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Power Systems
stability, transmission, compensation

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Outline

- 18.3
  - Basics of power systems analysis
  - Power transmission and compensation
- 19.3
  - Effect of power electronics to power system dynamics
  - Power grid from the POV of the grid-connected inverter

Power systems

- Power grid is a complex interconnected system
- Transmission lines are often have radial connections
  - More robust performance under faults and transients
  - Difficult to analyze (Newton-Raphson)
- Distribution lines are almost always connected point-to-point
  - Easy to analyze and control
  - Can be connected as circle, however only one of the lines are connected at a time

Stability for Power Grid

- Definition of stability:
  - Ability of the system to remain in the steady-state value in normal use and the capability to reach a new acceptable steady-state after a disturbance
- Frequency is the same in the whole power grid
  - Synchronous generators in power generation
  - Balance of power generation and consumption
  - Control of the generators can remove small frequency deviations
- Sufficient voltage levels for power transfer

Per Unit values - Example

- Allows modeling transformers without considering voltage ratio between different sides
  - Absolute impedance values seen from different sides of the transformer are different
- All the components are changed into equivalent components
  - Equivalent impedance or admittance values
  - The whole system has the same nominal power
    - Nominal power often set to 100 MVA or determined by the largest generator

Nominal values

S_{base} = 1 p.u.

V_{base} = 1 p.u.

$$I_{base} = \frac{S_{base}}{V_{base} * \sqrt{3}} = 1\, p.u.$$

$$Z_{base} = \frac{V_{base}^2}{S_{base}} = 1\, p.u.$$

$$Z_{base} = R + jX$$

Per Unit values - Example

- Used for simplifying the equations
  - Calculation by hand is much easier
  - Manufacturers state nominal impedances as p.u, values compared to nominal power and voltage
  - Similar equipment of different sizes can be compared ie. Relative reactance of generators
  - Simplifying the problem and understanding the math problem becomes easier
  - Most programs use p.u. values

Nominal values

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V_{base} = 1 p.u.

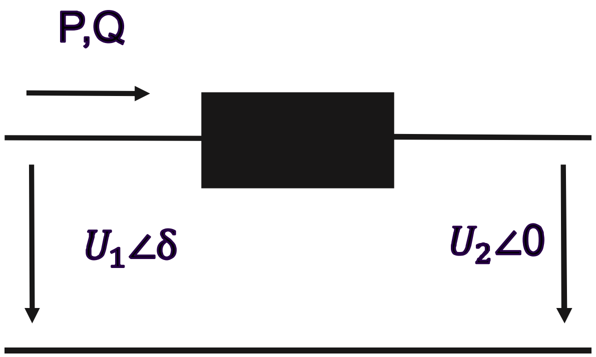
$$I_{base} = \frac{S_{base}}{V_{base} * \sqrt{3}} = 1\, p.u.$$

$$Z_{base} = \frac{V_{base}^2}{S_{base}} = 1\, p.u.$$

$$Z_{base} = R + jX$$

Power grid load flow

- Power flow equations in a simplified grid
    - $P = \frac{U_1 U_2}{X} sin\delta$
    - $Q = \frac{U_1^2}{X} - \frac{U_1 U_2}{X} cos\delta$
- If the receiving end voltage U_2 is considered constant, the active and reactive power flows depend on
    - Phase angle difference δ
    - The voltage at node U_1



Power grid load flow

- Active and reactive power flow changes depending on voltage amplitude U_1 and angle δ
  - $\Delta P = \frac{\partial P}{\partial \delta} d\delta + \frac{\partial P}{\partial U_1} dU_1 = \frac{U_1 U_2}{X} cos\delta * d\delta + \frac{U_2}{X} sin\delta * dU_1$
  - $\Delta Q = \frac{\partial Q}{\partial \delta} d\delta + \frac{\partial Q}{\partial U_1} dU_1 = \frac{U_1 U_2}{X} sin\delta * d\delta + \frac{2U_1 - U2}{X} cos\delta * dU_1$
- Change in power when
  - The angle difference changes but voltage is constant?
  - The voltage changes but angle difference is constant?

Power grid load flow

- Voltage difference determines the reactive power flow
- Change in power when the phase angle δ changes and voltage U_1 is constant
  - $\frac{\Delta Q}{\Delta P} = \frac{\frac{\partial Q}{\partial \delta}}{\frac{\partial P}{\partial \delta}} = \tan\delta$, U_1 = constant
  - The change in reactive power Q is small when angle δ is small
    - $\delta = 5° \rightarrow \frac{\Delta Q}{\Delta P}$=0.09, $\delta = 30° \rightarrow \frac{\Delta Q}{\Delta P}$=0.6 , $\delta = 60° \rightarrow \frac{\Delta Q}{\Delta P}$=1.7

Power grid load flow

- Angle difference determines the active power transfer
- Change in power when the voltage U_1 changes and the phase angle δ is constant
  - $\frac{\Delta P}{\Delta Q} = \frac{\frac{\partial P}{\partial U_1}}{\frac{\partial Q}{\partial U_1}} = \frac{sin\delta}{\frac{2U_1}{U_2} - cos\delta}$, δ = constant
  - The change in active power is small compared to reactive power
    - $\delta = 5°$ → $\frac{\Delta P}{\Delta Q}$ =0.09
  - Increases rapidly if angle δ is larger

Power grid load flow – Stability limits

- AC transmission systems capability to transmit power is limited by the following
    - Angular stability ($(\theta 1 - \theta 2) < 30°$)
    - Voltage magnitude (0.95 p.u. $< V1, V2 < 1.05$ p.u.)
    - Thermal limits (current flow limits)
    - Transient stability
    - Dynamic stability
- The limits define the maximum electrical power that can be transmitted without risking damage to transmission line and equipment

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Grid Power Balance

- Active power transfer is determined by phase angle difference
  - Frequency is a global variable in the power grid and it is same in the whole synchronized network
  - Easy to transfer long distances
- Balance of power generation and load consumption
  - Active power changes can be seen as variance of the grid frequency
  - Reactive power changes can be seen as variance of the node voltage

