces varying compensating voltage with changing line current.
- The maximum voltage and current limits are design values for which the thyristor valve, the reactor and capacitor banks are rated to meet specific application requirements.
- The TCSC, like its switched counterpart, the TSSC, is usually required to have transient voltage and current ratings, defined for specific time durations.
- The TCSC, with partial conduction of the TCR, injects harmonic voltages into the line.
- These harmonic voltages are caused by the TCR harmonic currents which circulate through the series compensating capacitor.
- The TCR, generates all odd harmonics, the magnitudes of which are a function of the delay angle α .
- The harmonic voltages corresponding to these currents in a TCSC circuit are clearly dependent on the impedance ratio of the TCR reactor to the series capacitor, XL/Xc, For XL/Xc = 0.133 (used in the existing TCSC installations), the most important harmonic voltages, the 3rd, 5th, and 7th, generated in the capacitive operating region, are plotted against the line current I in Figure 6.22, as percents of the fundamental capacitor voltage, VCo , with the TCR off, at rated current.

5.Subsynchronous Characteristics

- series capacitive line compensation can cause subsynchronous resonance when the series capacitor resonates with the total circuit
- inductance of the transmission line at a subsynchronous frequency, h, that is equal to the frequency difference between the power frequency, f, and one of the torsional resonant frequencies of the turbine generator set, 1m, i.e., when h = I - 1m.
- Variable impedance type series compensators do insert a series capacitor in series with the line, and therefore their behavior in the transmission network at subsynchronous frequencies is critical to their general applicability for unrestricted line compensation and power flow control.
- As indicated earlier, the limitations imposed by the subsynchronous resonance (SSR) on the use of series capacitors prompted considerable development effort to find an effective method for the damping of subsynchronous oscillations.
- Although this scheme could be used to complement the series capacitive compensators discussed in this chapter, subsequent research efforts found that the NGB damping principle can be extended to the basic TCSC circuit structure to make it substantially immune to subsynchronous resonance.
- The basic principle of the NGH Damper is to force the voltage of the series capacitor to zero at the end of each half-period if it exceeds the value associated with the fundamental voltage component of the synchronous power frequency.
- Thus, the NGH Damper is basically a thyristor-controlled discharge resistor (in series with a dildt limiting reactor), operated synchronously with the power system frequency in the region near the end of the half cycle on the capacitor voltage, as illustrated in Figure 23.

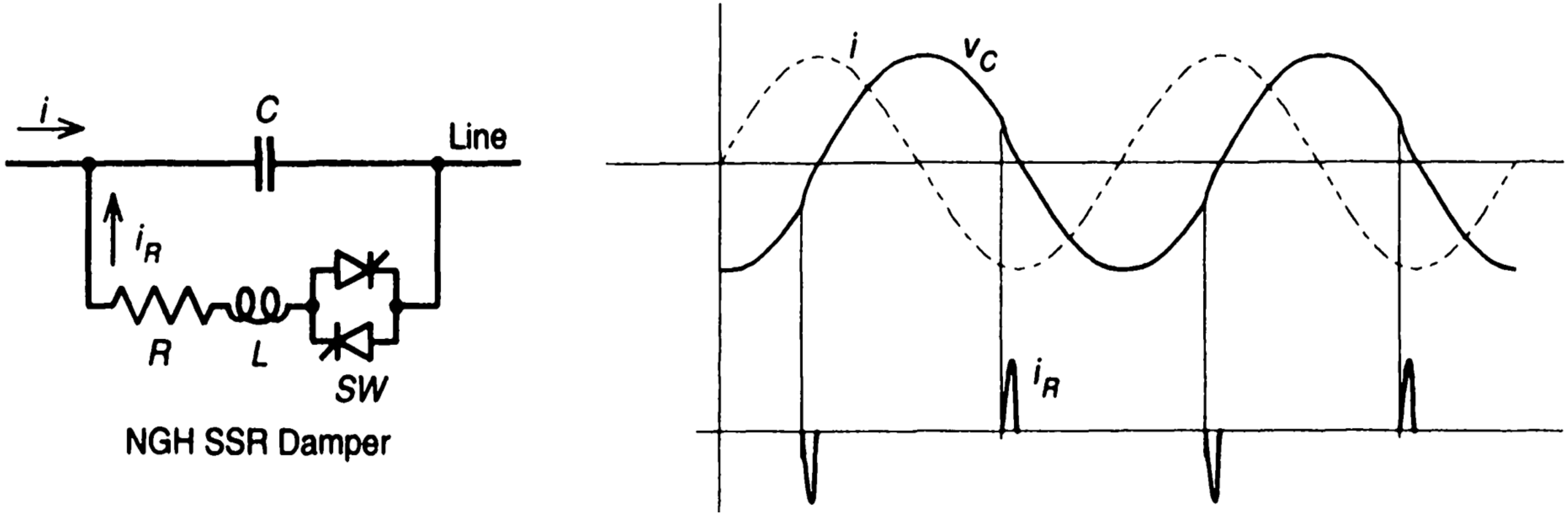


Figure 23 Basic NOH SSR Damper.

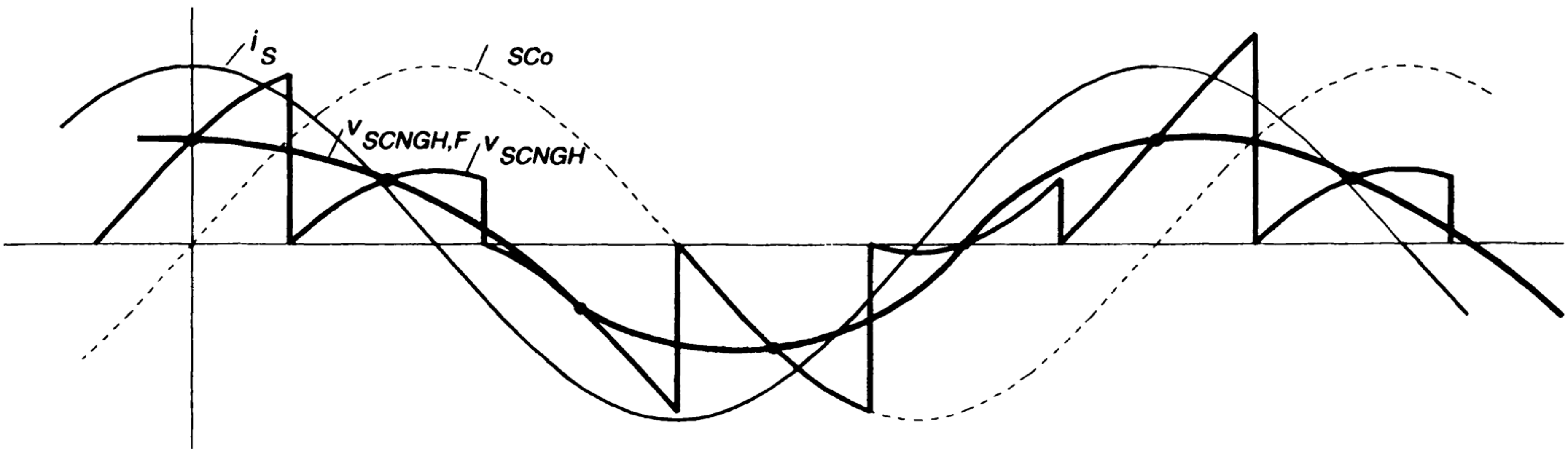


Figure 24 The capacitor voltage and its fundamental component produced by a 24 Hz subsynchronous current under the constraints imposed by the NGH Damper

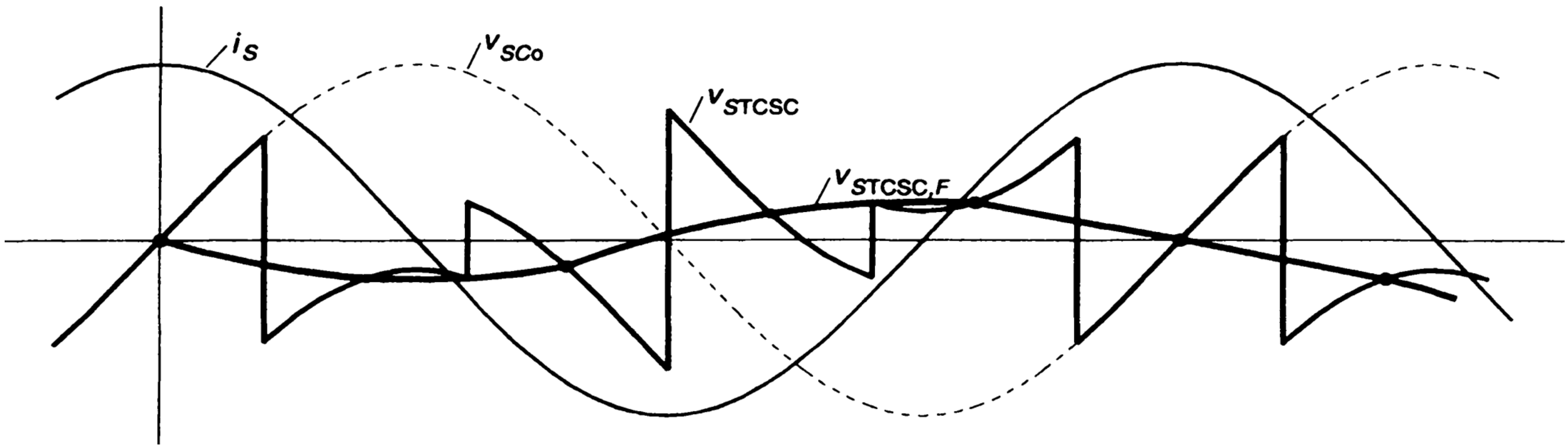


Figure 25 The capacitor voltage and its fundamental component produced by a 24 Hz subsynchronous current under the constraints imposed by the TCR executed capacitor voltage reversal

- The NGH Damper clearly interferes with the process of subsynchronous oscillation build up since the capacitor voltage cannot respond naturally to a subsynchronous line current.
- The actual effect of the NGH Damper on the capacitor voltage produced by a subsynchronous line current component is illustrated in Figure 24.
- For the illustration, the frequency of the subsynchronous line current is chosen to be 24 Hz and the NGH Damper is operated at 120 Hz to discharge the capacitor at regular half-cycle intervals corresponding to the 60 Hz power frequency.
- The figure shows the 24 Hz sinusoidal line current, *is,* the corresponding sinusoidal capacitor voltage, V_{SCo}, that would develop without the NGH Damper, the actual capacitor voltage, V_{SCNGH}, and its fundamental component, $V_{SCNGH,F}$ obtained with the activated NGH Damper.
- Inspection of this figure leads to an interesting observation that the NGH Damper shifts the capacitor voltage at the 24 Hz subsynchronous frequency so as to be in (or almost in) phase with the corresponding subsynchronous line current.
- In other words, the series capacitor with the NGH Damper exhibits a resistive rather than a capacitive impedance characteristic at the 24 Hz subsynchronous frequency.
- Although this observation is made on a single illustrative example, and not proven or generalized in a rigorous manner, studies and field measurements indicate conclusively that the actual circuit behavior is in agreement with this resistive impedance characteristic observed.

