SUBJECT: POWER SYSTEM OPERATION AND CONTROL

Automatic Generation Control in interconnected Power system (continued): State-Space Model for Two - Area System, Tie-Line Oscillations, Related Issues in Implementation of AGC.

Voltage and Reactive Power Control: Introduction, Production and Absorption of Reactive Power, Methods of Voltage Control, Dependence of Voltage on Reactive Power , Sensitivity of Voltage to Changes in P And Q, Cost Saving, Methods of Voltage Control by Reactive Power Injection, Voltage Control Using Transformers, Voltage Stability.

Revised Bloom's Taxonomy Level L3 – Applying.

State-Space Model for Two - Area System

STATE SPACE MODEL OF TWO AREA THERMAL (REHEAT) POWER SYSTEM:

The state variables are a minimum set of variables which contain sufficient information about the past history with which all future states of the system can be determined for known control inputs. The state space model of two area thermal (reheat) power system, with full state feedback (11 state feedback) has been developed as shown in Fig.1

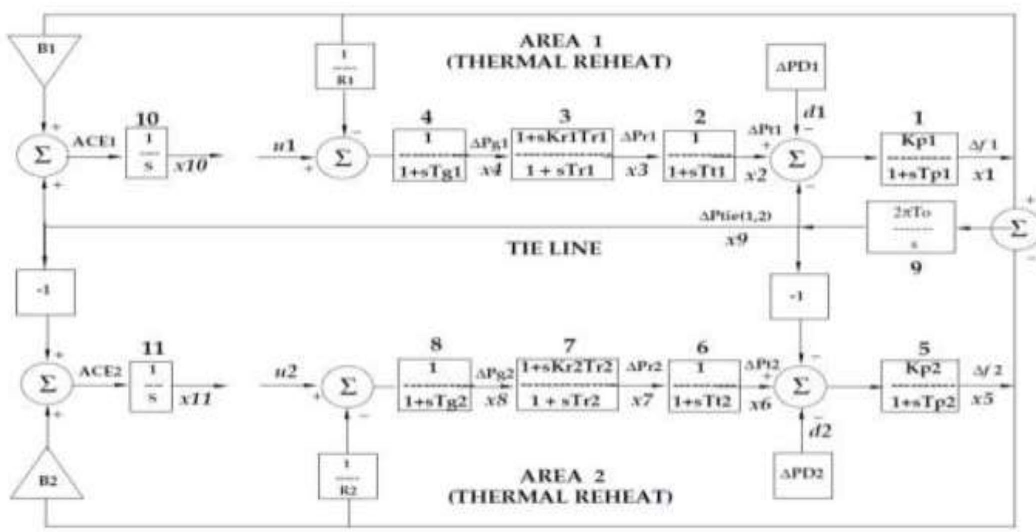


Fig.1: State Space model of two-area thermal (reheat) power system

For the Two area system,

State variables:

Area-1 Area-2

$x1 = \Delta f1$ $x5 = \Delta f2$

$x2 = \Delta Pt1$ $x6 = \Delta Pt2$

$x3 = \Delta Pr1$ $x7 = \Delta Pr2$

$x4 = \Delta Pg1$ $x8 = \Delta Pg2$

$x10 = \int ACE1dt$ $x11 = \int ACE2dt$

$x9 = \Delta Ptie(1,2)$

For Block 1:

$$x_1 + T_{P1}\dot{x}_1 = K_{P1}(x_2 - x_9 - d_1)$$
$$\text{i.e., } \dot{x}_1 = -\frac{1}{T_{P1}}x_1 + \frac{K_{P1}}{T_{P1}}x_2 - \frac{K_{P1}}{T_{P1}}x_9 - \frac{K_{P1}}{T_{P1}}d_1$$

For Block 2:

$$x_2 + Tt_1\dot{x}_2 = x_3$$
$$\text{i.e., } \dot{x}_2 = -\frac{1}{Tt_1}x_2 + \frac{1}{Tt_1}x_3$$

For Block 3:

$$x_3 + Tr_1\dot{x}_3 = x_4 + Kr_1Tr_1\dot{x}_4$$
$$\text{i.e., } \dot{x}_3 = -\frac{1}{Tr_1}x_3 + \frac{1}{Tr_1}x_4 + Kr_1\left(\frac{-1}{R_1Tg_1}x_1 - \frac{1}{Tg_1}x_4 + \frac{1}{Tg_1}u_1\right)$$
$$\text{i.e., } \dot{x}_3 = -\frac{Kr_1}{R_1Tg_1}x_1 - \frac{1}{Tr_1}x_3 + \left(\frac{1}{Tr_1} - \frac{Kr_1}{Tg_1}\right)x_4 + \frac{Kr_1}{Tg_1}u_1$$

For Block 4:

$$x_4 + Tg_1\dot{x}_4 = \frac{-1}{R_1}x_1 + u_1$$
$$\text{i.e., } \dot{x}_4 = \frac{-1}{R_1Tg_1}x_1 - \frac{1}{Tg_1}x_4 + \frac{1}{Tg_1}u_1$$

For Block 5:

$$x_5 + T_{P2}\dot{x}_5 = K_{P2}(x_6 + x_9 - d_2)$$

$$\text{i.e., } \dot{x}_5 = -\frac{1}{T_{P2}}x_5 + \frac{K_{P2}}{T_{P2}}x_6 + \frac{K_{P2}}{T_{P2}}x_9 - \frac{K_{P2}}{T_{P2}}d_2$$

For Block 6:

$$x_6 + Tt_2\dot{x}_6 = x_7$$

$$\text{i.e., } \dot{x}_6 = -\frac{1}{Tt_2}x_6 + \frac{1}{Tt_2}x_7$$

For Block 7:

$$x_7 + Tr_2\dot{x}_7 = x_8 + Kr_2Tr_2\dot{x}_8$$

$$\text{i.e., } \dot{x}_7 = -\frac{1}{Tr_2}x_7 + \frac{1}{Tr_2}x_8 + Kr_2\left(-\frac{1}{R_2Tg_2}x_5 - \frac{1}{Tg_2}x_8 + \frac{1}{Tg_2}u_2\right)$$

$$\text{i.e., } \dot{x}_7 = -\frac{Kr_2}{R_2Tg_2}x_5 - \frac{1}{Tr_2}x_7 + \left(\frac{1}{Tr_2} - \frac{Kr_2}{Tg_2}\right)x_8 + \frac{Kr_2}{Tg_2}u2$$

For Block 8:

$$x_8 + Tg_2\dot{x}_8 = -\frac{1}{R_2}x_5 + u_2$$

$$\text{i.e., } \dot{x}_8 = -\frac{1}{R_2Tg_2}x_5 - \frac{1}{Tg_2}x_8 + \frac{1}{Tg_2}u_2$$

For Block 9:

$$\dot{x}_9 = 2\pi T^0 x_1 - 2\pi T^0 x_5$$

For Block 10:

$$\dot{x}_{10} = B_1x_1 + x_9$$

For Block 11:

$$\dot{x}_{11} = B_2 x_5 - x_9$$

The above state equations of the two-area system can be represented in matrix form as