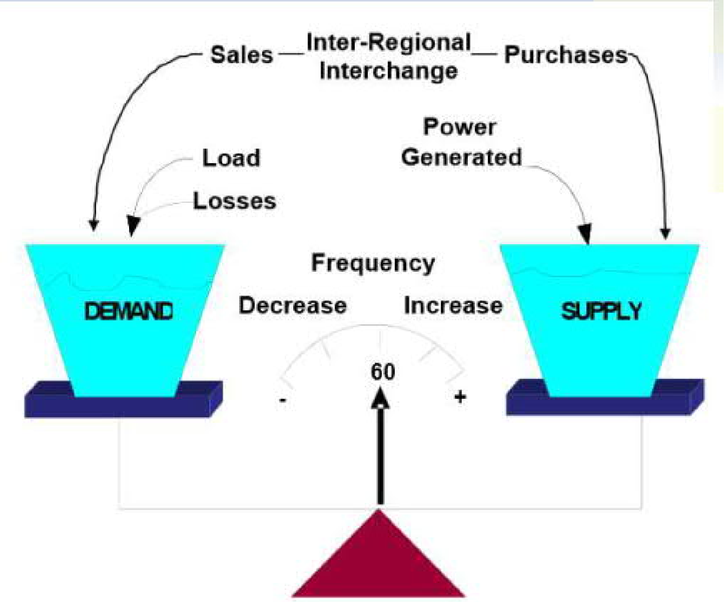


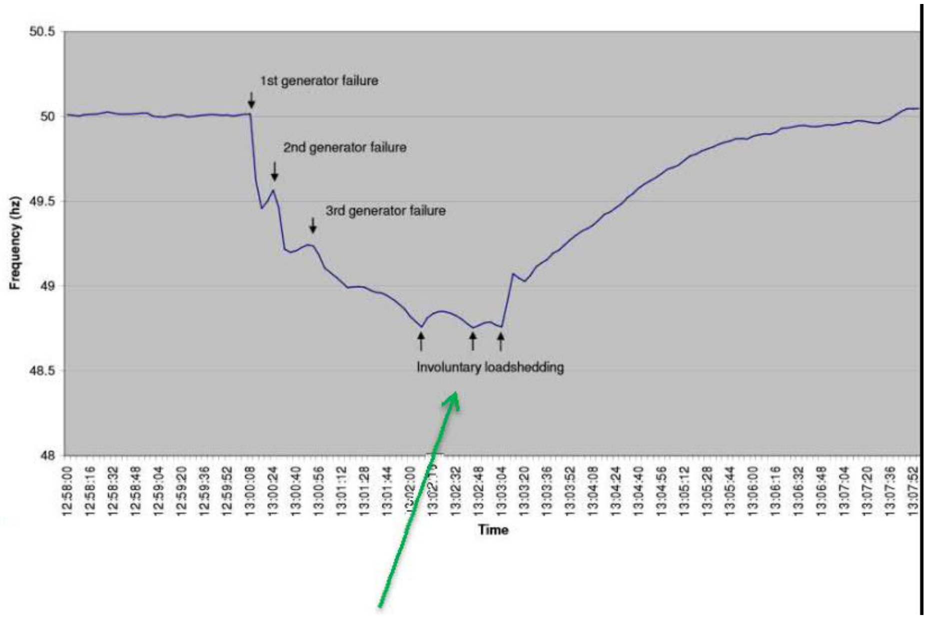
Figure 3a — Generation / Demand Balance

Frequency balance

- Frequency is usually not allowed to vary too much
  - Controlled through the active power generation
  - Droop-control of the generators
  - Rotating mass in synchronous generators aids in damping fluctuation
- Large changes in frequency can cause devices to disconnect or damage the equipment
  - Certain types of generators must be disconnected if frequency drops to 47 Hz in 50 Hz power grid
  - Grid frequency or its multiples are the same as the resonating frequency of the rotor blades

Frequency stability – Design requirements

- Power grid designed with capability of N-1
  - Can operate normally even if the largest possible single fault occurs
- Frequency nadir determined by the inertia of the power grid
  - Traditionally determined by the rotating mass present in the generators
  - Power electronics reducing the inertia
    - Larger frequency fluctuation is possible
    - New requirements for power electronic devices



Frequency activated load shedding

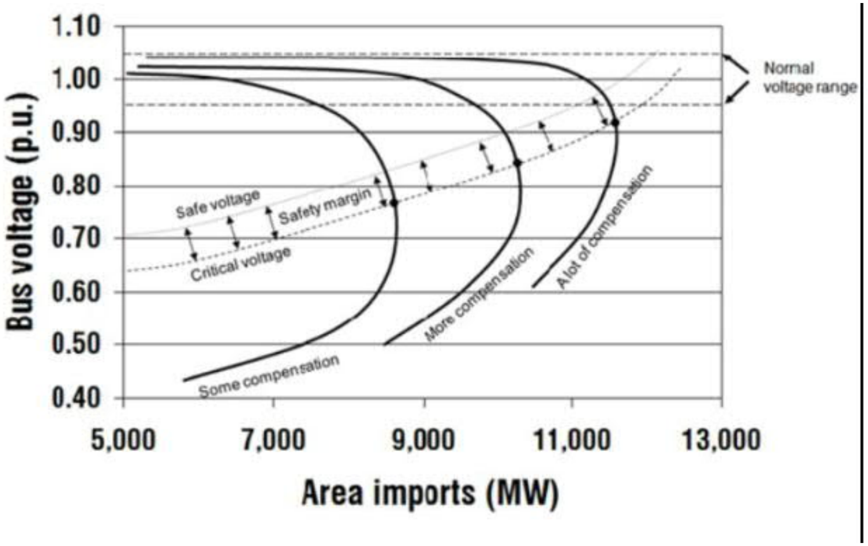
Example – Change of frequency during fault

- Change in frequency when a power grid with apparent power S_{nom} = 100 MWA with inertia H=5kWs/kVA is affected by load of 50 MW dropping. The turbine reacts in 0.4 seconds
- What is the frequency difference
- $\Delta \mathrm{P_D} = -50\mathrm{MW},\ \mathrm{t_{delay}} = 0.4s$
- The accelerating energy: $\mathrm{W} = \Delta P_d * t = 50\ 000\ kW * 0.4s = 20000kWs$
- Frequency change $f = f_0\sqrt{\frac{W_{kin}}{W_{kin,0}}} = 50\ \mathrm{Hz} * \sqrt{\frac{5*10^5+20000}{5*10^5}} = 51\ \mathrm{Hz}$
- The inertia stops large changes from happening to grid frequency
  - For comparison power grid in Northern Europe has inertia sufficient for at least 8000 MWA/Hz speed droop