- similarity between the NGH Damper and the TCSC circuit, the former being composed of a thyristor-controlled resistor, and the latter of a thyristor-controlled reactor, both in parallel with the series compensating capacitor.
- Although the TCSC circuit configuration was originally conceived for the realization of a variable series capacitor, the circuit similarity suggested the possibility to use it also to implement the NGH principles of SSR mitigation.
- It has been discussed that the thyristor-controlled reactor, when operated within the TCSC to increase the effective capacitive impedance, reverses the capacitor voltage in the region near to the end of each half cycle corresponding to the power frequency.
- Thus, it can be expected that this synchronous charge reversal, just like the synchronous discharge of the capacitor in the NGH scheme, will interfere with the normal response of the capacitor to a subsynchronous current excitation so as to hinder or prevent the build up of subsynchronous oscillation.
- However, it is also obvious that the charge reversal, in contrast to the synchronous discharge action of the NGH Damper, does not result in the dissipation of any energy (ignoring circuit losses) and thus SSR mitigation by actual damping through the extraction and dissipation of energy from the resonant LC circuit cannot take place.

- In order to draw a parallel between the operation of TCSC and the NGH circuit, the voltage waveform obtained across the series capacitor is illustrated in Figure 25 for the previously considered 24 Hz subsynchronous current excitation, with the regular half-cycle (60 Hz) capacitor voltage reversal characterizing the operation of the TCSC in the capacitive region.
- Figure 25, similarly to Figure 24, shows the 24 Hz line current, i_s, the corresponding capacitor voltage, U_{SCo}, that would develop without the TCR executed charge reversals, the actual capacitor voltage, U_{SCTCSC}, and its fundamental component, $V_{SCTCSC,F}$, obtained with periodically repeated charge reversal.
- Inspection of this figure reveals that the charge reversal shifts the fundamental 24 Hz voltage component so that it leads the corresponding 24 Hz line current by 90 degrees.
- In other words, the TCSC circuit exhibits the impedance characteristic of an inductor at subsynchronous frequencies.
- Thus, whereas the NGH Damper with actual energy dissipation establishes a resistive characteristic for the series capacitor, the TCR executed charge reversal transforms the impedance of the series capacitor into that of an inductor in the subsynchronous frequency band.
- This observation is evidently important since it would indicate that the TCSC compensated line could not cause or participate in a subsynchronous resonance.

- The general validity of the above observation is not proven rigorously to date and applicable relationships for the impedance versus frequency characteristic of TCSC, in terms of the relevant circuit and control parameters (e.g., *XL, Xc* and *a* or *u),* are not available in the form of mathematical expressions.
- However, extensive studies, computer simulations and actual tests in prototype installations seem to indicate that the TCSC is substantially neutral to subsynchronous resonance and would not aggravate subsynchronous oscillations.
- The single condition for this important circuit property is that the charge reversal must take place at equal half-period intervals corresponding to the fundamental system frequency.
- With varying delay and conduction angle of the TCR, this condition actually stipulates that the center of different conduction angles remain fixed to the successive half-period intervals, independently from the prevailing delay angle.
- In other words, the conduction angle in the total operating range is to be symmetrically positioned around the zero crossings of the capacitor voltage.
- Evidently, it is increasingly difficult to satisfy this condition with decreasing delay angles, since with the correspondingly increasing TCR conduction, the locations of the capacitor voltage zero crossings are, as previously explained, increasingly influenced by the line current.
- As shown above, the TCSC circuit arrangement, with proper gating control can be made immune to subsynchronous resonance. This method can, of course, be extended to the TSSC, in which case the TCR conduction would be kept at a minimum and used exclusively to achieve SSR neutrality.
- Actually, in a large series capacitive compensator probably several basic TCSC circuits would be connected in series, and most of them would be operated with the TCR fully on (bypass) or fully off (capacitor inserted) to minimize harmonics and operating losses.

Basic Operating Control Schemes for GCSC, TSSC, and TCSC

- The function of the operating or "internal" control of the variable impedance type compensators is to provide appropriate gate drive for the thyristor valve to produce the compensating voltage or impedance defined by a reference.
- The internal control operates the power circuit of the series compensator, enabling it to function
- in a self-sufficient manner as a variable reactive impedance.
- Thus, the power circuit of the series compensator together with the internal control can be viewed as a "black box" impedance amplifier, the output of which can be varied from the input with a low power reference signal.
- The reference to the internal control is provided by the "external" or system control, whose function it is to operate the controllable reactive impedance so as to accomplish specified compensation objectives of the transmission line.
- Thus the external control receives a line impedance, current, power, or angle reference and, within measured system variables, derives the operating reference for the internal control.
- As seen, the power circuits of the series compensators operate by rigorously synchronized current conduction and blocking control which not only define their effective impedance at the power frequency but could also determine their impedance characteristic in the critical subsynchronous frequency band.

- This synchronization function is thus a cornerstone of a viable internal control.
- Additional functions include the conversion of the input reference into the proper switching instants which result in the desired valve conduction or blocking intervals.
- The internal control is also responsible for the protection of the main power components (valve, capacitor, reactor) by executing current limitations or initiating bypass or other protective measures.
- An internal control scheme for the GTO-Controlled Series Capacitor scheme of Figure 5 is shown in Figure 26(a).
- Because of the duality between the shuntconnected GCSC and the series-connected TCR arrangements, this control scheme is analogous to that shown for the TCR in Figure 19(a) (unit-3) .
- It has four basic functions.
- The first function is synchronous timing, provided by a phase-locked loop circuit that runs in synchronism with the line current.
- The second function is the reactive voltage or impedance to tum-off delay angle conversion according to the relationship given in (6.8a) or (6.8b), respectively.
- The third function is the determination of the instant of valve turn-on when the capacitor voltage becomes zero. (This function may also include the maintenance of a minimum on time at voltage zero crossings to ensure immunity to subsynchronous resonance.)
- The fourth function is the generation of suitable turn-off and turn-on pulses for the GTO valve

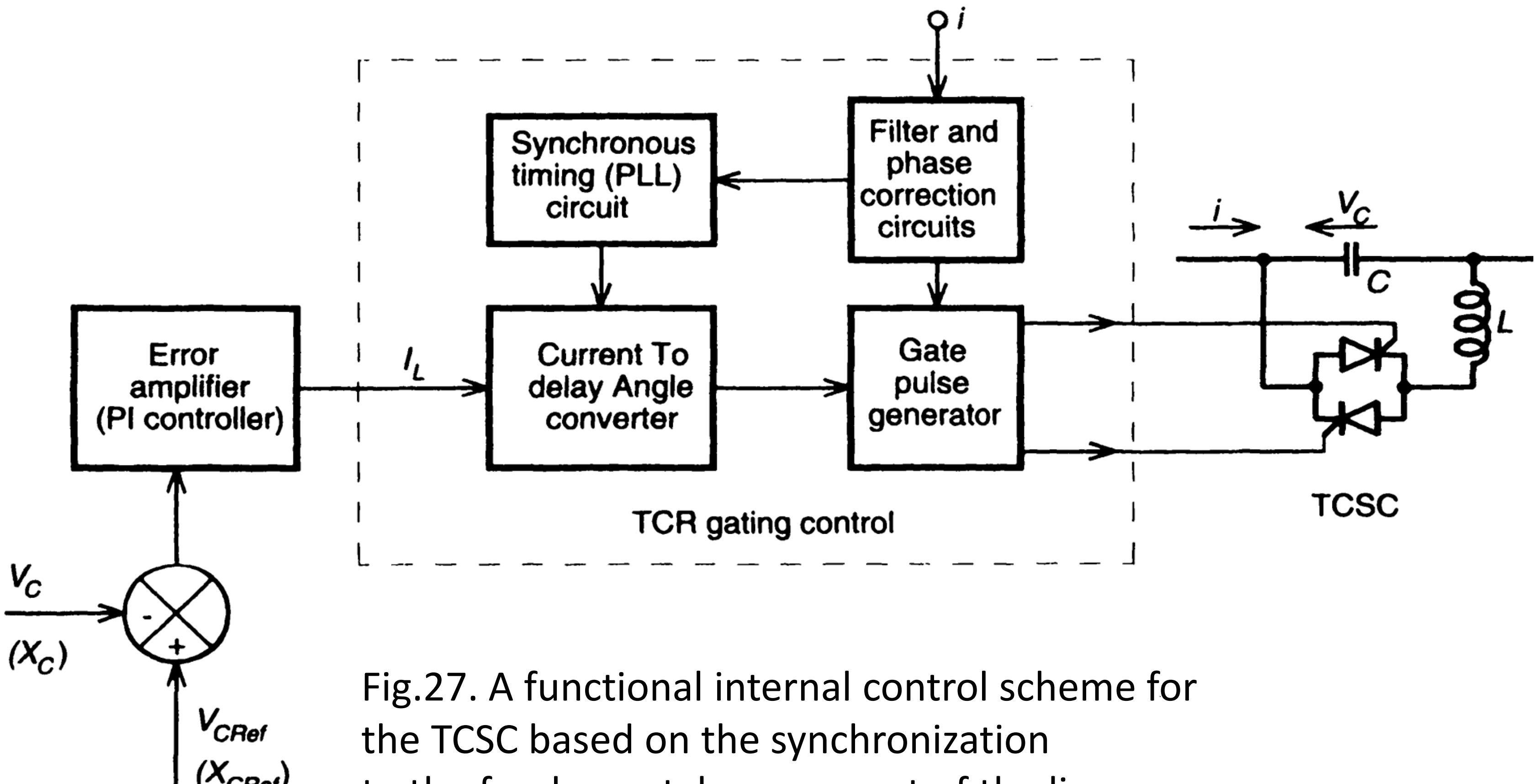


Fig.27. A functional internal control scheme for the TCSC based on the synchronization to the fundamental component of the line current

- The main consideration for the structure of the internal control operating the power circuit of the TCSC is to ensure immunity to subsynchronous resonance.
- Present approaches follow two basic control philosophies. One is to operate the basic phase locked- loop (PLL) from the fundamental component of the line current.
- In order to achieve this, it is necessary to provide substantial filtering to remove the super- and, in particular, the subsynchronous components from the line current and, at the same time, maintain correct phase relationship for proper synchronization.
- In this arrangement the conventional technique of converting the demanded TCR current into the corresponding delay angle, which is measured from the peak (or, with a fixed 90 degree shift, from the zero crossing) of the fundamental line current, is used.
- The second approach also employs a PLL, synchronized to the line current, for the generation of the basic timing reference. However, in this method the actual zero crossing of the capacitor voltage is estimated from the prevailing capacitor voltage and line current by an angle correction circuit.
- The delay angle is then determined from the desired angle and the estimated correction angle so as to make the TCR conduction symmetrical with respect to the expected zero crossing, as illustrated in Figure 28.