$\dot{x} = Ax + Bu$,

where A = (11x11)system matrix having constant coefficients

and B = (11x2) input or control matrix having constant coefficients

$$A = \begin{bmatrix} \frac{-1}{T_{P1}} & \frac{K_{P1}}{T_{P1}} & 0 & 0 & 0 & 0 & 0 & 0 & \frac{-K_{P1}}{T_{P1}} & 0 & 0 \\ 0 & \frac{-1}{Tt_1} & \frac{1}{Tt_1} & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ \frac{-Kr_1}{R_1 Tg_1} & 0 & \frac{-1}{Tr_1} & \left(\frac{1}{Tr_1} - \frac{Kr_1}{Tg_1}\right) & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ \frac{-1}{R_1 Tg_1} & 0 & 0 & \frac{-1}{Tg_1} & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & \frac{-1}{T_{P2}} & \frac{K_{P2}}{T_{P2}} & 0 & 0 & \frac{K_{P2}}{T_{P2}} & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & \frac{-1}{Tt_2} & \frac{1}{Tt_2} & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & \frac{-Kr_2}{R_2 Tg_2} & 0 & \frac{-1}{Tr_2} & \left(\frac{1}{Tr_2} - \frac{Kr_2}{Tg_2}\right) & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & \frac{-1}{R_2 Tg_2} & 0 & 0 & \frac{-1}{Tg_2} & 0 & 0 & 0 \\ 2\pi T^0 & 0 & 0 & 0 & -2\pi T^0 & 0 & 0 & 0 & 0 & 0 & 0 \\ B_1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & B_2 & 0 & 0 & 0 & -1 & 0 & 0 \end{bmatrix}; B = \begin{bmatrix} 0 & 0 \\ 0 & 0 \\ \frac{K_{r1}}{Tg_1} & 0 \\ \frac{1}{Tg_1} & 0 \\ 0 & 0 \\ 0 & 0 \\ 0 & \frac{Kr_2}{Tg_2} \\ 0 & \frac{1}{Tg_2} \\ 0 & 0 \\ 0 & 0 \\ 0 & 0 \end{bmatrix}$$

$$\textbf{State Vector (x)} = \begin{bmatrix} x_1 & x_2 & x_3 & x_4 & x_5 & x_6 & x_7 & x_8 & x_9 & x_{10} & x_{11} \end{bmatrix}^T$$

$$\textbf{Control Vector (u)} = \begin{bmatrix} u_1 \\ u_2 \end{bmatrix}$$

Related Issues in Implementation of AGC

Implementation of "Regulation" Ancillary Service in India through Automatic Generation Control (AGC):

In order to achieve constant frequency in Indian Grid and for large scale RE integration, operationalization of spinning reserves is essential and to be implemented at the earliest. As off now, there is no control system which can regulate the power generation to match minute to minutes balancing of Net Load. Manual Tertiary control through scheduling, forecasting and recently introduced Reserve Regulation Ancillary Services (RRAS) can reduce the band of frequency fluctuation but cannot achieve Target frequency of 50 Hz. Moreover, break even frequencies of different plants as per frequency linked Deviation Settlement Mechanism (DSM) will always try to deviate from the ultimate target frequency of 50 Hz.

Pilot Project Taken up at Dadri Stage-II:

Reason for Pilot at NTPC Dadri Stg-II

- Dadri Stage II power plant is located near Delhi.
- It is easy to visit and monitor the field level implementation process.
- The variable cost of the power plant is fairly high (of the order of 300-350 paise/kWh) than other thermal plants in Northern Region
- Load center plant
- Easy and economical to keep Spinning Reserves

Implementation Philosophy for AGC Pilot

The AGC system has been installed at NLDC control center. The purpose of this AGC system is to communicate the setpoints calculated for the Generating Units those are modeled in the mentioned AGC system. The Generating Units which are considered for the pilot implementation are from Dadri Power Plant Stage-2 Unit 5 & 6. The main purpose of the supplied AGC system is to calculate the Area Control Error for the considered control area of Northern Region and to distribute this ACE (based on pre-decided methodology) to the respective generating units i.e. Unit 5 & 6. The AGC system will use its Load Frequency Control (LFC) module to calculate the ACE and to distribute its unit specific control error to respective unit. The ACE calculated by LFC is on the basis of Area Interchange and Frequency signal received from NLDC SCADA system.

The calculated setpoints at the NLDC AGC system is transferred to Control Logic Unit at the Dadri Generation Plant over IEC104 protocol and further it is transferred to Unit DCS systems.

The scope of the work included communicating the setpoints to Dadri Generation Plant. In order to enable LFC to calculate ACE following real-time data are required:

From the SCADA/EMS system at NLDC Control Center:

- Real-time Analog Data for the Tie-Lines which are modeled in AGC
- Real-Time CB status for the Tie-Lines which are modeled in AGC
- Total Area Generation in considered Control Area
- Total Load Calculated for considered Control Area

Key challenges to Providers of AGC:

DSM management: DSM in its present form will be very difficult to manage. RGMO response are leading to high deviation from schedule. Changes in the prescription of both DSM & RGMO shall be in the offing.

Flexibility in Generation:

Essentially all generators can profit by selling ancillary services. Generators with greater flexibility can profit more than less flexible units. Flexibility of conventional generation: A plethora of challenges can be identified posing impediment to grid frequency control and the same could be more challenging in future while integrating RE sources in larger scale with penetration level more than 30-40%.

a) Technical: Cyclic operation / Load Ramping capabilities of machines of different age and technology

will pose difficulties in dealing with the impact of RE generation variation.

b) Commercial challenges of flexing conventional generation: It throws challenges on overall cycling cost compared to commonly assumed costs.

i) It increases maintenance and overall O&M expenses.

ii) Affects forced outage numbers and outage time.

iii) Cost of increased Heat rates, long term efficiencies

and efficiencies at low / variable loads.

iv) Cost of startup fuels, auxiliary power, and manpower cost

etc. all increases. Increased cost of generation will affect our merit order position in the highly

competitive power market.

c) Infrastructural challenges to participate in ancillary services like regulation and ‘Net Load following’ services through Automatic Generation Control (AGC).

d) Cheap Gas availability is a key issue in flexing gas plants generation.

e) Lack of Energy Storage capacities: NTPC do not have energy storage capacities in its portfolio.

Non availability of storage capacity will put pressure on flexing of conventional generation.

- This “wear and tear” cost depends on plant design, operation, maintenance, and repair history.
- Determining the wear and tear cost therefore requires significant investigation and analysis.
- Cycling and ramping of fossil-fueled generators also affect emissions and may result in higher emissions rates than steady-state operation.

a) Heat rates typically degrade at partial load.

b) NOX and SOX rates are also affected by loading. Startup emissions of CO_2, NOX, and SO_2 may be significantly higher than steady-state emissions rates.

c) Ramp ups in power output may also result in higher than steady-state emissions.

Control of Voltage and Reactive Power

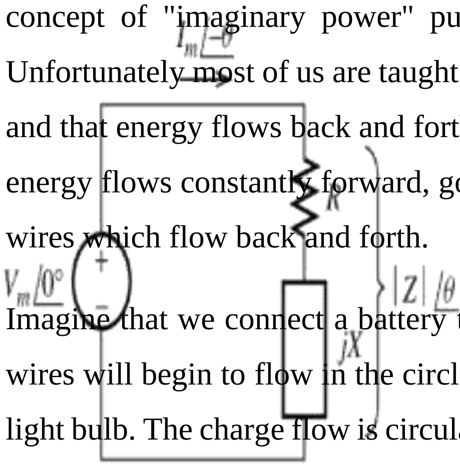
Reactive power is an odd topic in AC (Alternating Current) power systems, and it's usually explained with vector mathematics or phase-shift sine wave graphs. However, a non-math verbal explanation is possible.

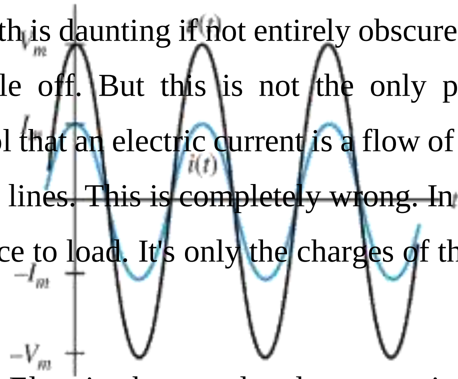
Note that Reactive power only becomes important when an "electrical load" or a home appliance contains coils or capacitors. If the electrical load behaves purely as a resistor, (such as a heater or incandescent bulb for example,) then the device consumes "real power" only. Reactive power and "power factor" can be ignored, and it can be analysed using an AC version of Ohm's law.