Voltage stability

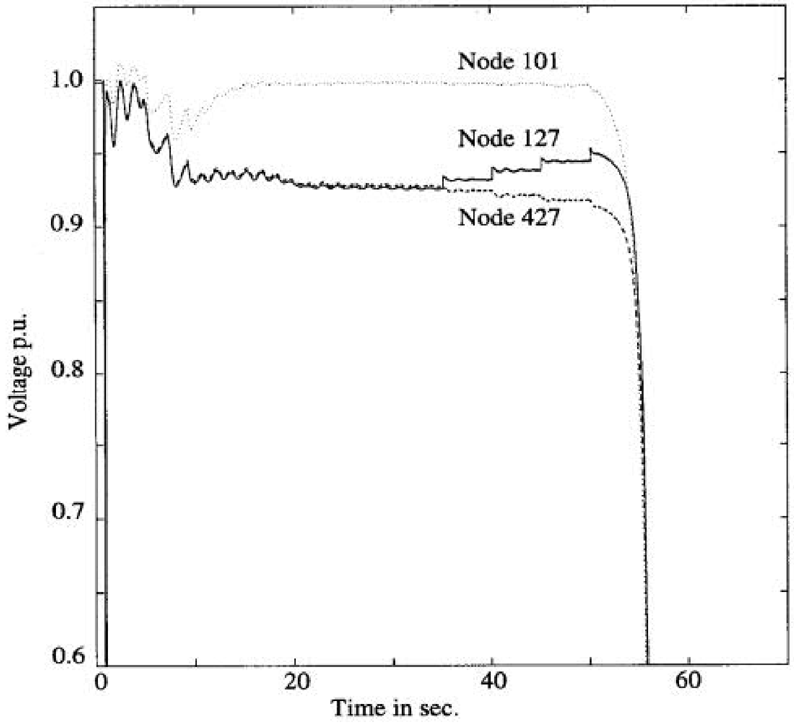
Power grid – Voltage stability

- Voltage stability is an issue when transferring large amounts of power through limited power network
  - Power transmission capability is traditionally limited by rotor angle stability and thermal loading capabilities
  - Voltage stability means the ability to maintain acceptable voltages at all buses in the system under normal conditions and after being subjected to disturbance

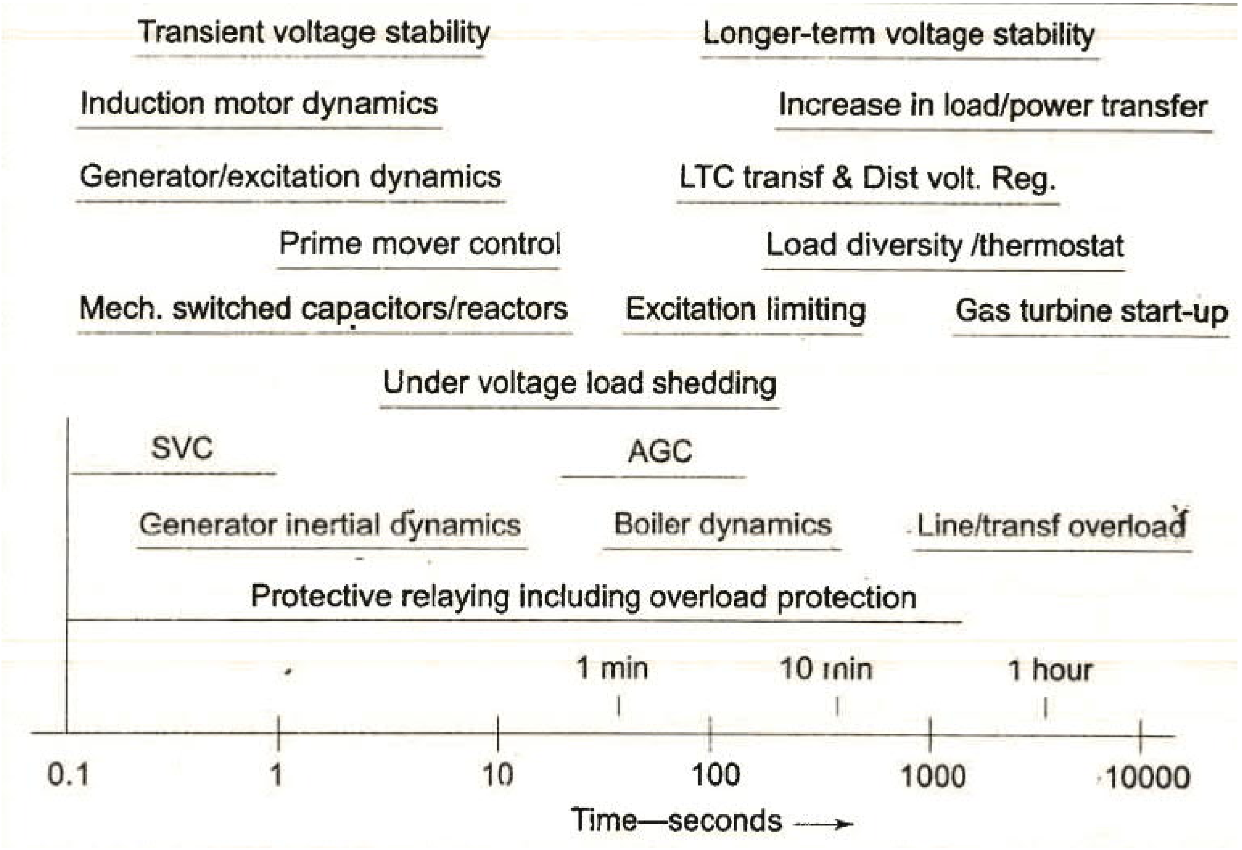


Power grid – Voltage stability

- Voltage instability can occur in a time frame of a second (Transient voltage stability) or take up to tens of minutes (Long-term voltage stability)
- The power system should be secure enough to be able remain stable after ny reasonable adverse system change such as load increases



Voltage stability causes



Voltage collapse

- Voltage collapse is a process by which the sequence of events lead to unacceptable voltage profile in significant part of the power system
- The voltage collapse can be characterized as follows
  - The initiating event may be due to variety of reasons:
    - Small gradual changes such as increase in system load
    - Sudden large disturbances such as loss of a generator or a heavily loaded line
- Core problem is the inability of the system to meet its reactive demands
  - Transport of reactive power is difficult and can additional need for reactive power support may cause eventually lead to voltage collapse
- Usually manifests as slow decay of voltage
  - Accumulative process involving interaction of many devices, controls and protective systems

Voltage collapse - causes

- Long transmission lines
  - The power systems with long lines without voltage control at the receiving end create voltage problems during light or heavy load conditions
- Radial transmission lines
  - Any loss of line causes and increase in system reactance
- Shortage of local reactive power
  - There may occur a disorganized combination of outage and maintenance schedule that may cause localized reactive power shortages leading to voltage control problem