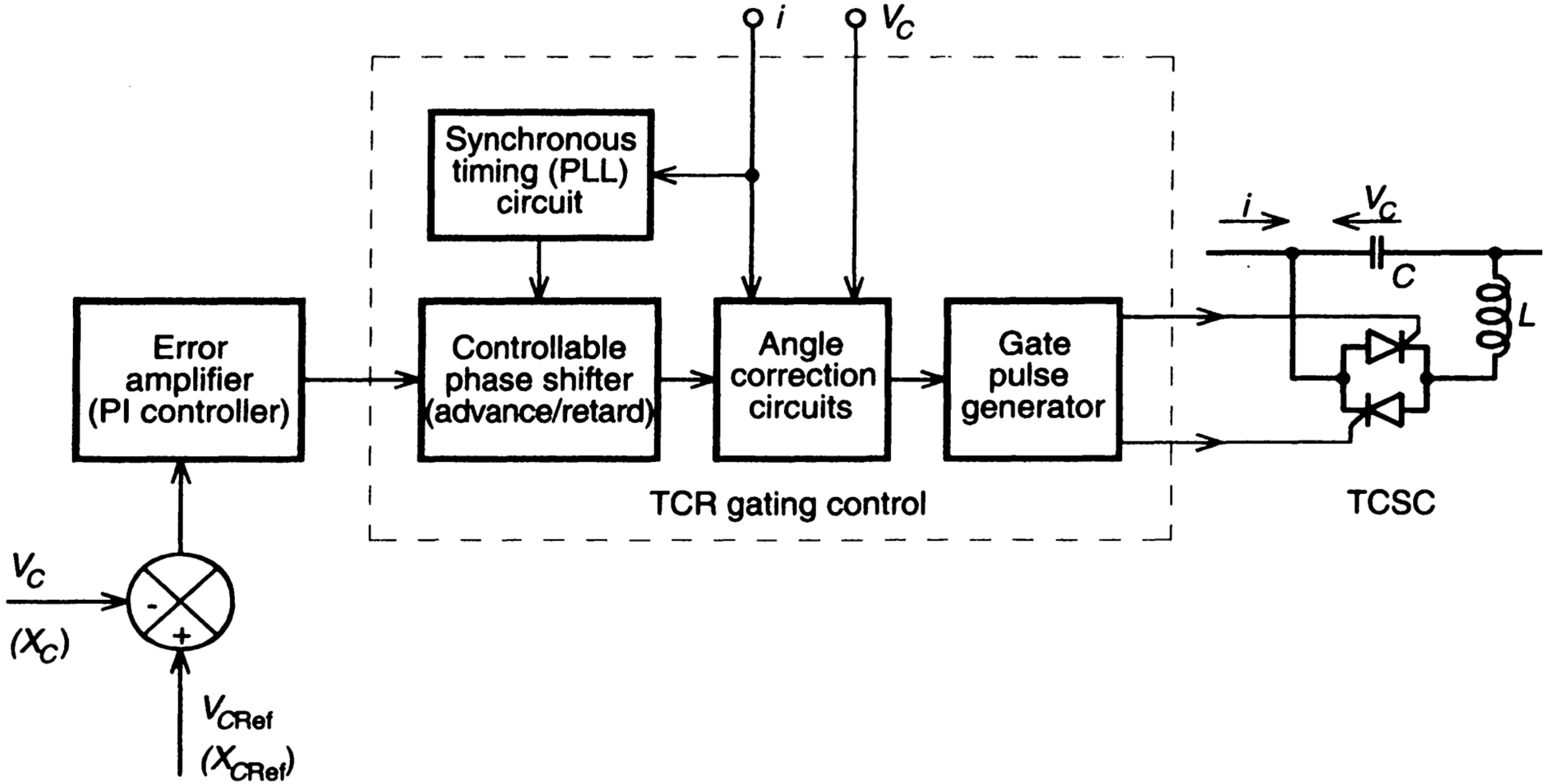


Figure 28 A functional internal control scheme
for the TCSC based on the prediction
of the capacitor voltage zero crossings.

- The delay angle of the TCR, and thus the compensating capacitive voltage, as in the previous case, is controlled overall by a regulation loop of the external control in order to meet system operating requirements.
- This regulation loop is relatively slow, with a bandwidth just sufficient to meet compensation requirements (power flow adjustment, power oscillation damping, etc.).
- Thus, from the standpoint of the angle correction circuit, which by comparison is very fast (correction takes place in each half cycle), the output of the phase shifter is almost a steady state reference.

The Static Synchronous Series Compensator (SSSC)

- The voltage-sourced converter-based series compensator, called Static Synchronous Series Compensator (SSSC), was proposed by Gyugyi in 1989 within the concept of using converter-based technology uniformly for shunt and series compensation, as well as for transmission angle control.
- The phasor diagram clearly shows that at a given line current the voltage across the series capacitor forces the opposite polarity voltage across the series line reactance to increase by the magnitude of the capacitor voltage.
- Thus, the series capacitive compensation works by increasing the voltage across the impedance of the given physical line, which in turn increases the corresponding line current and the transmitted power.
- the same steady-state power transmission can be established if the series compensation is provided by a synchronous ac voltage source, as shown in Figure 31, whose output precisely matches the voltage of the series capacitor, i.e.,

$$\boldsymbol{V}_q = \boldsymbol{V}_C = -j X_C \boldsymbol{I} = -jkX\boldsymbol{I}$$

- where, as before, Vc is the injected compensating voltage phasor, I is the line current, Xc is the reactance of the series capacitor, X is the line reactance, k = Xc/X is the degree of series compensation, andj =$\sqrt{-1}$

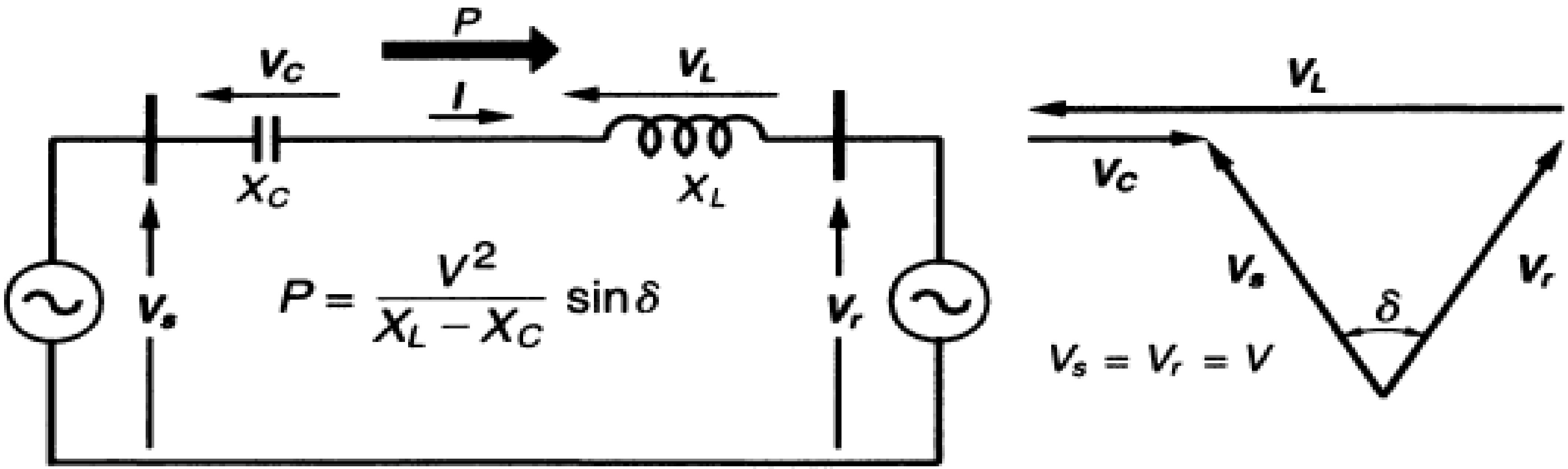


Figure 30 Basic two-machine system with a series capacitor compensated line and associated phasor diagram

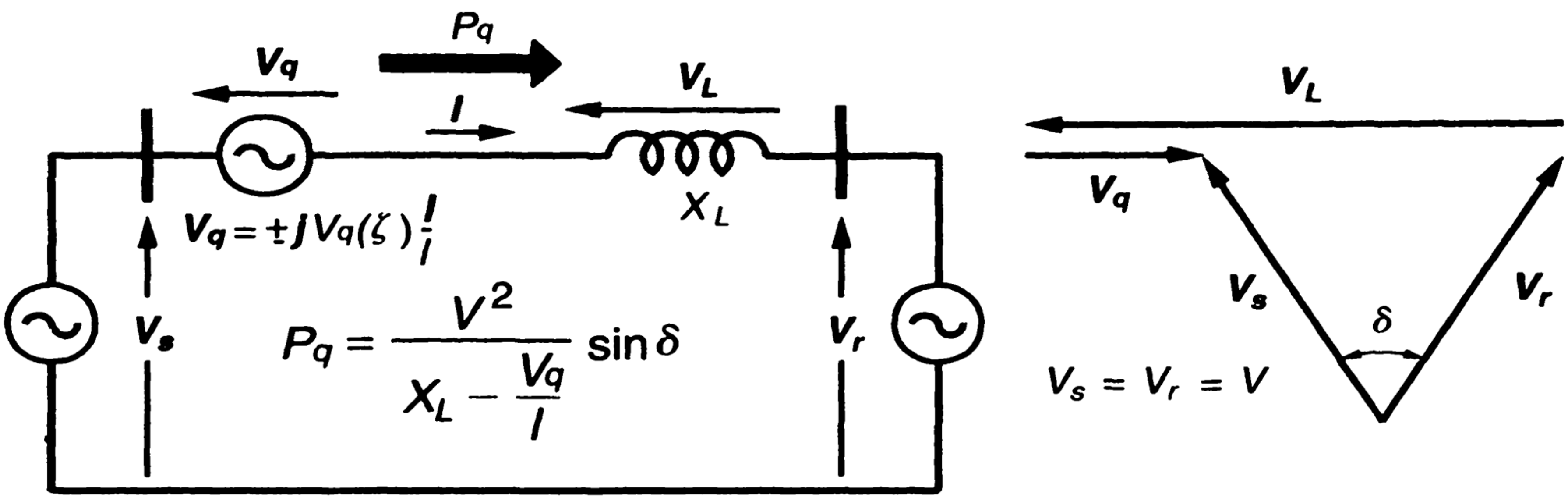


Figure 31 Basic two-machine system as in Figure 30 but with synchronous voltage source replacing the series capacitor.

- However, in contrast to the real series capacitor, the SVS is able to maintain a constant compensating voltage in the presence of variable line current, or control the amplitude of the injected compensating voltage independent of the amplitude of the line current.
- For normal capacitive compensation, the output voltage lags the line current by 90 degrees.
- For SVS, the output voltage can be reversed by simple control action to make it lead or lag the line current by 90 degrees.
- In this case, the injected voltage decreases the voltage across the inductive line impedance and thus the series compensation has the same effect as if the reactive line impedance was increased.
- With the above observations, a generalized expression for the injected voltage, Vq can simply be written:

$$\boldsymbol{V}_q = \pm j V_q(\zeta) \frac{\boldsymbol{I}}{I}$$

- where Vq(() is the magnitude of the injected compensating voltage ($0 \leq V_q(\delta) \leq V_{qmax}$) and δ is a chosen control parameter.
- The series reactive compensation scheme, using a switching power converter (voltage-sourced converter) as a synchronous voltage source to produce a controllable voltage in quadrature with the line current as defined by (Vq) is, per IEEE and ClGRE definition, termed the Static Synchronous Series Compensator (SSSC).

Transmitted Power Versus Transmission Angle Characteristic

- The SSSC injects the compensating voltage in series with the line irrespective of the line current.
- The transmitted power Pq versus the transmission angle 8 relationship therefore becomes a parametric function of the injected voltage, Vq(δ), and it can be expressed for a two-machine system as follows:

$$P = \frac{V^2}{X}\sin\delta + \frac{V}{X}V_q\cos\frac{\delta}{2}$$

- Comparison of the corresponding plots in Figures 32 and 33 clearly shows that the series capacitor increases the transmitted power by a fixed percentage of that transmitted by the uncompensated line at a given Band, by contrast, the SSSC can increase it by a fixed fraction of the maximum power transmittable by the uncompensated line, independent of B, in the important operating range of $0 \leq \delta \leq \pi/2$.