Reactive power is simply this: when a coil or capacitor is connected to an AC power supply, the coil or capacitor stores electrical energy during one-fourth of an AC cycle. But then during the next quarter-cycle, the coil or capacitor dumps all the stored energy back into the distant AC power supply. Ideal coils and capacitors consume no electrical energy, yet they create a significant electric current. +12This is very different from a resistor which genuinely consumes electrical energy, and where the electrical energy flows continuously in one direction; moving from source to load.

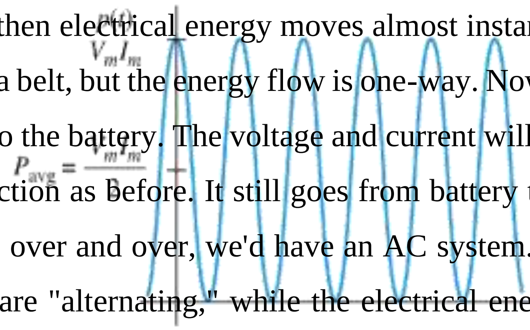
In other words, if your electrical appliance contains inductance or capacitance, then electrical energy will periodically return to the power plant, and it will flow back and forth across the power lines. This leads to an extra current in the power lines, a current which heats the power lines, but which isn't used to provide energy to the appliance. The coil or capacitor causes electrical energy to begin " sloshing" back and forth between the appliance and the distant AC generator. Electric companies must install heavier wires to tolerate the excess current, and they will charge extra for this "unused" energy. This undesired "energy sloshing" effect can be eliminated. If an electrical load contains both a coil and capacitor, and if their resonant frequency is adjusted to exactly 60Hz, then the coil and capacitor like magic will begin to behave like a pure resistor. The "energy sloshing" still occurs, but now it's all happening between the coil and capacitor, and not in the AC power lines. So, if your appliance contains a large coil induction motor, you can make the motor behave as a pure resistor, and reduce the current in the power lines by connecting the right value of capacitance across the motor coil.

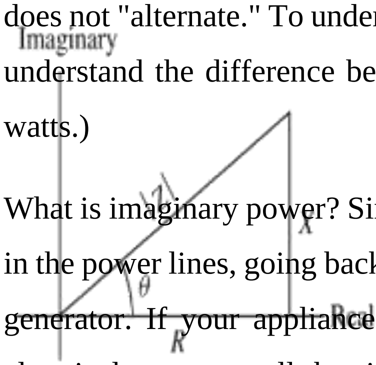
Why is reactive power so confusing? Well, the math is daunting if not entirely obscure and the concept of "imaginary power" puts many people off. But this is not the only problem. Unfortunately most of us are taught in grade school that an electric current is a flow of energy, and that energy flows back and forth in AC power lines. This is completely wrong. In fact the energy flows constantly forward, going from source to load. It's only the charges of the metal wires which flow back and forth.





Imagine that we connect a battery to a light bulb. Electric charges already present inside the wires will begin to flow in the circle, and then electrical energy moves almost instantly to the light bulb. The charge flow is circular like a belt, but the energy flow is one-way. Now imagine that we suddenly reverse the connections to the battery. The voltage and current will reverse... but the energy still flows in the same direction as before. It still goes from battery to bulb. If we keep reversing the battery connections over and over, we'd have an AC system. So, in an AC system, only the voltage and current are "alternating," while the electrical energy flows one-way, going from source to load. Where AC resistive loads are concerned, electrical energy does not "alternate." To understand energy flow in AC systems, it's critically important that we understand the difference between charge flow (current, amperes) and energy flow (power, watts.)





What is imaginary power? Simple: it's the unused power which flows backwards and forwards in the power lines, going back and forth between the load's coil or capacitor and the distant AC generator. If your appliance was a pure capacitor or inductor, then it would consume no electrical energy at all, but instead all the flowing energy would take the form of "sloshing energy," and we'd call it "imaginary power." Of course it's not actually imaginary. Instead it's reflected by the load.

What is real power? Even more simple: it's the energy flow which goes continuously from the AC generator and into the appliance, without any of it returning back to the distant generator.

Finally, what is "reactive" power? It's just the combination of the above two ideas: it is the continuous-forward-moving or "real" energy flow, combined with the sloshing or "imaginary" energy flow.

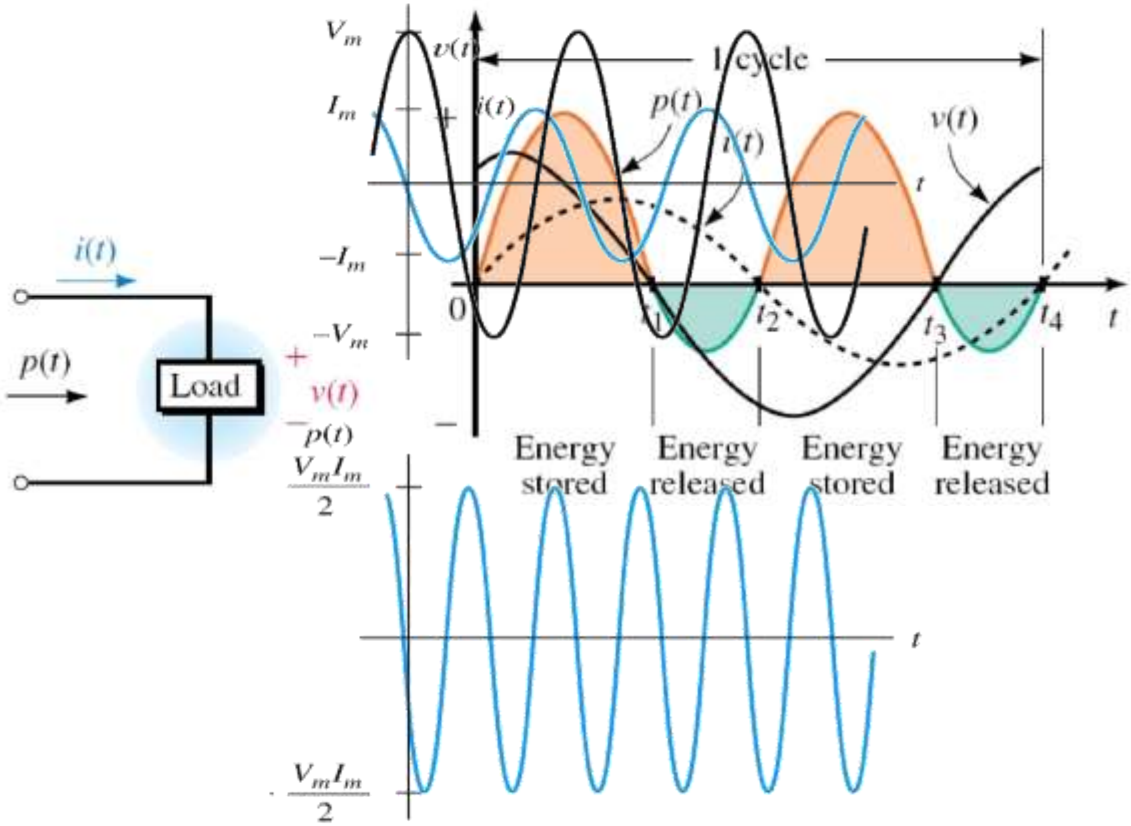
Power in A.C. Networks Active Power

Reactive Power Apparent Power

Power Factor (p.f.) Power Factor Correction

Instantaneous power, $p(t) = v(t)i(t)$ Power, $p(t)$ value
positive – power transmit/dissipate by load *negative*
power return from the load

Since p(t) is power transmits by load, then it is the average power, P at load Sometimes P is also known as *active power, real power* or *true power* measured in unit of Watts.



i(t)
p(t)
Load
+
v(t)
−
V_m
I_m
$-I_m$
$-V_m$
v(t)
i(t)
p(t)
1 cycle
0
t_1
t_2
t_3
t_4
t
Energy stored
Energy released
Energy stored
Energy released
$\frac{V_m I_m}{2}$
$-\frac{V_m I_m}{2}$