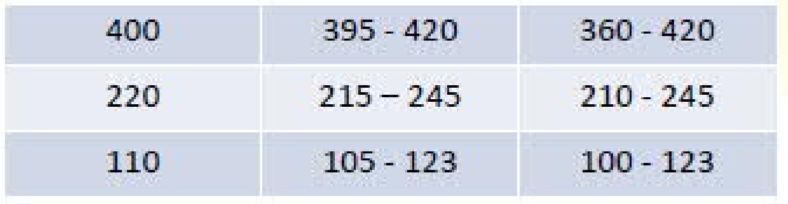
Improving voltage stability

- Voltage stability can be improved by adopting the following means
  - Enhancing the local reactive power support
    - Reactive power injection
  - Compensating the power line reactance
  - Additional power lines
  - Enhancing excitation of generator
    - Terminal voltage increase
  - HVDC to connect different regional grids
  - Strategic load shedding

Power grid – Voltage control

- Goals:
  - Avoid over- and under voltages
  - Quality of the delivered electric power
  - Minimazing the losses
- Insufficient reactive power support from generators can and has lead to voltage instability
- Sufficient controllable compensation capacity
  - Reactive power is not efficient to transfer due to large voltage differences → Must be generated locally

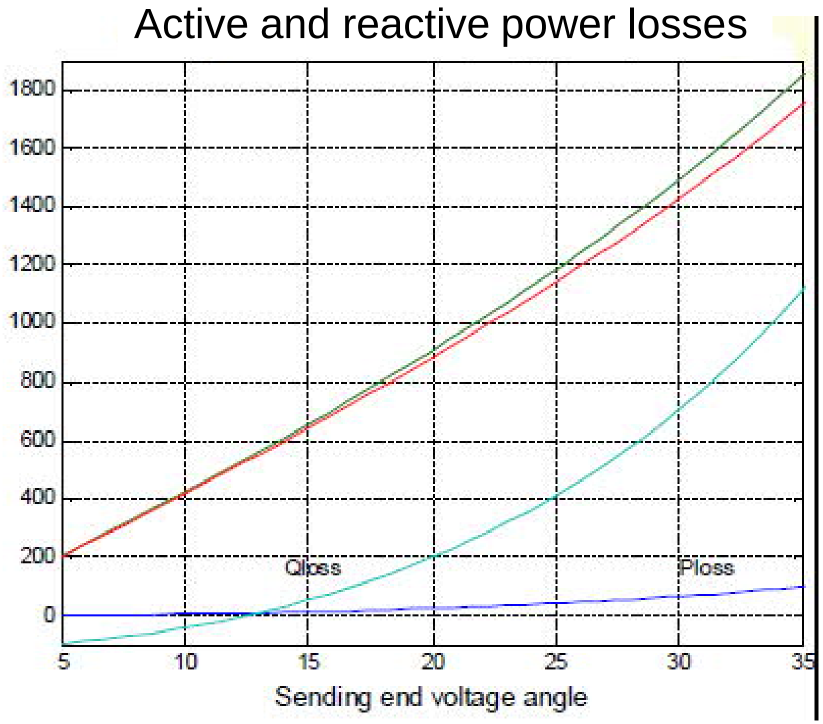
Finnish transmission voltage levels



Voltage(kV)	Normal	Fault
400	395 - 420	360 - 420
220	215 – 245	210 - 245
110	105 - 123	100 - 123

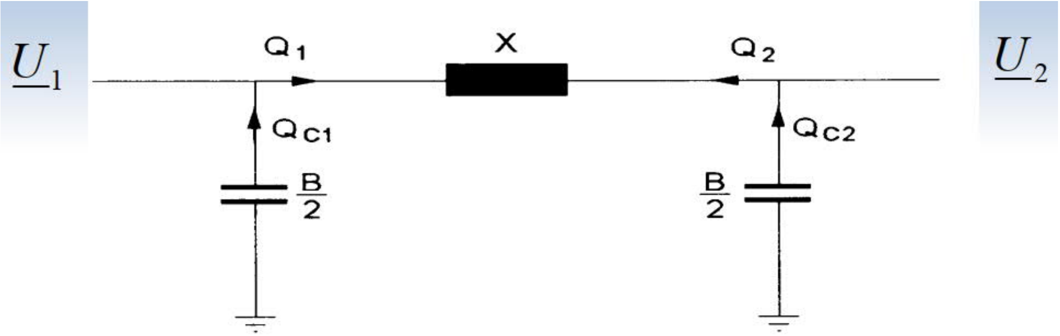
Power transmission

- For a network with
  - Active power P and reactive power Q
  - Transmission line resistance R and reactance X
  - Both end node voltages are U
- Power grid transmission losses
  - Active power losses $= 3I^2R$
  - Reactive power losses $= 3I^2X$
  - $I^2 = I * I^* = \frac{S^*}{\sqrt{3}*U^*} * \frac{S}{\sqrt{3}U} = \frac{P-jQ}{\sqrt{3}*U^*} * \frac{P+jQ}{\sqrt{3}*U} = \frac{P^2+Q^2}{3U^2}$
  - Which means losses are relative to both active and reactive power
  - $P_{loss} = 3I^2R = \frac{P^2+Q^2}{U^2}R$ and $Q_{loss} = 3I^2X = \frac{P^2+Q^2}{U^2}X$



Power lines – Reactive Power

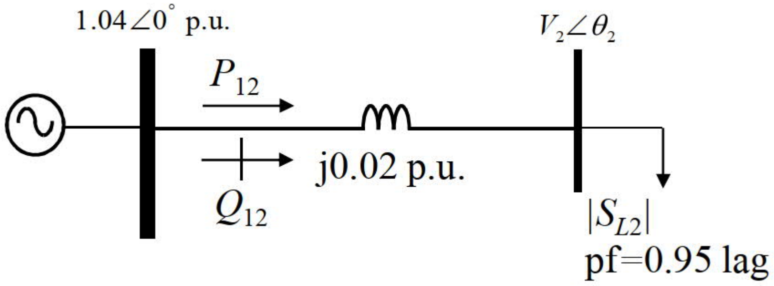
- Power lines generate some reactive power
  - Caused by stray capacitances
- Increased power transfer increases the consumed reactive power due to inductive nature of power lines
- Natural power of the power line
  - Power line has equal reactive power generation and consumption