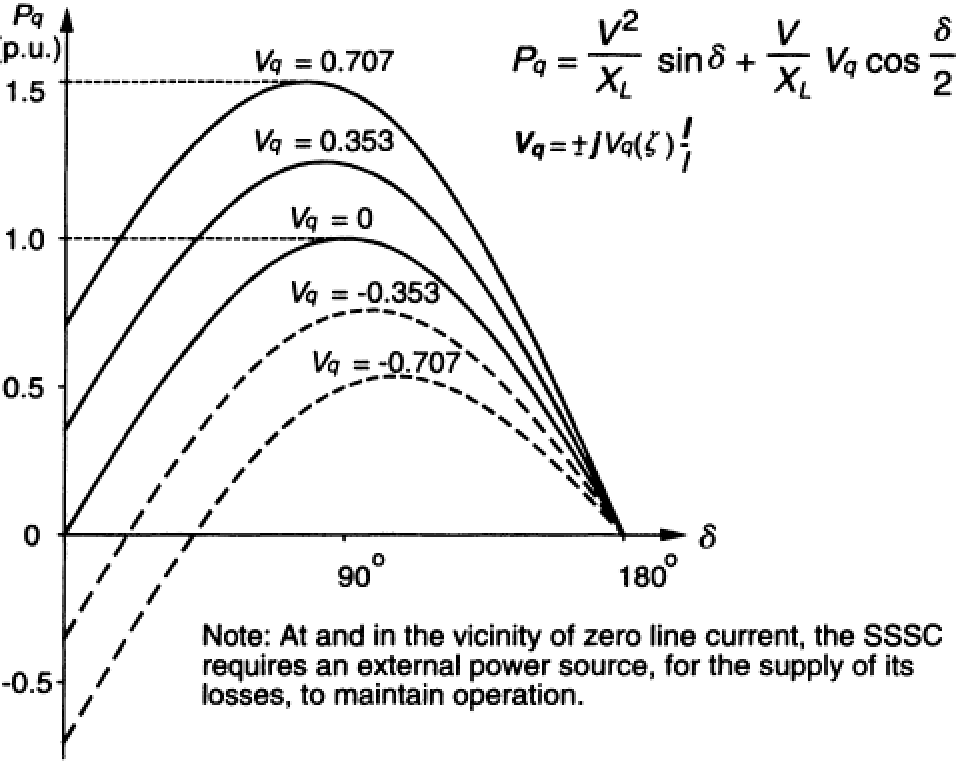
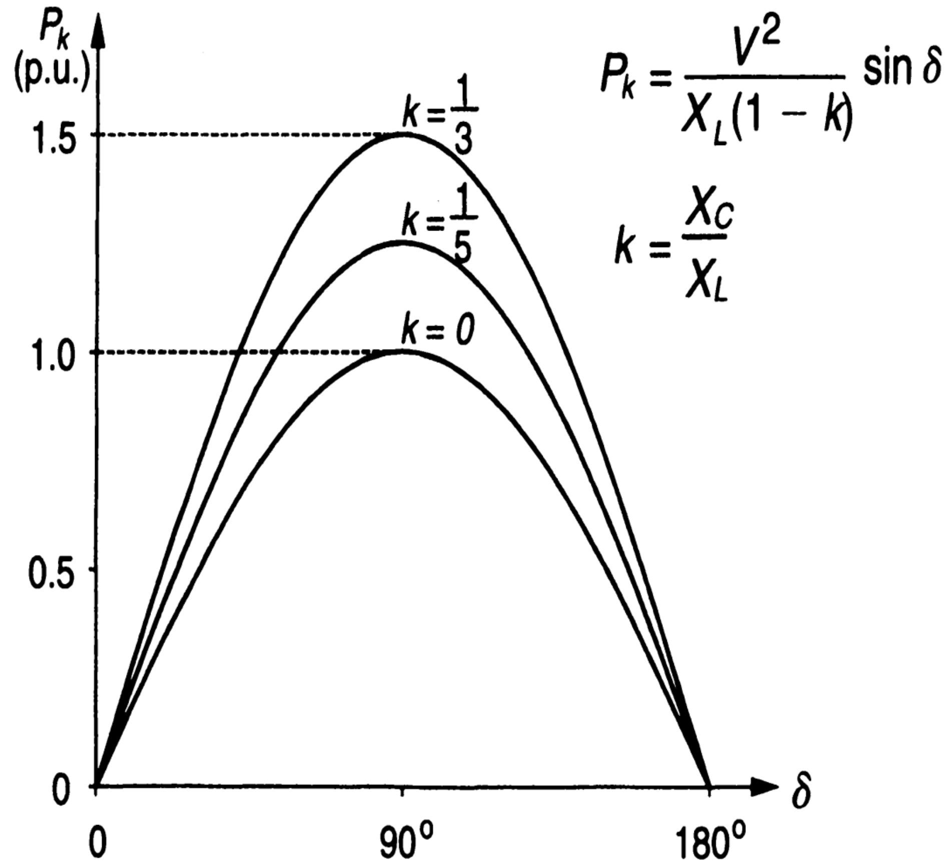


Figure 32 Transmitted power vs. transmission angle provided by the SSSC as a parametric function of the series compensating voltage.

Flgure 33 Transmitted power vs. transmission angle attainable with series capacitive compensation as a parametric function of the degree of series compensation



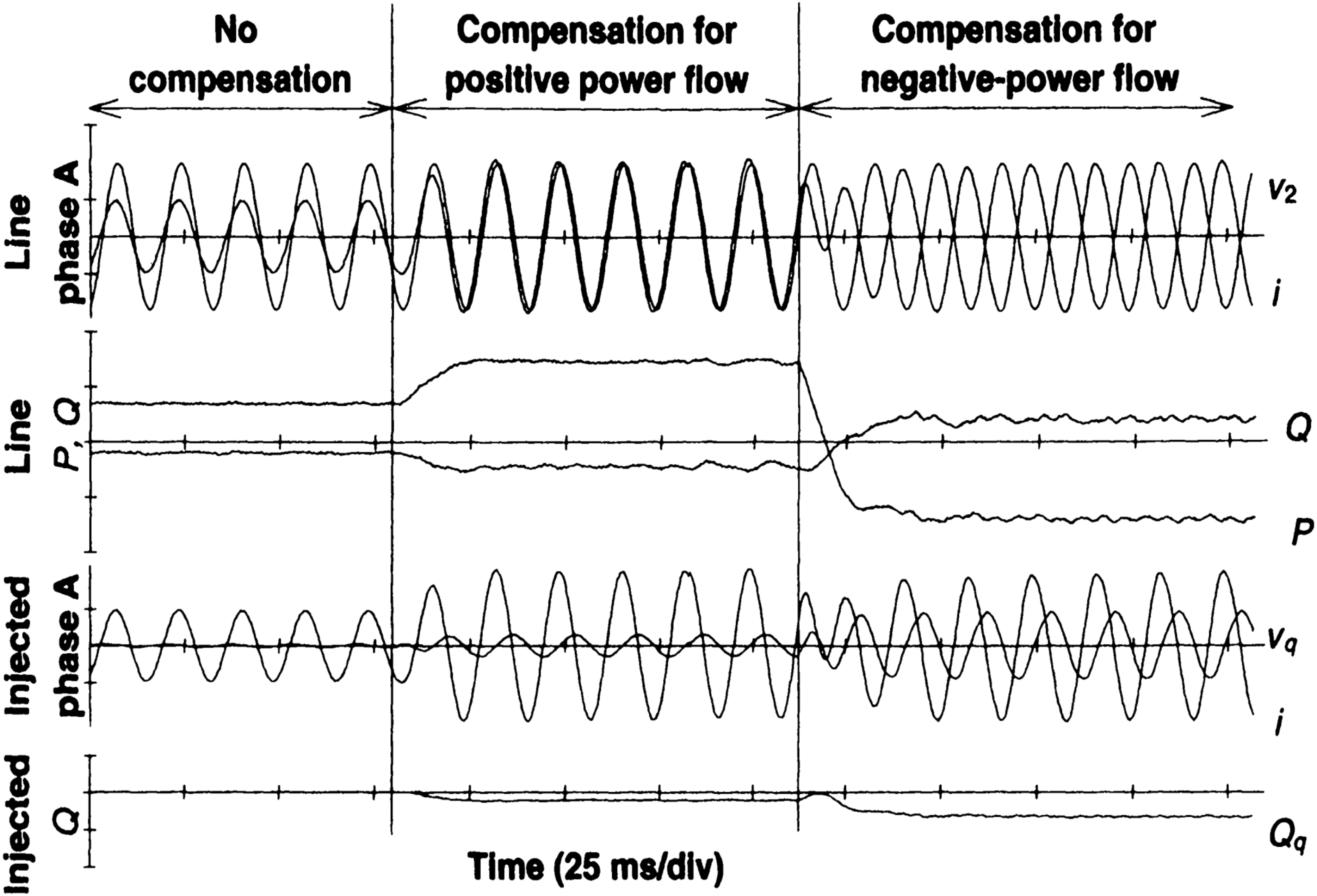


Figure 34 Oscillograms from TNA simulation showing the capability of the SSSC to control as well as reverse real power flow.

- This means that the SSSC can decrease, as well as increase the power flow to the same degree, simply by reversing the polarity of the injected ac voltage.
- The reversed (180° phase-shifted) voltage adds directly to the reactive voltage drop of the line as if the reactive line impedance was increased.
- Furthermore, if this (reverse polarity) injected voltage is made larger than the voltage impressed across the uncompensated line by the sending- and receiving-end systems, that is, if $V_q > |V_s - V_r|$, then the power flow will reverse with the line current $I = (V_q - |V_s - V_r)/ X$, as indicated in Figure 32.
- in Figure 34 by the results obtained from the TNA simulation of a simple twomachine system controlled by a precisely detailed SSSC hardware model.
- The plots in the figure show, at $\delta = 10°$, the line current i together with the receiving-end (I n) voltage $V_r = V_2$ for phase A, the transmitted power P together with the reactive power Q supplied by the receiving end, the same line current i together with the voltage V_q injected by the SSSC in phase A, and the reactive power the SSSC exchanged with the ac system for no compensation ($V_q = 0$), purely reactive compensation for positive power flow ($V_q = IX - |V_s - V_r|$), and purely reactive compensation for negative power flow ($V_q = IX + |V_s - V_r|$).