ACTIVE POWER

Z = R (purely resistive)

P = VI = I R = V /R (Watt)

REACTIVE POWER

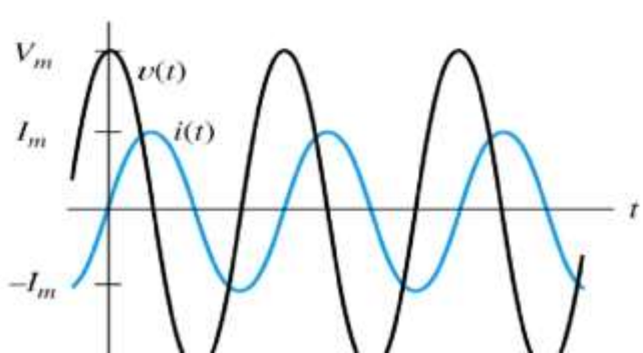
Z = jX L (inductive)

Instantaneous power $p(t) = v(t)i(t) = VI \sin 2\omega t$

Average power is zero

The product of VI is called reactive power (Q_L) with unit Volt-Amp

Reactive (VAR) $Q_L = VI = I^2X_L = V^2/X_L$



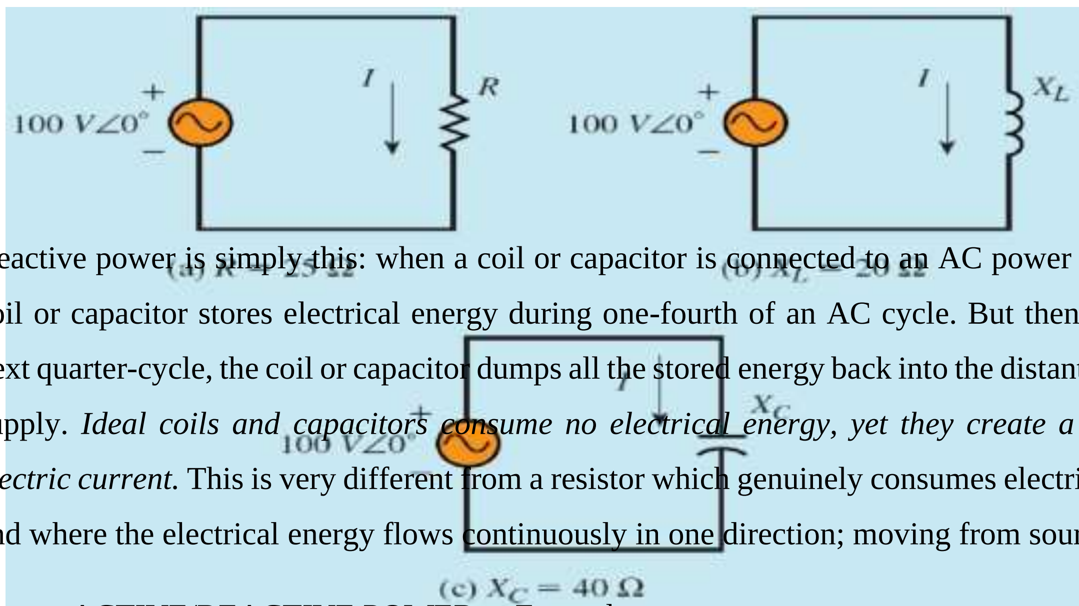
$Z_C = -jX$ (capacitive)

Reactive power (capacitive) $Q_C = VI = I\ X_C = V\ /X_C$ (VAR)

Note:

To distinguish between inductive reactive power (Q_L) and capacitive reactive power (Q_C), we use two different signs (+ or –) depending on our reference (i or v), for example jQ_L and $-jQ_C$ or otherwise.

Note that Reactive power only becomes important when an "electrical load" or a home appliance contains coils or capacitors. If the electrical load behaves purely as a resistor, (such as a heater or incandescent bulb for example,) then the device consumes "real power" only. Reactive power and "power factor" can be ignored,



Reactive power is simply this: when a coil or capacitor is connected to an AC power supply, the coil or capacitor stores electrical energy during one-fourth of an AC cycle. But then during the next quarter-cycle, the coil or capacitor dumps all the stored energy back into the distant AC power supply. *Ideal coils and capacitors consume no electrical energy, yet they create a significant electric current.* This is very different from a resistor which genuinely consumes electrical energy, and where the electrical energy flows continuously in one direction; moving from source to load.

ACTIVE/REACTIVE POWER – Example

I = 100 V/25 Ω = 4 A, $P = VI$ = (100 V)(4 A) = 400 W,

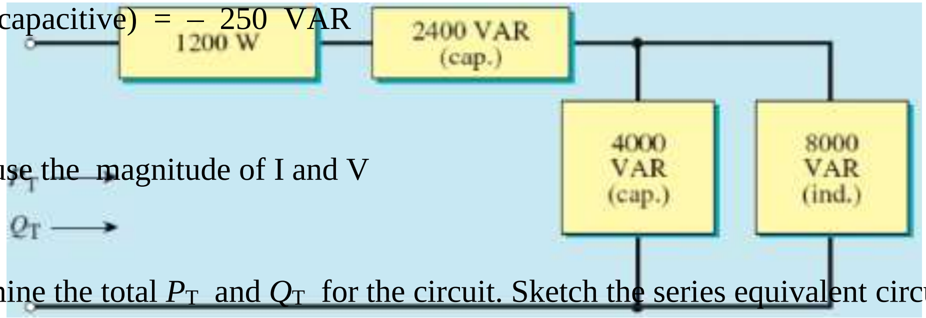
= 0 VAR

I = 100 V/20 Ω = 5 A, $P = 0$, $Q_L = VI$ = (100 V)(5 A) =

500 VAR (inductive)

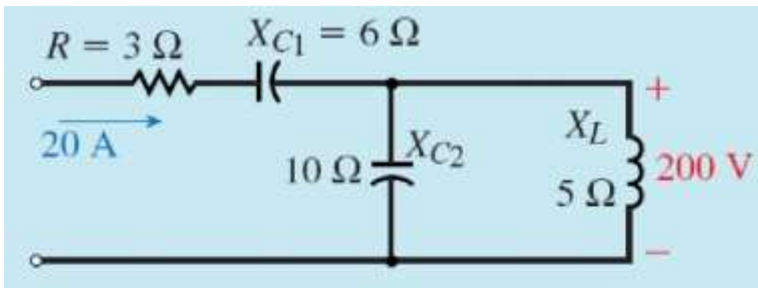
I = 100 V/40 Ω = 2.5 A, $P = 0$, $Q_C = VI$ = (100 V)(2.5) =

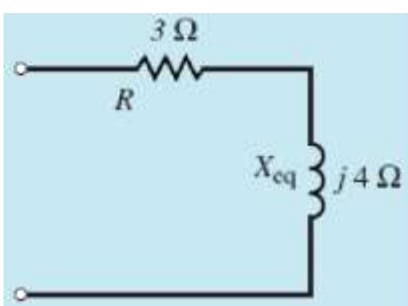
VAR (capacitive) = – 250 VAR

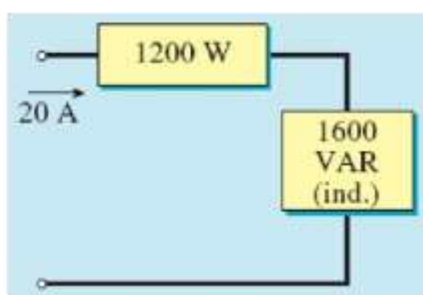


<u>Note:</u> use the magnitude of I and V

Determine the total P_T and Q_T for the circuit. Sketch the series equivalent circuit.







$$P = I^2R = (20\ \text{A})^2(3\ \Omega) = 1200\ \text{W}$$

$$Q_{C_1} = I^2X_{C_1} = (20\ \text{A})^2(6\ \Omega) = 2400\ \text{VAR (cap.)}$$

VAR (cap.)