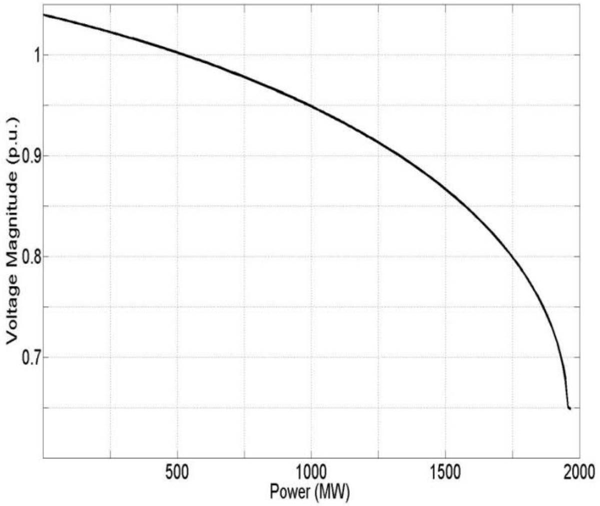


Grid compensation

Compensation methods

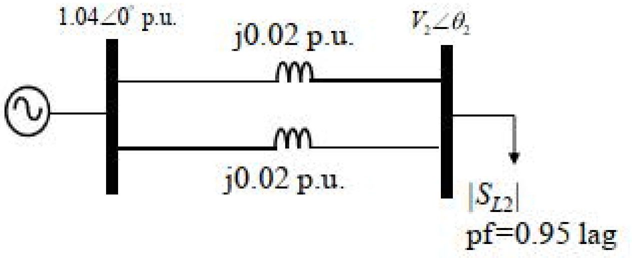
- The power transmission over long distances is limited by the reactive power
- Voltage loss increases when active power increases
  - High-voltage power lines have much larger reactive components than resistive X>>R
  - Higher current increase reactive power consumption of the power line
- The capability of the power line to transfer active power can be increased by compensating the line reactance

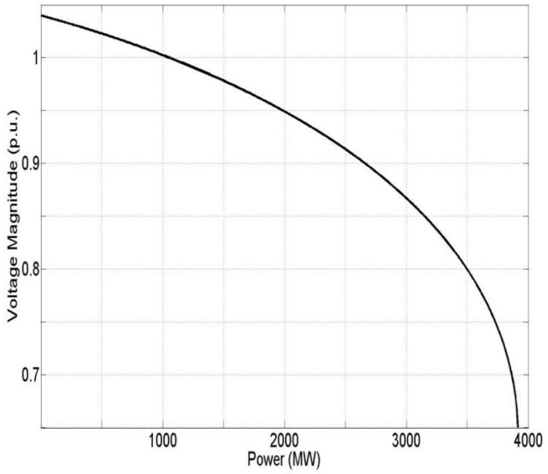




Conventional system reinforcement solution

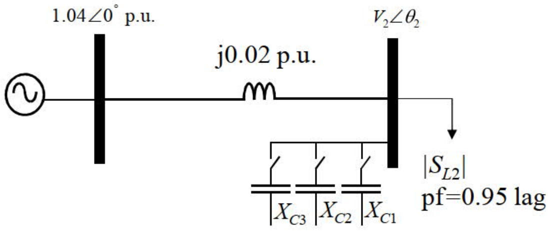
- Building an additional identical transmission line parallel
  - Effectively halves the circuit reactance
  - Easy solution
  - Expensive
- Second line doubles the transmission capacity
  - The line impedance must be equal
    - Same type of conductors must be used

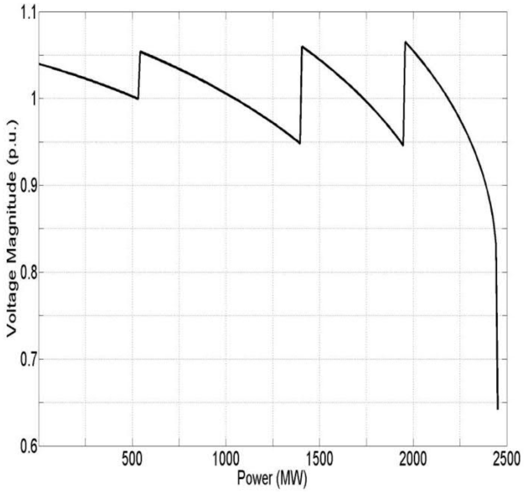




Shunt Compensation - Parallel Capacitor Bank

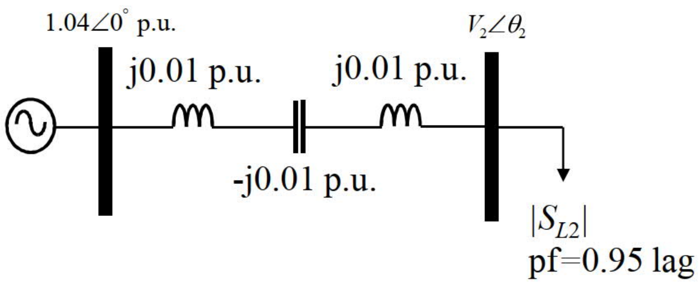
- A bank of switched capacitors installed at the load side with following values Xc1 = 0.42 p.u. Xc2=0.24 p.u. Xc3=0.32p.u.
- Increases the voltage at bus 2 by generating reactive power
- Requires switching of the capacitors depending on the load
  - High compensation with low load increases voltages
- Stabilizes voltages

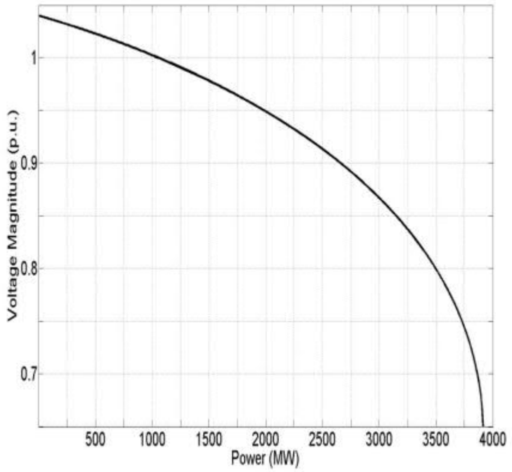




Series Compensation - Series capacitor bank

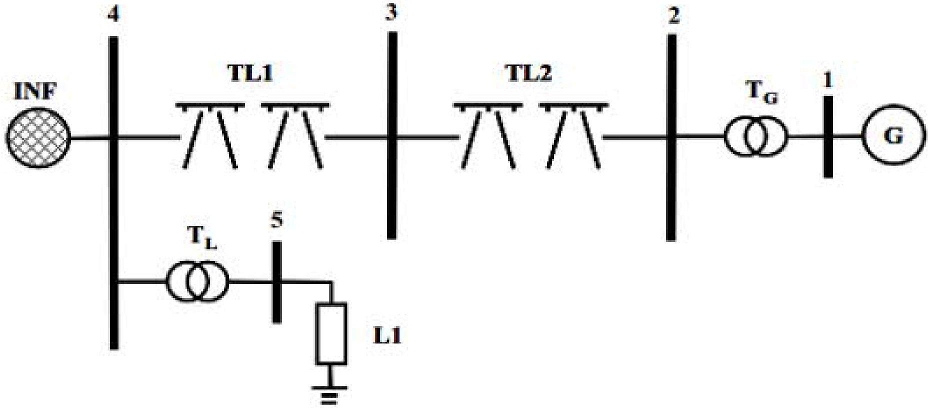
- A bank of series capacitors are installed half-way the transmission line to reduce electrical length of the line
  - Permanent connection
- Increases power transmission by halving the length of the line
  - 50% series compensation
- Compensation depends on the load as the reactive power is relates to current squared
- Series resonance with inductance can cause subsynchronous harmonics