Control Range and VA Rating

- The SSSC can provide capacitive or inductive compensating voltage independent of the line current up to its specified current rating.
- Thus, in voltage compensation mode the SSSC can maintain the rated capacitive or inductive compensating voltage in the face of changing line current theoretically in the total operating range of zero to *Iqmax,* as illustrated in Figure 35(a1).
- The corresponding loss, as percent of the (capacitive or inductive) rating of the SSSC, versus line current characteristic is shown in Figure 35(a2).
- The VA rating of the SSSC (solid-state converter and coupling transformer) is simply the product of the maximum line current (at which compensation is still desired) and the maximum series compensating voltage:
- VA = Imax Vqmax

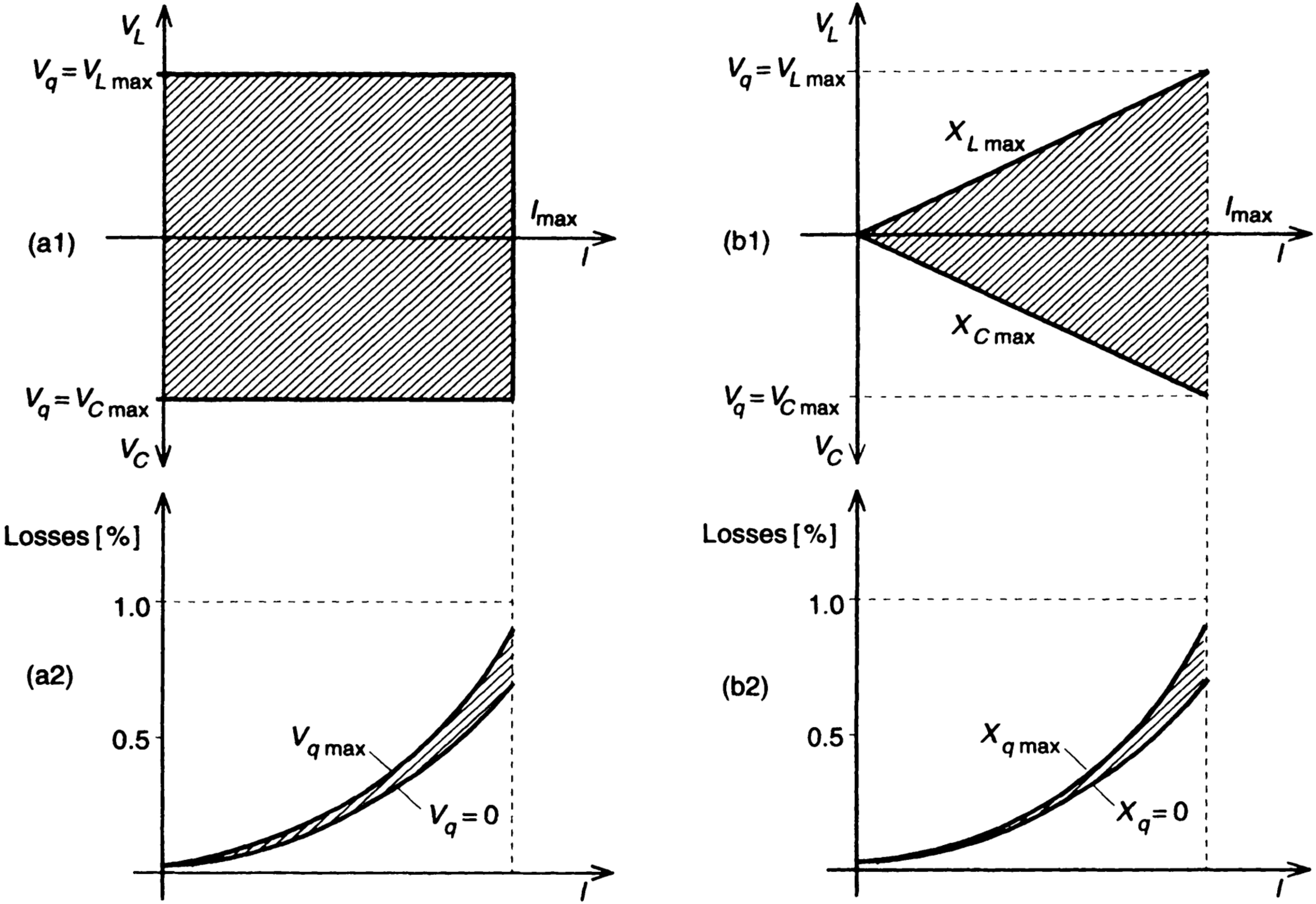


Figure 35 Attainable V-I (compensating voltage vs. line current) characteristics of the SSSC when operated in voltage control (a 1) and reactance control (b1) modes, and the associated loss vs. line current characteristics (a2 and b2, respectively)

- In impedance compensation mode, the SSSC is established to maintain the maximum rated capacitive or compensating reactance at any line current up to the rated maximum, as illustrated in Figure 35(b1).
- The corresponding loss versus line current characteristic is shown in Figure 35(b2).
- Note that in practical applications, as indicated previously for variable impedance type compensators, *I max* may be separately defined for the rated maximum steady-state line current and for a specified short duration overcurrent.
- The basic VA rating of the major power components of the SSSC must be rated for these currents and for the relevant maximum voltages.

Unit-5

THE UNIFIED POWER FLOW CONTROLLER

Syllabus

- Combined Compensators: Introduction to Unified Power Flow Controller, Basic operating principles, Conventional control capabilities, Independent control of real and reactive power.

Introduction

- The Unified Power Flow Controller (UPFC) concept was proposed by Gyugyi in 1991.
- The UPFC was devised for the real-time control and dynamic compensation of ac transmission systems, providing multifunctional flexibility required to solve many of the problems facing the power delivery industry.
- Within the framework of traditional power transmission concepts, the UPFC is able to control, simultaneously or selectively, all the parameters affecting power flow in the transmission line (i.e., voltage, impedance, and phase angle), and this unique capability is signified by the adjective "unified“ in its name.
- Alternatively, it can independently control both the real and reactive power flow in the line.
- The reader should recall that, for all the Controllers discussed in the previous chapters, the control of real power is associated with similar change in reactive power, i.e., increased real power flow also resulted in increased reactive line power.

Basic Operating Principles

- the UPFC is a generalized synchronous voltage source (SVS), represented at the fundamental (power system) frequency by voltage phasor Vpq with controllable magnitude Vpq ($0 \leq Vpq \leq Vpqmax$) and angle p ($0 \leq p \leq 2\pi$), in series with the transmission line, as illustrated for the usual elementary two machine system (or for two independent systems with a transmission link intertie) in Figure 1.
- In this functionally unrestricted operation, which clearly includes voltage and angle regulation, the SVS generally exchanges both reactive and real power with the transmission system.
- Since, as established previously, an SVS is able to generate only the reactive power exchanged, the real power must be supplied to it, or absorbed from it, by a suitable power supply or sink.
- In the UPFC arrangement the real power exchanged is provided by one of the end buses (e.g., the sending-end bus), as indicated in Figure 1.

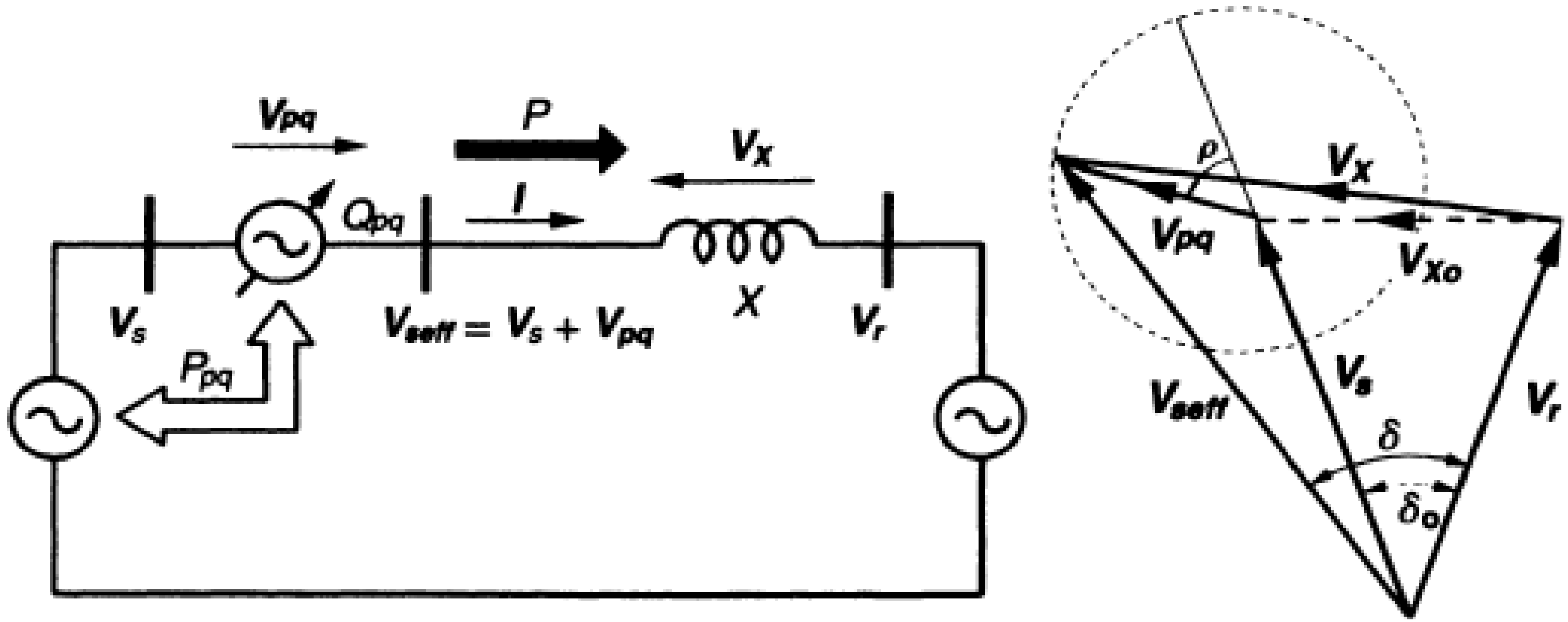


Figure 1. Conceptual representation of the UPFC in a two-machine power system.