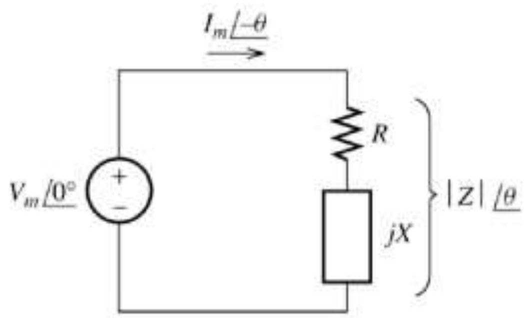
$$Q_{C_2} = \frac{V_2^2}{X_{C_2}} = \frac{(200\ \text{V})^2}{(10\ \Omega)} = 4000\ \text{VAR (cap.)}$$

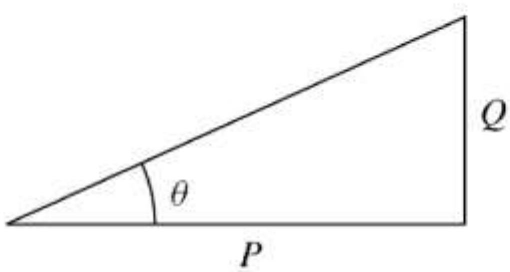
(cap.)

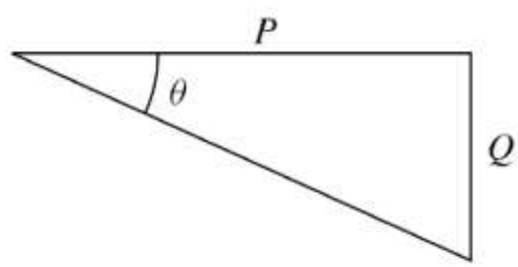
$$Q_L = \frac{V_2^2}{X_L} = \frac{(200\ \text{V})^2}{(5\ \Omega)} = 8000\ \text{VAR (ind.)}$$

APPARENT POWER

For load consisting of series resistance and reactance, $Z = R + \mathrm{j}\,X = \mathrm{Z}\ \underline{/\Delta\theta}$, the power produced is called *Apparent Power* or *Complex Power*), S or P_S with unit Volt-Amp (VA)







$S = P + jQ$

θ positive, inductive load

$S = P - jQ$

θ negative, capacitive load

$S = VI$ (VA)

$P = VI \cos\theta = I\ R = V_R\ /R$ (W)

$= S\ \cos\theta$ (W)

$Q = VI \sin\theta = I\ X = V_x\ /X$
(VAR) $= S \sin\theta$

$S = \sqrt{(P\ \ + Q\ )} = V\ I$

Power Triangle

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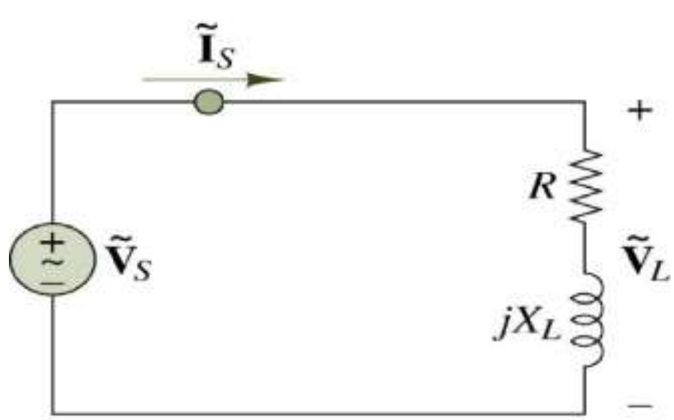
POWER FACTOR

Find the complex power for the circuit. Correct the circuit power factor to p.f. = 1 using parallel reactance.



Reactive Power is a Byproduct of Alternating Current (AC) Systems

• Transformers, transmission lines, and motors require reactive power

• Transformers and transmission lines introduce inductance as well as resistance (Both oppose the flow of current)

• Must raise the voltage higher to push the power through the inductance of the lines (Unless capacitance is introduced to offset inductance)

• The farther the transmission of power, the higher the voltage needs to be raised

• Electric motors need reactive power to produce magnetic fields for their operation Generation and Absorption of Reactive Power Synchronous Generators - Synchronous machines can be made to generate or absorb reactive power depending upon the excitation (a form of generator control) applied. The ability to supply reactive power is determined by the short circuit ratio.

Synchronous Compensators - Certain smaller generators, once run up to speed and synchronized to the system, can be declutched from their turbine and provide reactive power without producing real power.

Capacitive and Inductive Compensators - These are devices that can be connected to the system to adjust voltage levels. A capacitive compensator produces an electric field thereby generating reactive power An inductive compensator produces a magnetic field to absorb reactive power. Compensation devices are available as either capacitive or inductive alone or as a hybrid to provide both generation and absorption of reactive power.

Overhead Liines,, Underground Cablles and Transformers..

• Overhead lines and underground cables, when operating at the normal system voltage, both produce strong electric fields and so generate reactive power.

• When current flows through a line or cable it produces a magnetic field which absorbs reactive power.

• A lightly loaded overhead line is a net generator of reactive power while a heavily loaded line is a net **absorber of reactive power**. In the case of cables designed for use at 275 or 400kV the reactive power generated by the electric field is always greater than the reactive power absorbed by the magnetic field and so cables are always net generators of reactive power.

• Transformers always absorb reactive power.

Relation between voltage, Power and Reactive Power at a node

The phase voltage V at a node is a function of P and Q at that node.

i. e $V = f(P,Q)$

The voltage is also independent of adjacent nodes and assume that these

are infinite busses.

the total differential of V,

$dV = (\partial v/ \partial p) . dp + (\partial v/ \partial Q) . dQ$

and using the relation $(\partial p/ \partial v) . (\partial v/ \partial p) = 1$ and

$(\partial Q/ \partial v) . (\partial v/ \partial Q) = 1$

$dv = dp /(\partial p/ \partial v) + dQ / (\partial Q/ \partial v)$ ---------(1)

From the above equation it is seen that the change in voltage at a node

is defined by two quantities,

$(\partial p/ \partial v)$ and $(\partial Q/ \partial v)$

Normally ($\partial Q / \partial v$) is the quantity of greater interest and can be experimentally determined using Network Analyser by injecting known quantity of VARs at the node in question and measuring the difference in voltage produced.

Methods of voltage control

• By Reactive Power Injection

• By Tap Changing Transformers

• Combined use of Tap Changing Transformers and Reactive Power Injection

• Booster Transformers.

Reactive Power Injection

This is the most fundamental method and is used only in places where the transformer alone is not sufficient to control the voltage. since many years we use capacitors to improve the power factors of industrial loads. The injection of reactive power required for the power factor improvement is determined like this. A load of P 1 kw at a lagging power factor of cos_ 1 has a KVA of P 1 / cos δ 1. If this power factor is improved to cos δ **2**, the new KVA is P 1 / cos δ **2.**

The reactive power required from the capacitors is (P 1 tan δ 1 – P 1 tan δ **2) KVAr** Now the question is why the power factor is to be improved. What if the power is transmitted at non unity power factor. We all know very well that the voltage drop depends on reactive power (Q) while the load angle (or) power transmission angle (δ) depends on real power (P) At non unity power factors if the power is transmitted then it results in higher line currents which increases the $I^2 R$ losses and hence reduces the thermal capability. one of the ideal place for the injection of reactive power is at the loads itself.

Generally reactive power injections are of the following types.