Grid Compensation - Example

- Example cases
  - LF1 Maximum load, heavily loaded grid
  - LF2 50 % load, normally loaded grid

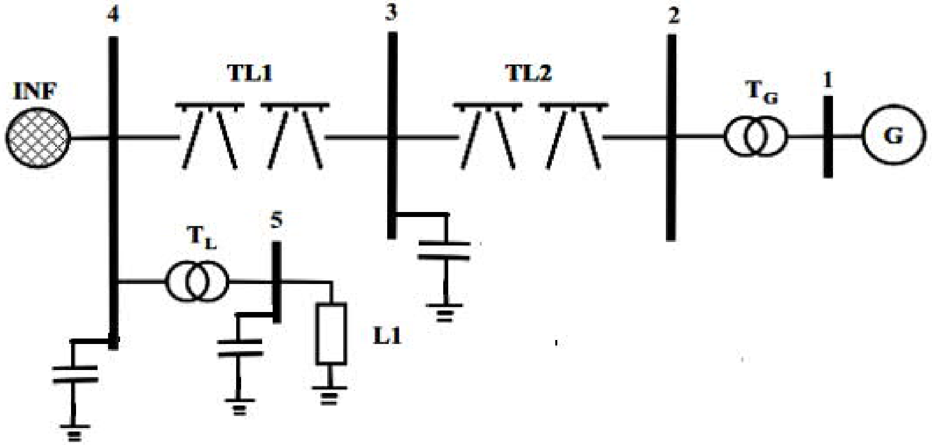


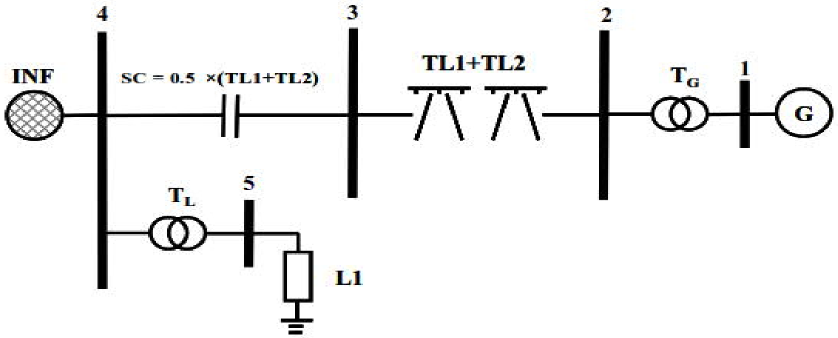
Case 1 - LF 1			**Case 2 - LF2**		
L1	G	Uinf	L1	G	Uinf
Un=110kV	P = 550 MW	U = 390 kV	Un=110 kV	500 MW	U = 415 kV
Pn=600MW	Q according to power flow analysis		Pn=300 MW	Q according to power flow analysis	
Qn=200 MVAr			Qn=200 MVAr		

Grid Compensation - Example

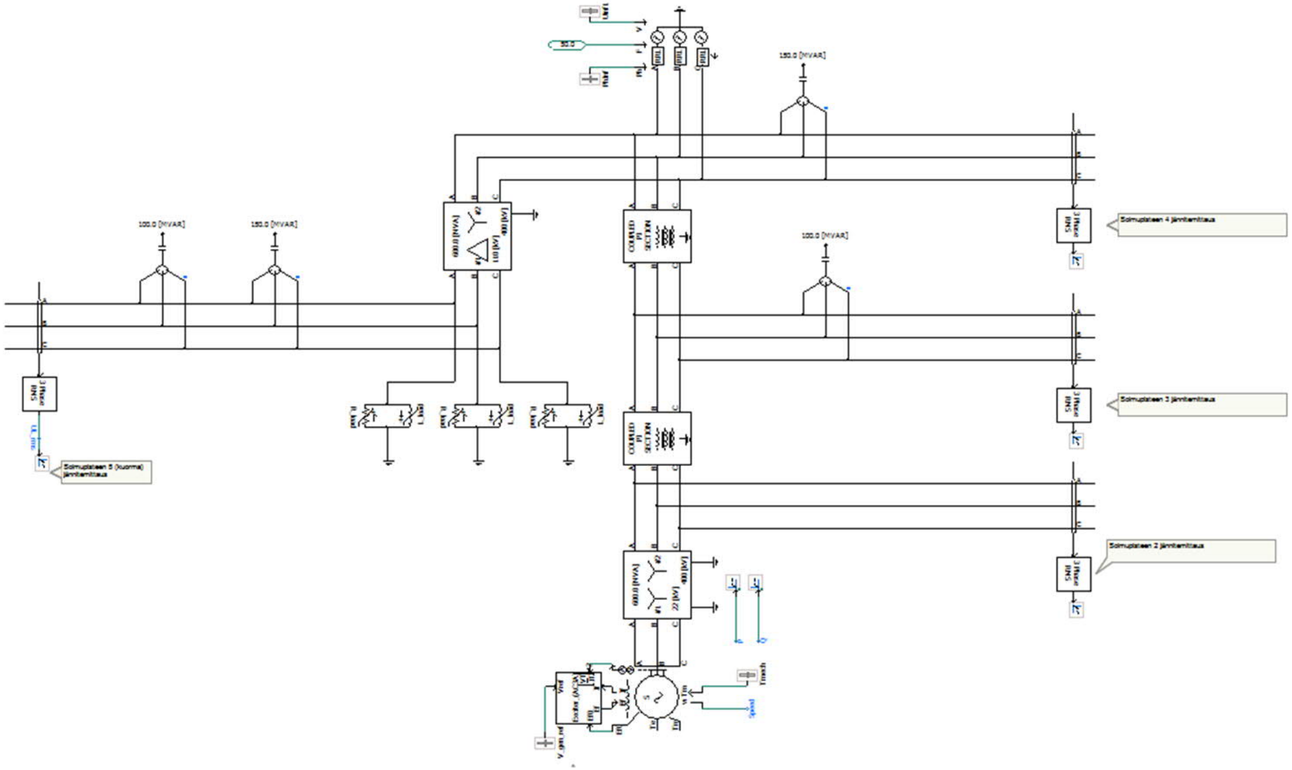
- Goal: Keep voltages within acceptable values (0.95 p.u. - 1.05 p.u.)
- Shunt compensation
- Series compensation