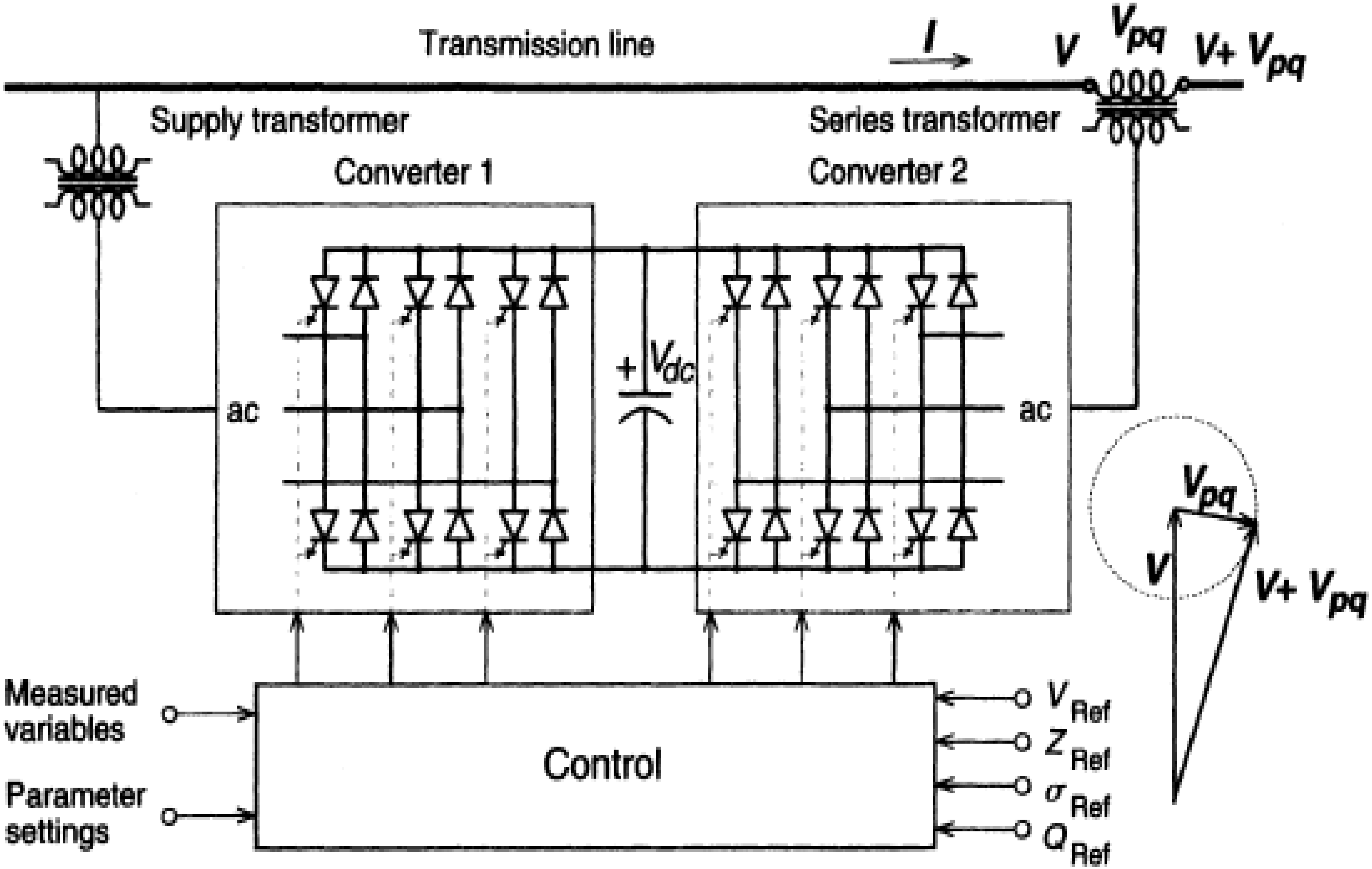


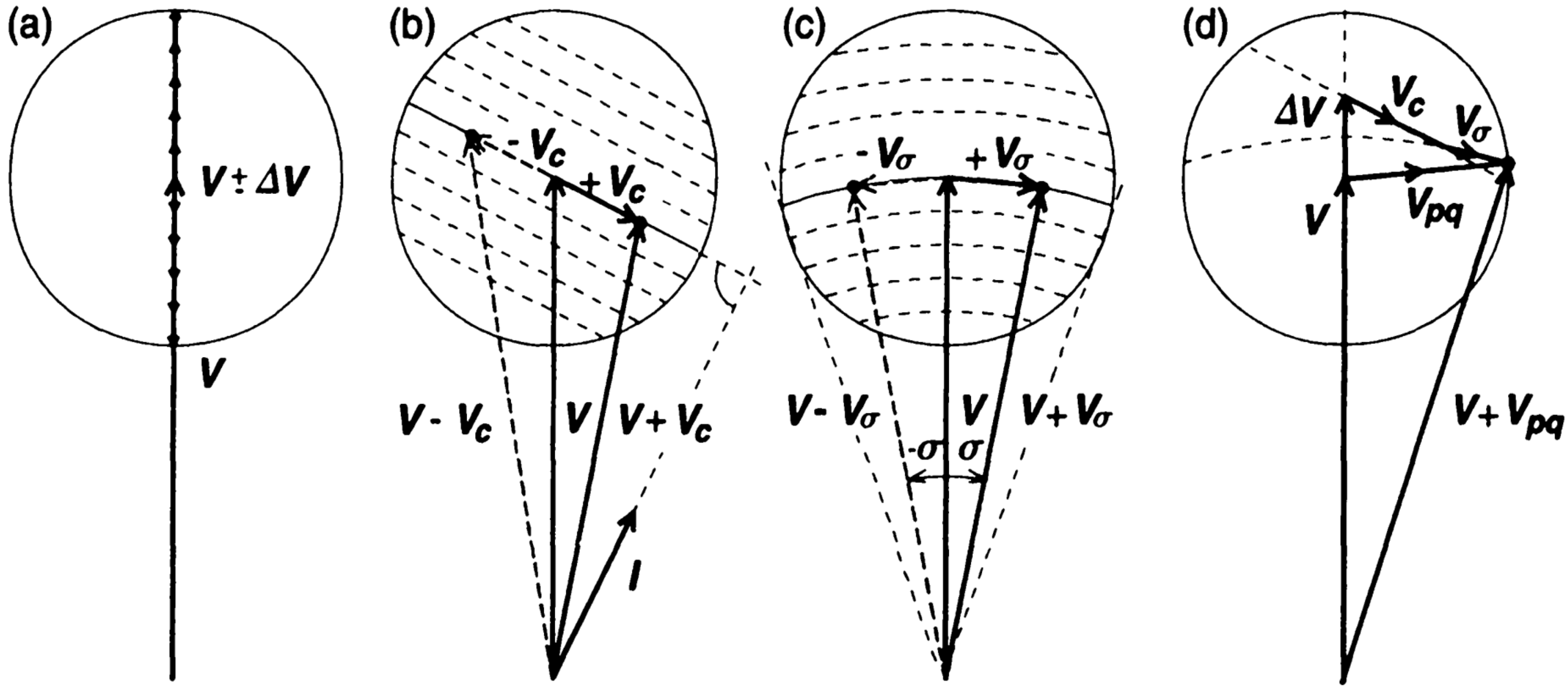
Figure 2 Implementation of the UPFC by two back-to-back voltage-sourced converters.

- In the presently used practical implementation, the UPFC consists of two voltage- .sourced converters, as illustrated in Figure 2.
- These back-to-back converters, labeled "Converter 1" and "Converter 2" in the figure, are operated from a common dc link provided by a de storage capacitor.
- As indicated before, this arrangement functions as an ideal ac-to-ac power converter in which the real power can freely flow in either direction between the ac terminals of the two converters, and each converter can independently generate (or absorb) reactive power at its own ac output terminal.
- Converter 2 provides the main function of the UPFC by injecting a voltage Vpq with controllable magnitude Vpq and phase angle p in series with the line via an insertion transformer.
- This injected voltage acts essentially as a synchronous ac voltage source. The transmission line current flows through this voltage source resulting in reactive and real power exchange between it and the ac system.
- The reactive power exchanged at the ac terminal (ie., at the terminal of the series insertion transformer) is generated internally by the converter. The real power exchanged at the ac terminal is converted into dc power which appears at the dc link as a positive or negative real power demand.

- The basic function of Converter 1 is to supply or absorb the real power demanded by Converter 2 at the common dc link to support the real power exchange resulting from the series voltage injection.
- This dc link power demand of Converter 2 is converted back to ac by Converter 1 and coupled to the transmission line bus via a shunt connected transformer.
- In addition to the real power need of Converter 2, Converter 1 can also generate or absorb controllable reactive power, if it is desired, and thereby provide independent shunt reactive compensation for the line.
- It is important to note that whereas there is a closed direct path for the real power negotiated by the action of series voltage injection through Converters 1 and 2 back to the line, the corresponding reactive power exchanged is supplied or absorbed locally by Converter 2 and therefore does not have to be transmitted by the line.
- Thus, Converter 1 can be operated at a unity power factor or be controlled to have a reactive power exchange with the line independent of the reactive power exchanged by Converter 2.
- Obviously, there can be no reactive power flow through the UPFC dc link.

Conventional Transmission Control Capabilities

- the Unified Power Flow Controller from the standpoint of traditional power transmission based on reactive shunt compensation, series compensation, and phase angle regulation, the UPFC can fulfill all these functions and thereby meet multiple control objectives by adding the injected voltage *Vpq* with appropriate amplitude and phase angle, to the (sending-end) terminal voltage *Vs,* Using phasor representation, the basic UPFC power flow control functions are illustrated in Figure 3.



(a) Voltage regulation
(b) Line impedance compensation
(c) Phase shifting
(d) Simultaneous control of voltage, impedance, and angle

Figure 3. Phasor diagrams illustrating the conventional transmission control capabilities of the UPFC.

- Voltage regulation with continuously variable in-phase/anti-phase voltage injection, is shown in Figure 3 (a) for voltage increments $V_{pq} = \pm\Delta V$ ($p = 0$).
- Series reactive compensation is shown in Figure 3(b) where $V_{pq} = V_q$ is injected in quadrature with the line current I.
- Functionally this is similar to series capacitive and inductive line compensation attained by the SSSC the injected series compensating voltage can be kept constant, if desired, independent of line current variation, or can be varied in proportion with the line current to imitate the compensation obtained with a series capacitor or reactor.
- Phase angle regulation (phase shift) is shown in Figure 3(c) where $V_{pq} = V\sigma$ is injected with an angular relationship with respect to V, that achieves the desired o phase shift (advance or retard) without any change in magnitude.
- Thus the UPFC can function as a perfect Phase Angle Regulator which, as discussed previous unit, can also supply the reactive power involved with the transmission angle control by internal var generation.
- Multifunction power flow control, executed by simultaneous terminal voltage regulation, series capacitive line compensation, and phase shifting, is shown in Figure 3(d) where $V_{pq} = \Delta V + V_q + V\sigma$.
- This functional capability is unique to the UPFC. No single conventional equipment has similar multifunctional capability.

- With reference to this figure, the transmitted power *P* and the reactive power - *jQr* supplied by the receiving end, can be expressed as follows:
- $$P - jQ_r = V_r\left(\frac{V_s + V_{pq} - V_r}{jX}\right)^* \quad \text{--------1}$$
- where symbol * means the conjugate of a complex number and j = $e^{j\pi/2}$ =$\sqrt{-1}$. If *Vpq* = 0, then (1) describes the uncompensated system, that is,
- $$P - jQ_r = V_r\left(\frac{V_s - V_r}{jX}\right)^* \quad \text{----2}$$
- Thus, with *Vpq* ≠0, the total real and reactive power can be written in the form
- $$P - jQ_r = V_r\left(\frac{V_s - V_r}{jX}\right)^* + \frac{V_r V_{pq}^*}{-jX} \quad \text{-----3}$$

- Substituting
- $$V_s = Ve^{j\delta/2} = V\left(\cos\frac{\delta}{2} + j\sin\frac{\delta}{2}\right)$$ --------4
- $$V_r = Ve^{-j\delta/2} = V\left(\cos\frac{\delta}{2} - j\sin\frac{\delta}{2}\right)$$ -------5
- $$V_{pq} = V_{pq}e^{j(\delta/2+\rho)} = V_{pq}\left\{\cos\left(\frac{\delta}{2}+\rho\right) + j\sin\left(\frac{\delta}{2}+\rho\right)\right\}$$ -----6
- the following expressions are obtained for P and Q,:

$$P(\delta, \rho) = P_0(\delta) + P_{pq}(\rho) = \frac{V^2}{X}\sin\delta - \frac{VV_{pq}}{X}\cos\left(\frac{\delta}{2}+\rho\right)$$

- -- 7

$$Q_r(\delta, \rho) = Q_{0r}(\delta) + Q_{pq}(\rho) = \frac{V^2}{X}(1-\cos\delta) - \frac{VV_{pq}}{X}\sin\left(\frac{\delta}{2}+\rho\right)$$ -8

- $$P_0(\delta) = \frac{V^2}{X}\sin\delta$$ ------------9
- $$Q_{0r}(\delta) = -\frac{V^2}{X}(1 - \cos\delta)$$ ----------10
- are the real and reactive power characterizing the power transmission of the uncompensated system at a given angle δ.
- Since angle δ is freely variable between 0 and *2π* at any given transmission angle δ (0 ≤ δ ≤ *π),* it follows that *Ppq(ρ)* and *Qpq(ρ)* are controllable between -*VVpq/X* and +*VVpq/X* independent of angle δ.
- Therefore, the transmittable real power *P* is controllable between
- $$P_0(\delta) - \frac{VV_{pqmax}}{X} \le P_0(\delta) \le P_0(\delta) + \frac{VV_{pqmax}}{X}$$ ---------11
- and the reactive power Q, is controllable between
-
- $$Q_{0r}(\delta) - \frac{VV_{pqmax}}{X} \le Q_{0r}(\delta) \le Q_{0r}(\delta) + \frac{VV_{pqmax}}{X}$$ ---------12