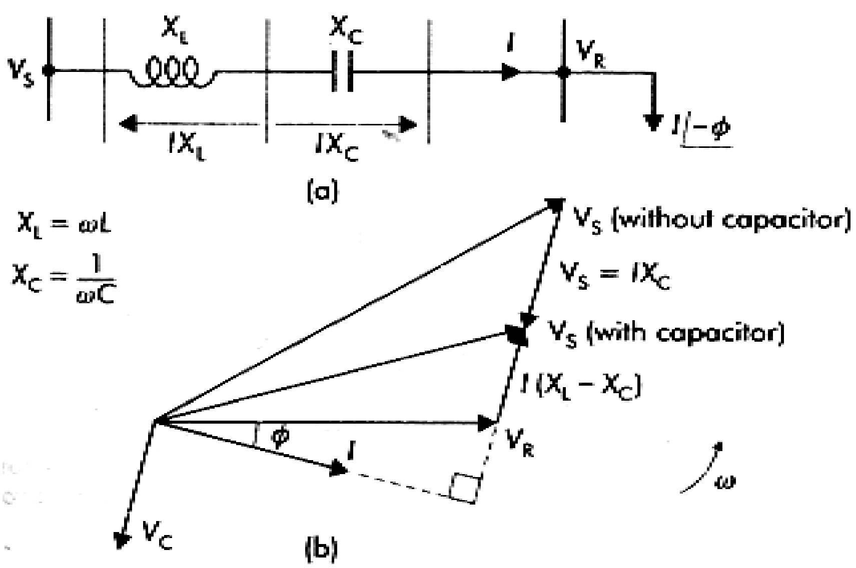
- **Static shunt capacitors**
- **Static series capacitors**
- **Synchronous compensators**

Shunt capacitors and Reactors:

shunt capacitors are used for lagging power factor circuits whereas shunt reactors are used for leading power factors that are created by lightly loaded cables. In both the cases the effect is to supply the required amount of reactive power to maintain the voltage. Capacitors are connected either directly to the bus bar or to

the tertiary winding of the main transformer and are distributed along the line to minimise the losses and the voltage drops. Now when the voltage drops, the vars produced by shunt capacitor or reactor falls, so when required most, the effectiveness of these capacitors or the reactors also falls. On the other hand, on light loads when the voltage is high, the capacitor output is large and the voltage tends to rise to excessive level, so some of the capacitors or reactors are to be switched out by over voltage relays. For fast control of voltages in power systems, switched capacitors in parallel with semiconductor controlled reactors are generally used to provide var compensation.

Series capacitors:



(a) Line with series capacitor, C load. (b) Phasor diagram for fixed V_R

Here the capacitors are connected in series with the line. The main aim is to reduce the inductive reactance between supply point and the load. The major disadvantage of the method is, whenever a short circuit current flows through the capacitor, protective devices like spark gaps and non linear resistors are to be incorporated. Phasor diagram for a line with series capacitor is shown in the figure (b).

Relative merits between shunt and series capacitors.

• If the load var requirement is small, series capacitors are of little help.

• If the voltage drop is the limiting factor, series capacitors are effective, also to some extent the voltage fluctuations can be evened.

• If the total line reactance is high, series capacitors are very effective and stability is improved.

• With series capacitors the reduction in line current is small, hence if the thermal considerations limits the current, little advantage is from this, so shunt compensation is to be used.

Synchronous compensators.

A synchronous compensator is a synchronous motor running without a mechanical load and depending on the excitation level, it can either absorb or generate reactive power. when used with a voltage regulator the compensator can

automatically run overexcited at times of high loads and under excited at light loads. A typical connection of a compensator is shown in the figure along with the associated voltage – var output characteristics.

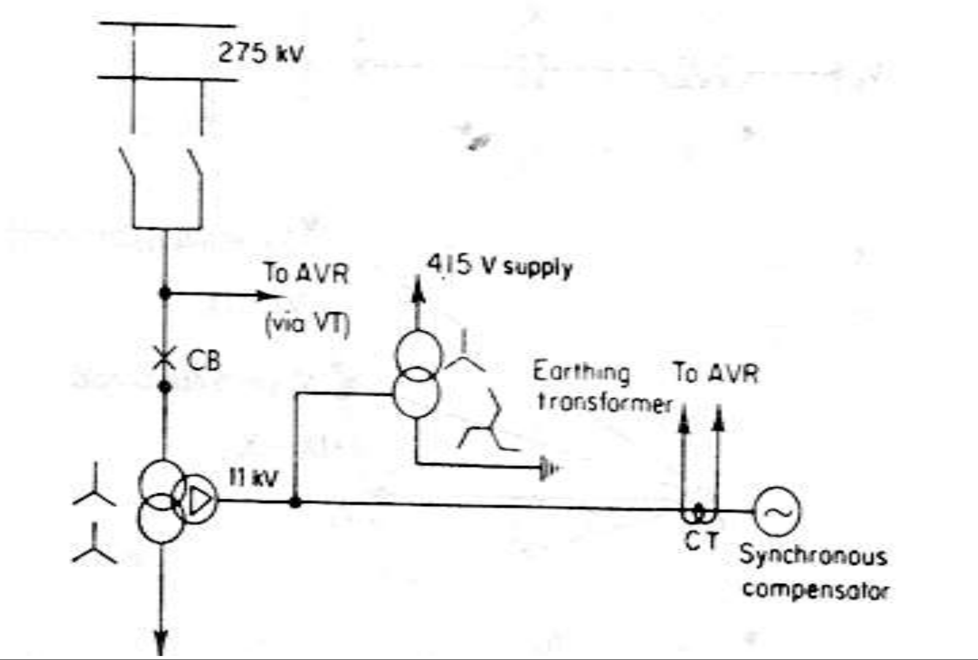


Fig: Typical Installation with synchronous compensator connected to tertiary (delta) winding of main transformer

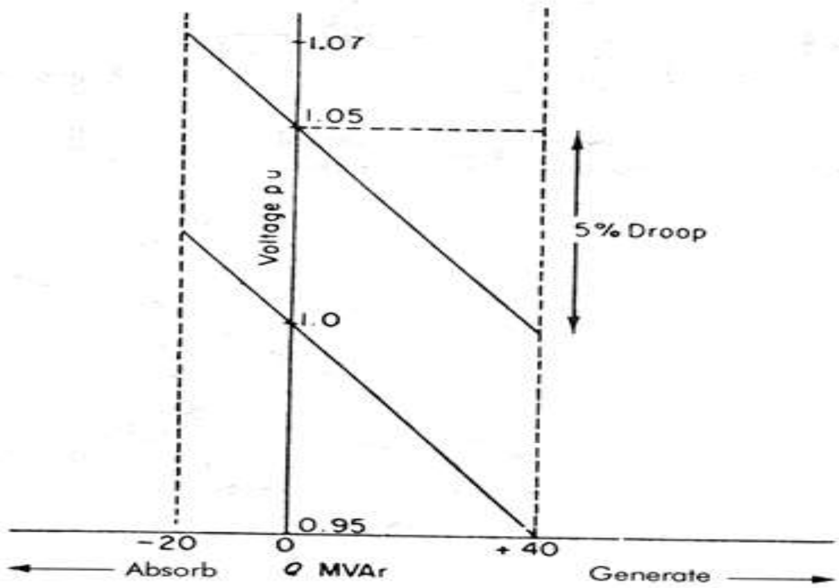


Fig: Voltage-reactive power output of a typical 40MVAr synchronous compensator

A great advantage of the method is the flexible operation for all load conditions.

• Being a rotating machine, its stored energy is useful for riding through transient disturbances, including voltage drops.

Sub Synchronous Resonance

Series capacitors are installed in series with long lines for providing compensation of reactive power and giving higher power transfer ability. Series compensated lines have a tendency to produce series resonance at frequencies lower than power frequencies. This is called **Sub Synchronous Resonance (SSR)** The sub synchronous resonance currents produce mechanical resonance in Turbo generator shafts, which causes the following in the generator shaft-

(i)Induction generator effect

(ii) torsional torques and (iii) transient torques.

These problems have resulted in damage to rotor shafts of turbine generators. Therefore the sub synchronous resonance is analysed in the design of series compensated lines. Now let us derive a relationship between the normal frequency and the sub synchronous resonance frequency.

Let fn be the normal frequency (synchronous) let fr be the sub synchronous frequency of series compensated line. 2_fn L be the series inductive reactance of EHV line at normal frequency. 1/2_fn C be the series capacitive reactance of series compensation at normal frequency.