No compensation		
	LF 1	LF 2
$\theta_{inf} - \theta_{gen}$	-47.9 deg	-39 deg
U2	0.99 p.u.	1.01 p.u.
U3	0.90 p.u.	0.98 p.u
U4	0.86 p.u.	0.98 p.u.
Uload	0.82 p.u.	0.95 p.u.



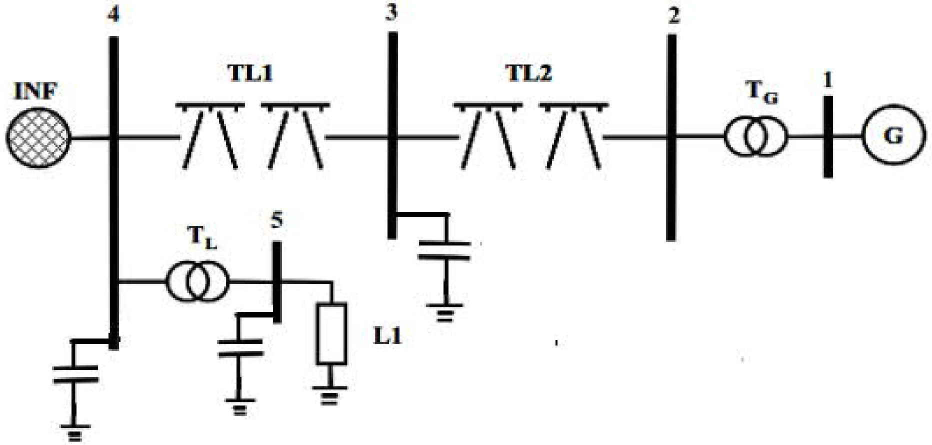


Shunt compensation – Simulation model



Grid Compensation - Example LF1

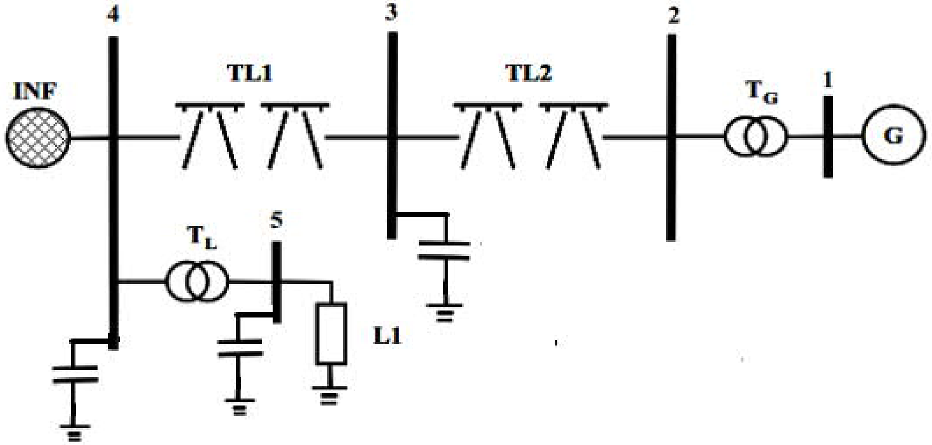
- Goal: Keep voltages within acceptable values (0.95 p.u. - 1.05 p.u.)
- Shunt compensation in situation LF1
- Added compensation
  - Node 5: 250 MVAr
  - Node 4: 150 MVAr
  - Node 3: 100 MVAR



No compensation		Compensation
$\theta_{inf} - \theta_{gen}$	-47.9 deg	-34.4 deg
U2	0.99 p.u.	1.01 p.u.
U3	0.90 p.u.	1.01 p.u.
U4	0.86 p.u.	0.996 p.u.
Uload	0.82 p.u.	0.998 p.u.

Grid Compensation - Example LF2

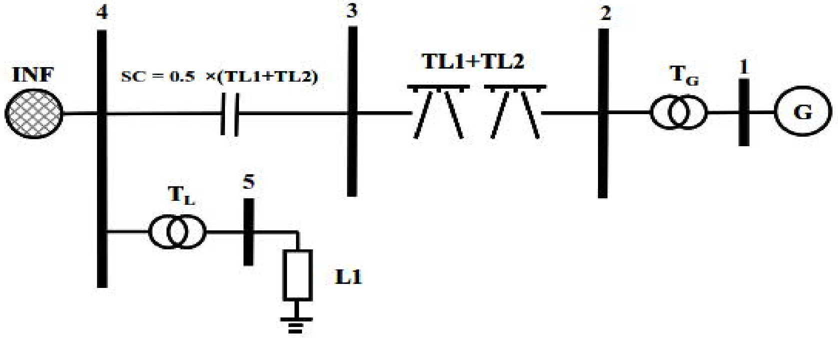
- Goal: Keep voltages within acceptable values (0.95 p.u. - 1.05 p.u.)
- Shunt compensation in situation LF2
- Added compensation
  - Node 5: 250 MVAr
  - Node 4: 150 MVAr
  - Node 3: 100 MVAR
- Overvoltage due to compensation
  - Compensation related to voltage not load
  - Must be able to switched off



No compensation		Compensation
$\theta_{inf} - \theta_{gen}$	-39 deg	-37 deg
U2	1.01 p.u.	1.02 p.u.
U3	0.98 p.u.	1.11 p.u.
U4	0.98 p.u.	1.14 p.u.
Uload	0.95 p.u.	1.18 p.u.