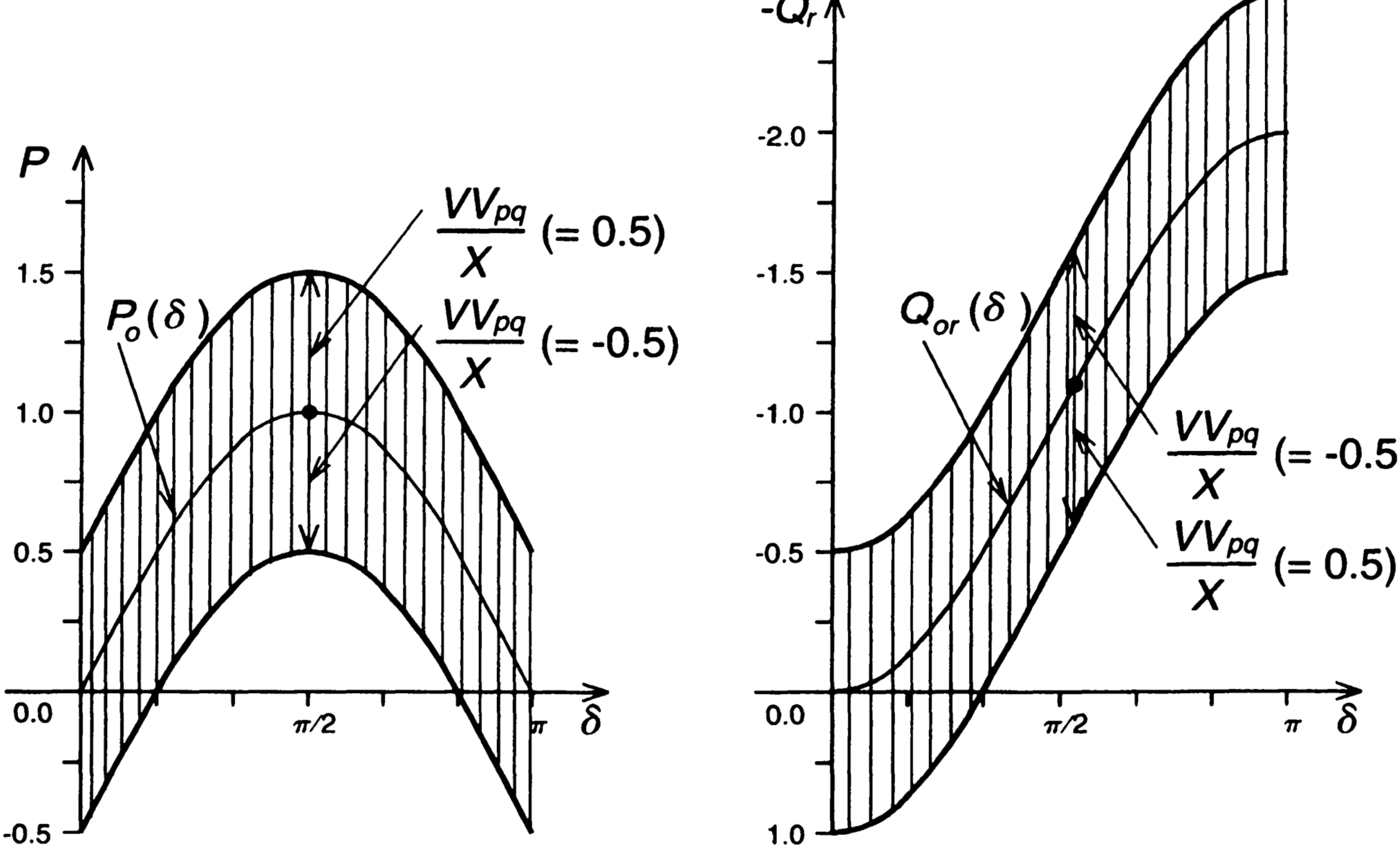


Figure 4 Range of transmittable real power P and receiving-end reactive power demand Q vs. transmission angle 6 of a UPFC controlled transmission line.

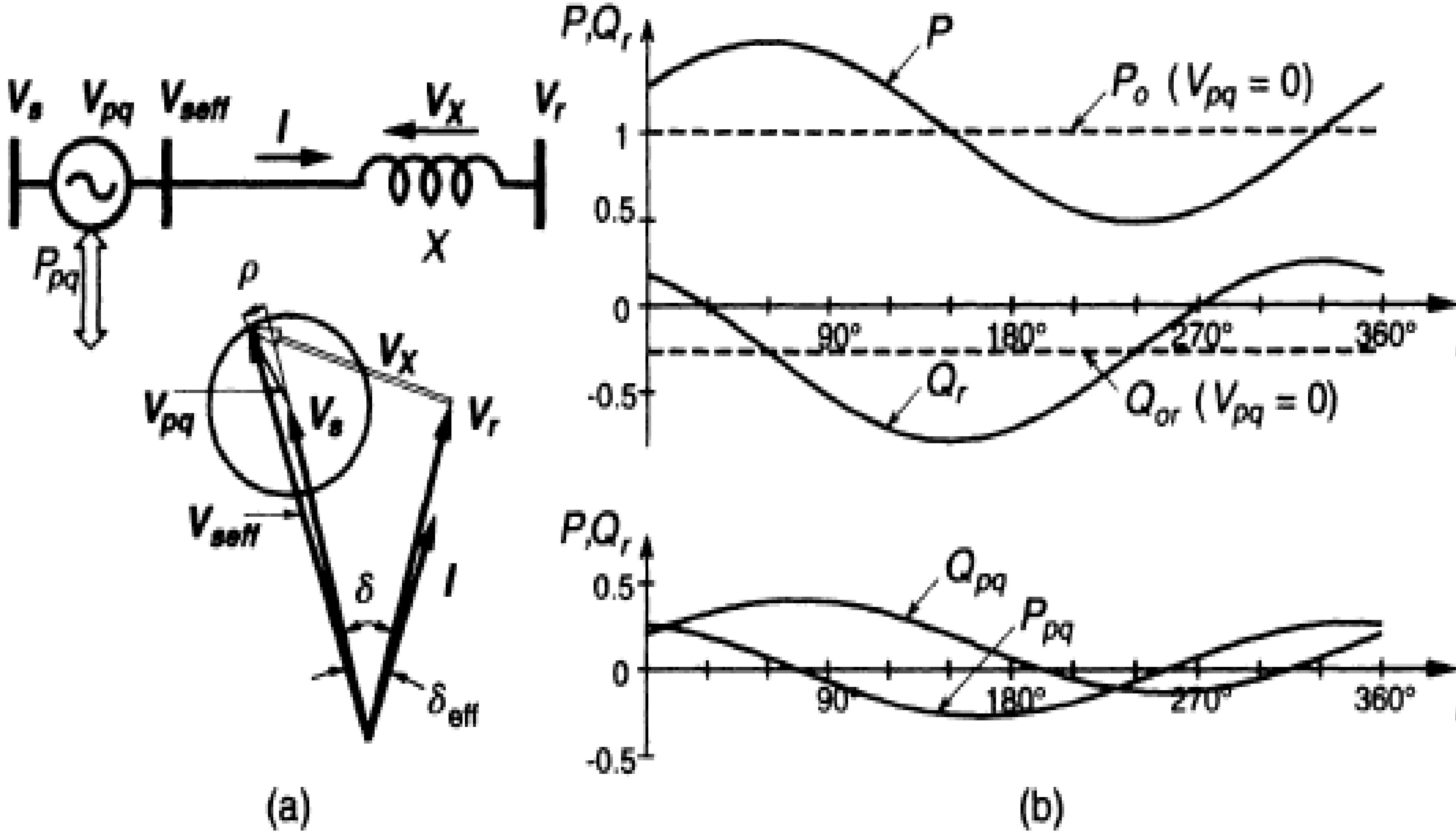


Figure 5 Phasor diagram representation of the UPFC (a) and variation of the receiving-end real and reactive power, and the real and reactive power supplied by the UPFC, with the angular rotation of the injected voltage phasor (b).

- A phasor diagram, defining the relationship between Vs, Vr, Vx (the voltage phasor across X) and the inserted voltage phasor Vpq , with controllable magnitude ($0 \leq Vpq \leq Vpqmax$) and angle ($0 \leq Ppq \leq 360°$), is shown in Figure 5 (a). (For the illustrations, $\delta = 30°$ and V s = V, = 1, X = 0.5, Vpqmax = 0.25 p.u. values were assumed.)
- As illustrated, the inserted voltage phasor Vpq is added to the fixed sending-end voltage phasor Vsto produce the effective sending-end voltage V_{seff} = Vs+ Vpq.
- The difference, V_{seff} - Vr provides the compensated voltage phasor, Vx , across X.
- As angle Ppq is varied over its full 360 degree range, the end of phasor Vpq moves along a circle with its center located at the end of phasor Vs.
- The area within this circle, obtained with Vpqmax, defines the operating range of phasor Vpq and thereby the achievable compensation of the line.
- The rotation of phasor Vpq with angle Ppq modulates both the magnitude and angle of phasor Vx and, therefore, both the transmitted real power, P, and the reactive power, Q" vary with Ppq in a sinusoidal manner, as illustrated in Figure 5 (b).
- This process, of course, requires the voltage source (Vpq) to supply and absorb both reactive and real power, Qpq and Ppq , which are also sinusoidal functions of angle Ppq, as shown in the figure.