K = Xc/X

L be the degree of compensation.

X = (XL – Xc) = XL(1 – K) is the equivalent reactance of the compensated line.

Let the SSR occur at a frequency fr. Then f2= (1/ 2_L) * (1/ 2_C)

(OR) (fr/ fn)2= Xc/XL=Kor **fr= fn*sqrt(K)**

Thus SSR occurs at a frequency fr which is the product of normal frequency and the root of the degree of compensation K. The condition of SSR can occur during the faults on the power system, during switching operations and changing system

configurations. Solution to SSR problems

1. Use of filters: For eliminating/damping the harmonics. The various filters include: static blocking filters, bypass damping filters, dynamic filters.

2. Bypassing the series capacitor bank under resonance condition

3. Tripping of generator units under conditions of SSR

Reactive Power and Voltage Collapse

Voltage collapse is a system instability and it involves many power system components and their variables at once. Indeed, voltage collapse involves an entire power system although it usually has a relatively larger involvement in one particular section of the power system. Voltage collapse occurs in power systems which are usually **Heavily loaded,** faulted and/or have reactive power shortages. Voltage collapses can occur in a transient time scale or in a long term time scale. Voltage collapse in a long term time scale can include effects from the transient time scale; for example, a slow voltage collapse taking several minutes may end in a fast voltage collapse in the transient time scale.

Changes in power system contributing to voltage collapse

There are several power system disturbances which contribute to the voltage collapse.

i. increase in inductive loading

ii. Reactive power limits attained by reactive power compensators and generators.

iii. On Load Tap Changing operation

iv. Load recovery dynamics.

v. Generator outage

vi. Line tripping.

most of these factors have significant effects on reactive power production, transmission and consumption. Switching of shunt capacitors, blocking of OLTC operation, generation rescheduling, bus voltage control, strategic load shedding and allowing temporary reactive power over loading of generators may be used as some of the effective countermeasures against voltage collapse.

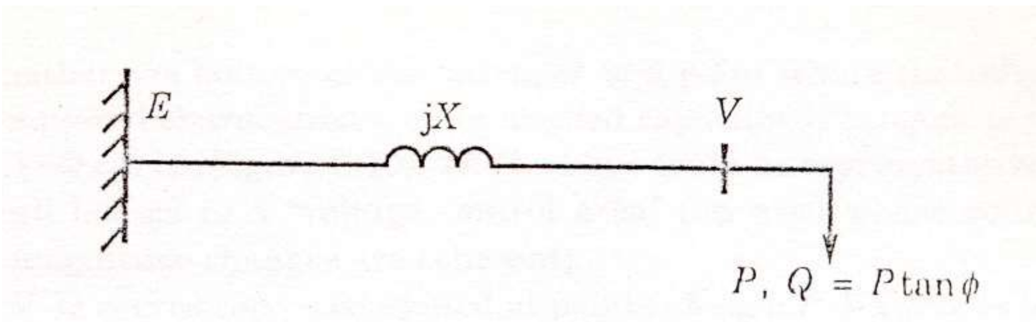
Voltage Stability

The voltage stability may be defined as the ability of a power system to maintain steady acceptable voltage at all busses in the system at normal operating conditions and after being subjected to disturbances/ perturbations. OR

Voltage stability is the ability of a system to maintain voltage so that when load admittance is increased, load power will increase, and so that both power and voltage are controllable. Power system is “Voltage Stable “if voltages at respective busses after a disturbance are close to the voltages at normal operating conditions. So voltage instability is that appears when the attempt of load dynamics to restore power consumption is just beyond the capability of the combined transmission and generator system. Though voltage instability may be a local problem, its consequences may have a widespread effect. Voltage collapse is the catastrophic result of a sequence of events leading to a sudden low-voltage profile in a major part of the system, i.e. in a significant part of the system. Voltage Stability can also be called Load Stability. A Power system lacks the capability to transfer an infinite amount of electrical power to the loads. The main factor causing voltage instability is the inability of the power system to meet the demands for reactive power in the heavily stressed system keeping desired voltages. Other factors contributing to voltage instability are the generator reactive power limits. Transfer of reactive power is difficult due to extremely high reactive power losses, which is why the reactive power required

for voltage control is generated and consumed at the control area. A classification of power system stability is shown in the table below. The driving forces for instability are named generator– driven and load-driven. It is to be noted that these terms do not exclude the effect of other components to the mechanism. The time scale is divided into short and long-term time scale.

Now let us analyse voltage stability using Q-V curves. Consider a simple system as shown below and its P-V curves.



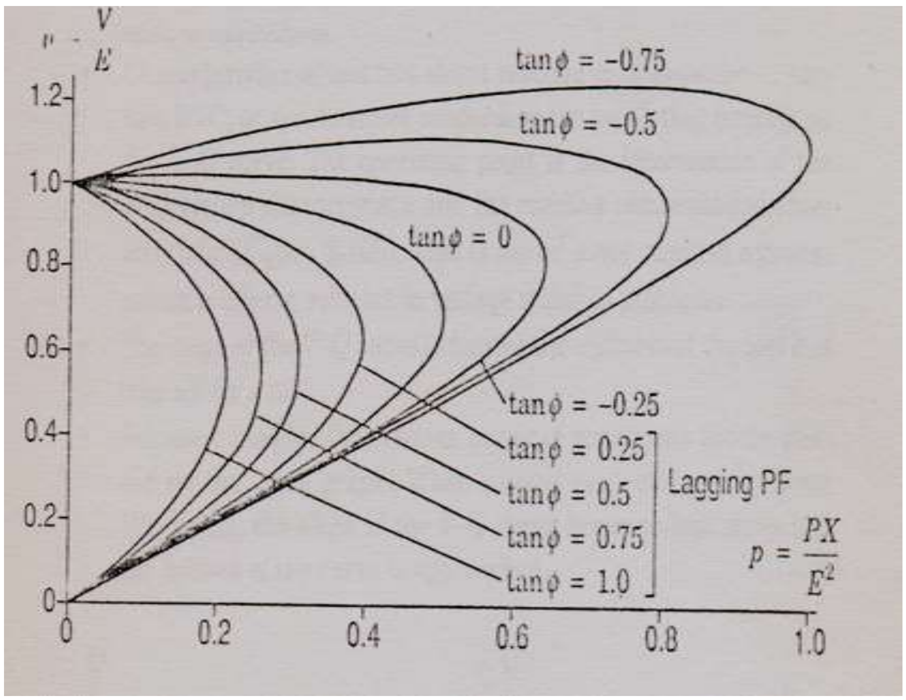


Fig: Normalised P-V curves for fixed (infinite) source Now map the normalised P-V curves onto V-Q curves. for constant value of P, note the values of Q and V and then re plot to get Q-V curves as shown below. from P-V curves it is observed that the critical voltage is very high for high loadings. V is above 1.0p.u for P = 1.0p.u The right side represents normal conditions where applying a capacitor bank raises voltage.

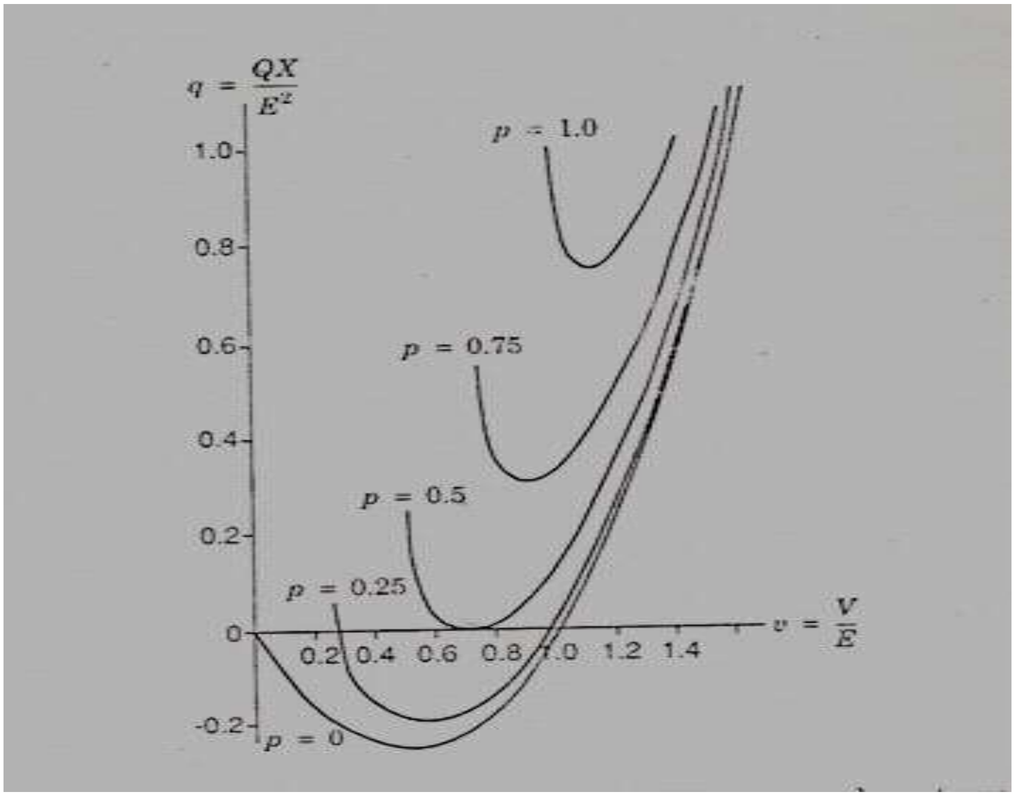


Fig : Normalised Q-V curves for fixed (infinite) source.

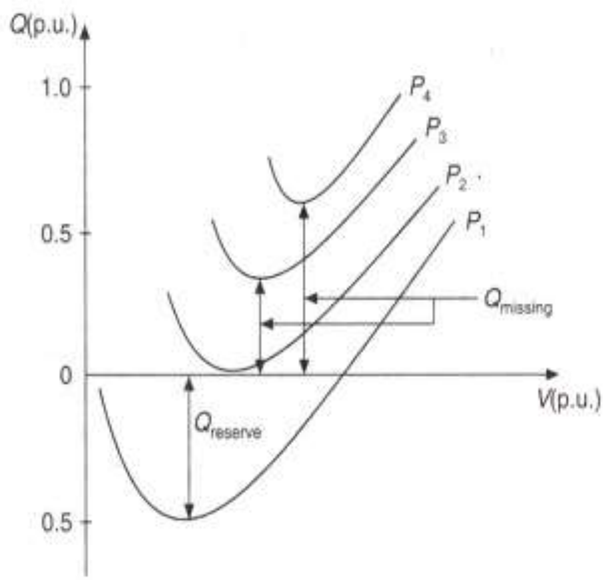


Fig : Q – V Curves

Figure shows the Q-V diagram of a bus in a particular power system at four different loads: P1, P2, P3, P4 . the Q axis shows the amount of additional reactive power that must be injected into the bus to operate at a given voltage. The operating point is the intersection of the power curve with the voltage axis, where no reactive power is required to be injected or absorbed. If the slope of the curve at the intersection point is positive, the system is stable**,** because any additional reactive power will raise the voltage and vice-versa. Hence for P 1 load, there is a reserve of reactive power that can be used to maintain stability even if the load increases. For load P 2 the system is marginally stable. For higher load P3 and P4 the system is not stable (Since a certain amount of reactive power must be injected into the bus to cause an intersection with the voltage axis.) Thus the measure of Q reserve gives an indication of the margin between stability and instability. The slope of the Q-V curve represents the stiffness of the test bus. when nearby generators reach their Var limits, the slope of the Q-V curve becomes less steep and the bottom of the curve is approached. V-Q curves are presently the workhorse method of voltage stability analysis at many utilities. Since the method artificially stresses a single bus, conclusions should be confirmed by more realistic methods.

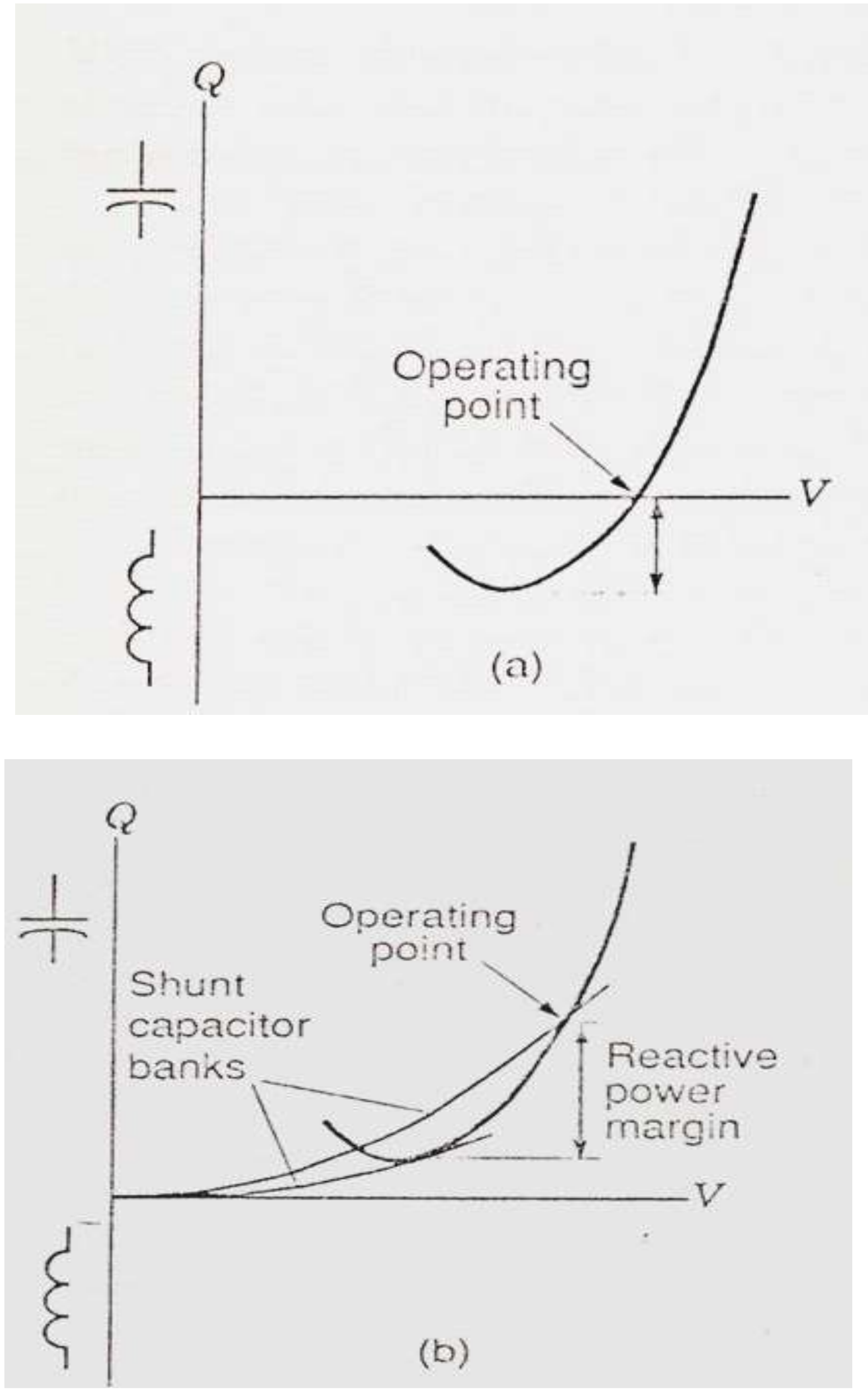


Fig: Reactive Power Margins

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