Independent Real and Reactive Power Flow Control

- In order to investigate the capability of the UPFC to control real and reactive
- power flow in the transmission line, refer to Figure 5(a).
- Let it first be assumed that the injected compensating voltage, Vpq is zero.
- Then the original elementary two machine (or two-bus ac intertie) system with sending-end voltage Vs receiving-end voltage Vr transmission angle δ, and line impedance X is restored.
- With these, the normalized transmitted power, Po(δ) = $\{V^2$/X} sin δ = sin δ, and the normalized reactive power, Qo(δ) = Qas(δ) = -Qo,(δ) = $\{V^2$/X}{I - cos δ} = I-cos δ, supplied at the ends of the line, are shown plotted against angle (δ) in Figure 6(a).
- The relationship between real power Po(δ) and reactive power Qo,(δ) can readily be expressed with V^2/X = 1 in the following form:

$$Q_{0r}(\delta) = -1 - \sqrt{1 - \{P_0(\delta)\}^2} \qquad \text{-------1}$$

$$\{Q_{0r}(\delta) + 1\}^2 + \{P_0(\delta)\}^2 = 1 \qquad \text{--------2}$$

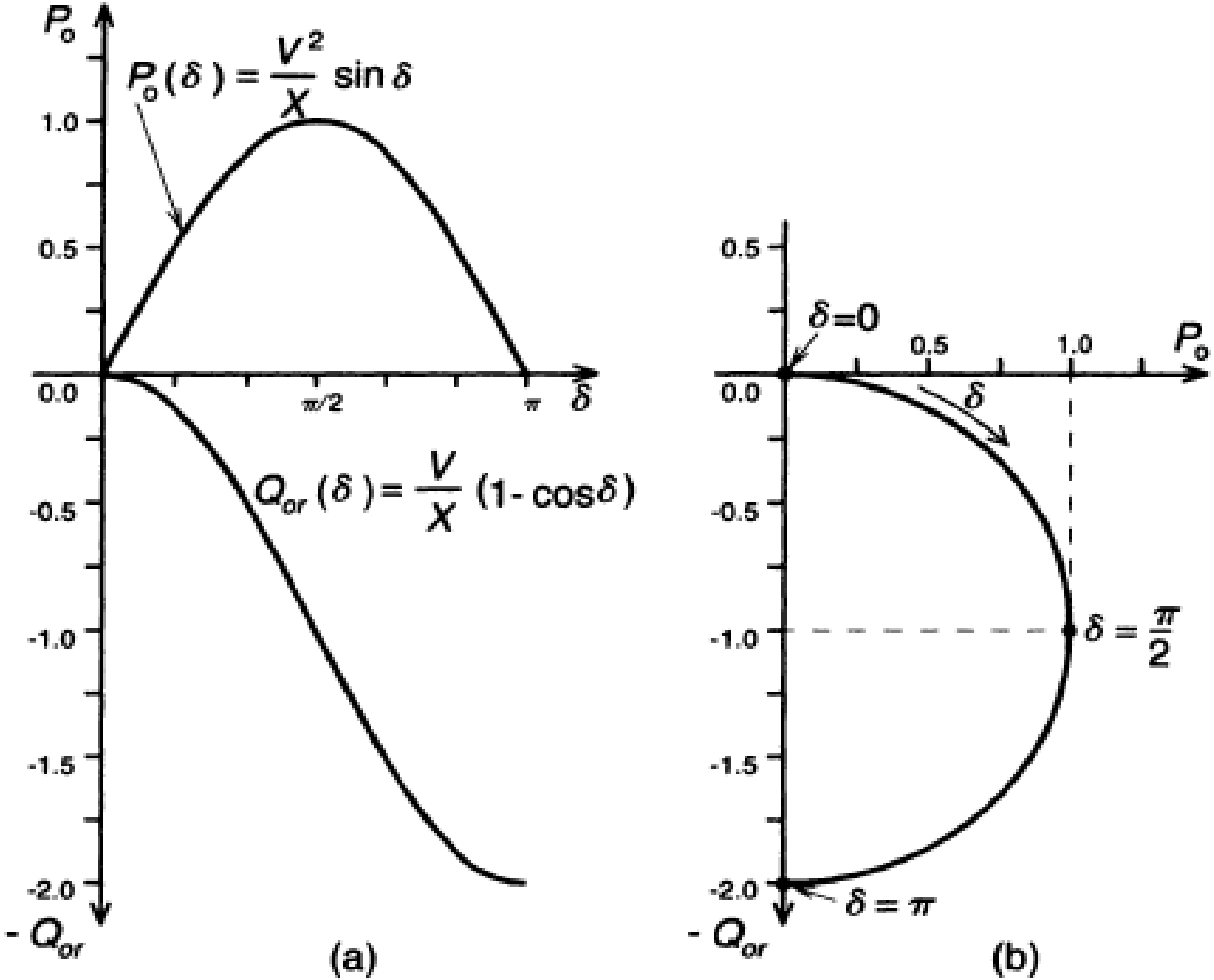


Figure 6 Transmittable real power Poand receiving-end reactive power demand Qorvs. transmission angle 8 of a two-machine system (a) and the corresponding Qor vs. Po loci (b).

- Equation (8.14) describes a circle with a radius of 1.0 around the center defined by coordinates P = 0 and Qr = -1 in a {Qr,P} plane, as illustrated for positive values of ρ in Figure 6(b).
- Each point of this circle gives the corresponding Po and Qor values of the uncompensated system at a specific transmission angle δ.
- For example, at δ = 0, Po = 0 and Qor = 0; at δ = 30°, Po = 0.5 and Qor = -0.134; at δ = 90°, Po = 1.0 and Qor = -1.0; etc
- Refer again to Figure 5(a) and assume now that Vpt ≠0. It follows from fig (1),
- or (5) and (6), and from Figure 85 (b), that the real and reactive power change from their uncompensated values, Po(δ) and Qor(δ), as functions of the magnitude Vpq and angle ρ of the injected voltage phasor Vpq.
- Since angle p is an unrestricted variable .($0 \leq p \leq 2\,\pi$), the boundary of the attainable control region for P(δ, ρ) and Q,(δ, ρ) is obtained from a complete rotation of phasor Vpq with its maximum magnitude Vpqmuax.
- It follows from the above equations that this control region is a circle with a center defined by coordinates Po(δ) and Qo,(δ) and a radius of VrVpq/X.
- With Vs = Vr = V, the boundary circle can be described by the following equation

$$\{P(\delta,\rho) - P_0(\delta)\}^2 + \{Q_r(\delta,\rho) - Q_{0r}(\delta)\}^2 = \left\{\frac{VV_{pqmax}}{X}\right\}^2$$

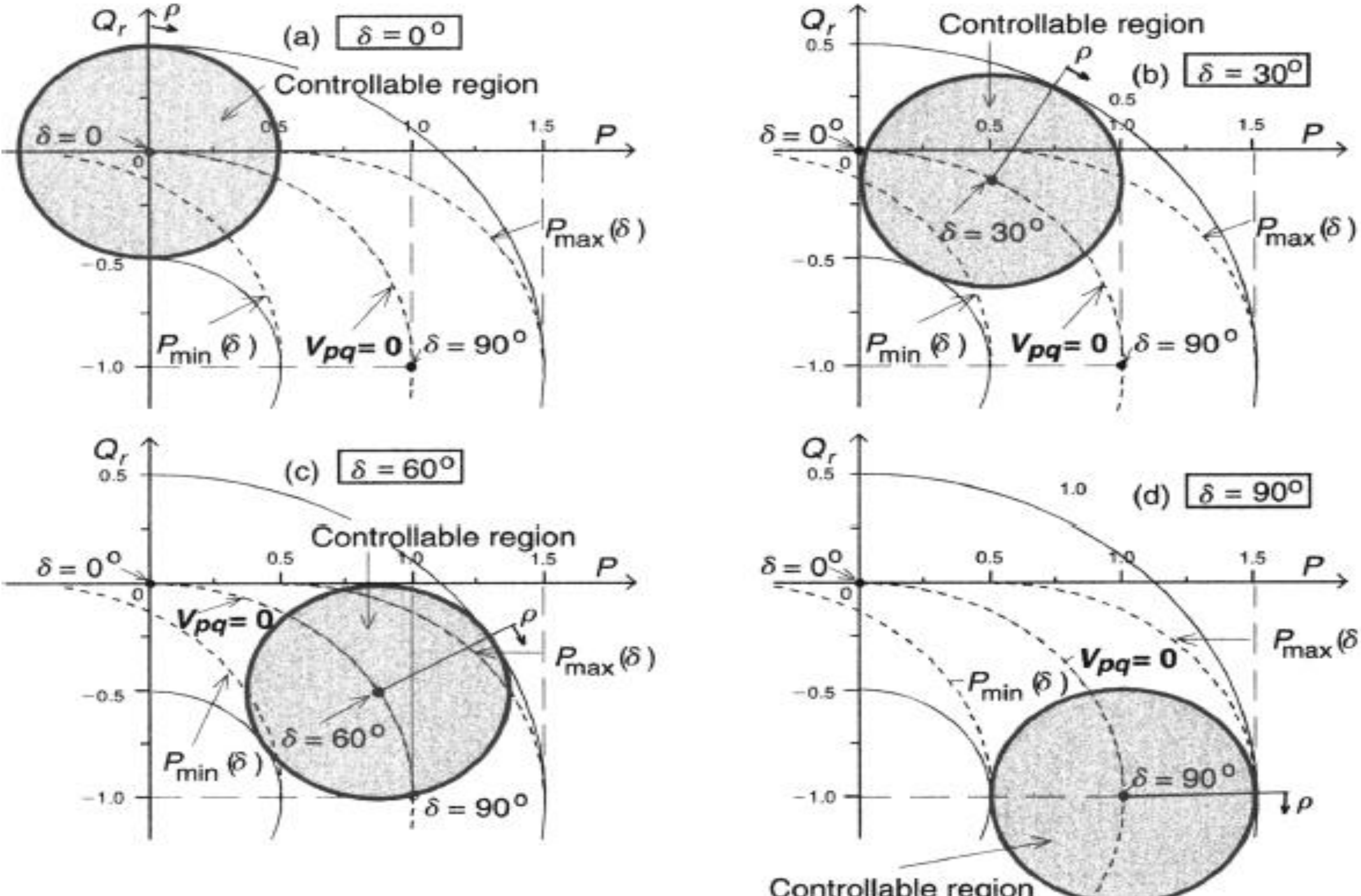


Figure 7 Control region of the attainable real power P and receiving-end reactive power demand Q, with a UPFC-controlled transmission line at δ = 0° (a), δ = 30 deg (b), δ = 60° (c), and δ = 90° (d).

- The circular control regions defined are shown in Figures 7(a) through (d) for V = 1.0, Vpqmax = 0.5, and X = 1.0 (per unit or p.u. values) with their centers on the circular arc characterizing the uncompensated system at transmission angles $\delta = 0°, 30°, 60°$, and $90°$. In other words, the centers of the control regions are defined
- Consider first Figure 7 (a), which illustrates the case when the transmission angle is zero ($\delta = 0$). With Vpq = 0, P, Qr (and Qs) are all zero, i.e., the system is at standstill at the origin of the Qr, P coordinates. The circle around the origin of the {Qr, P} plane is the loci of the corresponding Q, and P values, obtained as the voltage phasor Vpq is rotated a full revolution ($0 \leq P \leq 360°$) with its maximum magnitude
- Vpqmax.
- The area within this circle defines all P and Q, values obtainable by controlling the magnitude Vpq and angle p of phasor Vpq.
- In other words, the circle in the {Qr, P} plane defines all P and Q, values attainable with the UPFC of a given rating.
- It can be observed, for example, that the UPFC with the stipulated voltage rating of 0.5 p.u. is able to establish 0.5 p.u. power flow, in either direction, without imposing any reactive power demand on either the sending-end or the receiving-end generator.
- (This statement tacitly assumes that the sending-end and receiving-end voltages are provided by independent power systems which are able to supply and absorb real power without any internal angular change.)

- Of course, the UPFC, as illustrated, can force the system at one end to supply reactive power for, or absorb that from, the system at the other end. Similar control characteristics for real power P and the reactive power Qr can be observed at angles $\delta = 30°, 60°$, and 90° in Figures 7(b), (c), and (d).
- In general, at any given transmission angle δ, the transmitted real power *P,* as well as the reactive power demand at the receiving end *Qr* can be controlled freely by the UPFC within the boundary circle obtained in the *{Qr, P}* plane by rotating the injected voltage phasor *Vpq* with its maximum magnitude a full revolution.
- Furthermore, it should be noted that, although the above presentation focuses on the receiving end reactive power, *Qr* the reactive component of the line current, and the corresponding reactive power can actually be controlled with respect to the voltage selected at any point of the line.
- Figures 7(a) through (d) clearly demonstrate that the UPFC, with its unique capability to control independently the real and reactive power flow at any transmission angle, provides a powerful, hitherto unattainable, new tool for transmission system control.