Grid Compensation - Example LF1

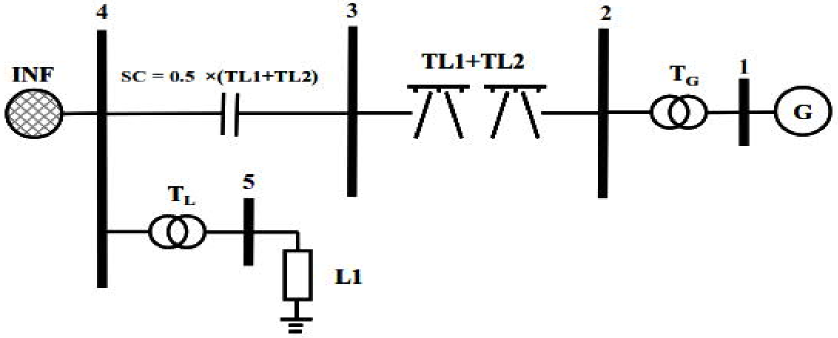
- Goal: Keep voltages within acceptable values (0.95 p.u. - 1.05 p.u.)
- Series compensation in situation LF1
- Added compensation 55% in series



No compensation		Compensation
$\theta_{inf} - \theta_{gen}$	-47 deg	-23 deg
U2	0.99 p.u.	0.99 p.u.
U3	0.90 p.u.	0.92 p.u.
U4	0.86 p.u.	0.93 p.u.
Uload	0.82 p.u.	0.87 p.u.

Grid Compensation - Example LF2

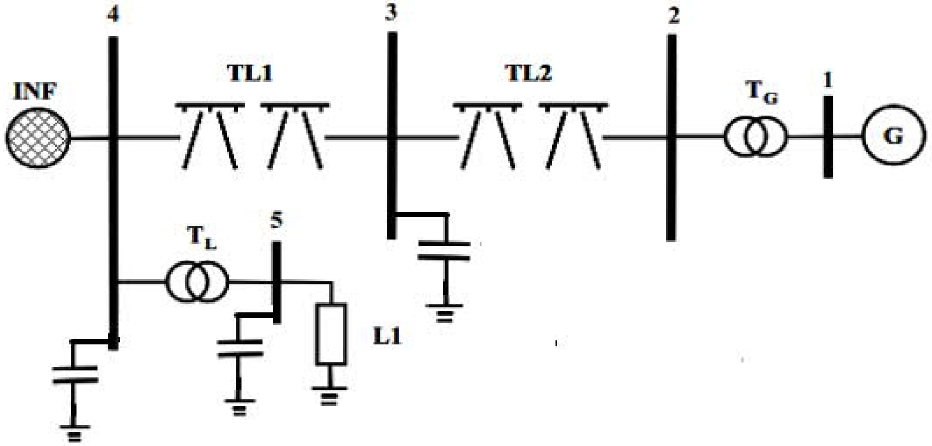
- Goal: Keep voltages within acceptable values (0.95 p.u. - 1.05 p.u.)
- Series compensation in situation LF2
- Added compensation 55% in series



No compensation		Compensation
$\theta_{inf} - \theta_{gen}$	-39 deg	-23 deg
U2	1.01 p.u.	1.00 p.u.
U3	0.98 p.u.	0.97 p.u.
U4	0.98 p.u.	0.97 p.u.
Uload	0.95 p.u.	0.95 p.u.

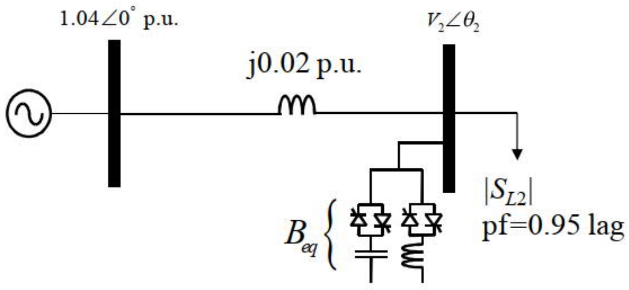
Grid Compensation - Example

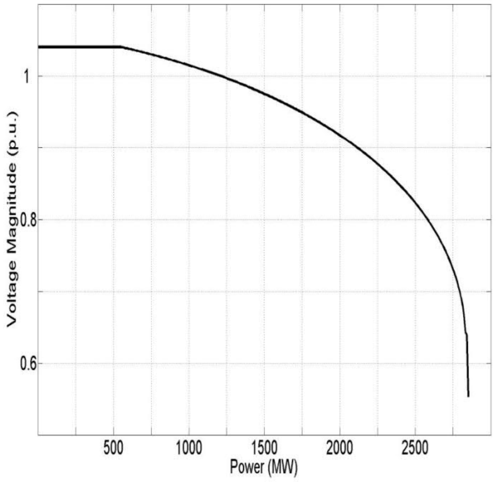
- Chosen compensation should be shunt capacitors with ability to switch the capacitor bank on/off
- Shunt compensation
  - Works well under high loading
  - Overvoltage may occur when low load
- Series compensation
  - Decreases the phase angle difference significantly
  - Series resonances with power grid may cause problems



Shunt Compensation – SVC

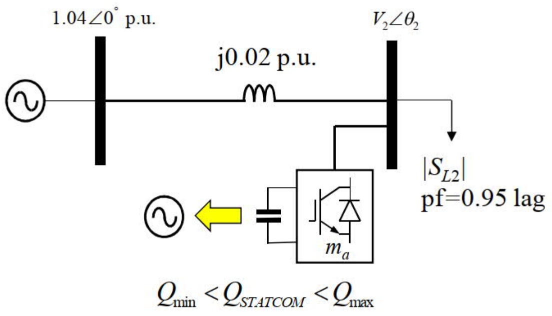
- Static Var Compensator – SVC
- Is composed of a capacitor and an inductor connected through thryristors
- Injected reactive power can be controlled
  - Has capability for flat voltage profile up to rated capacity
- Transmission system dynamic margin increases with the use of an SVC
  - However, reactive power support is impaired by low voltages
  - $Q_{SVC} = B_{eq} V_2^2$

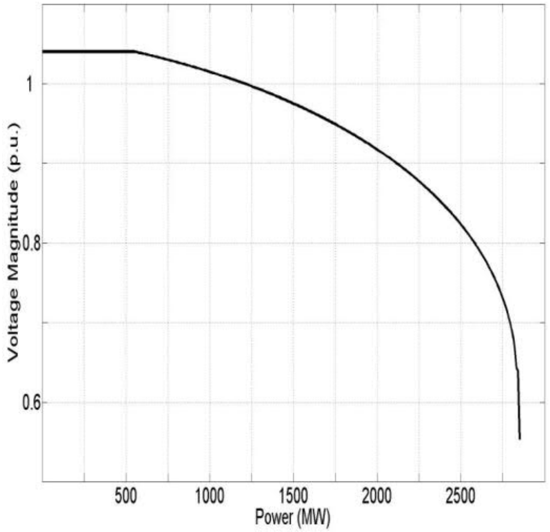




Shunt Compensation – Statcom

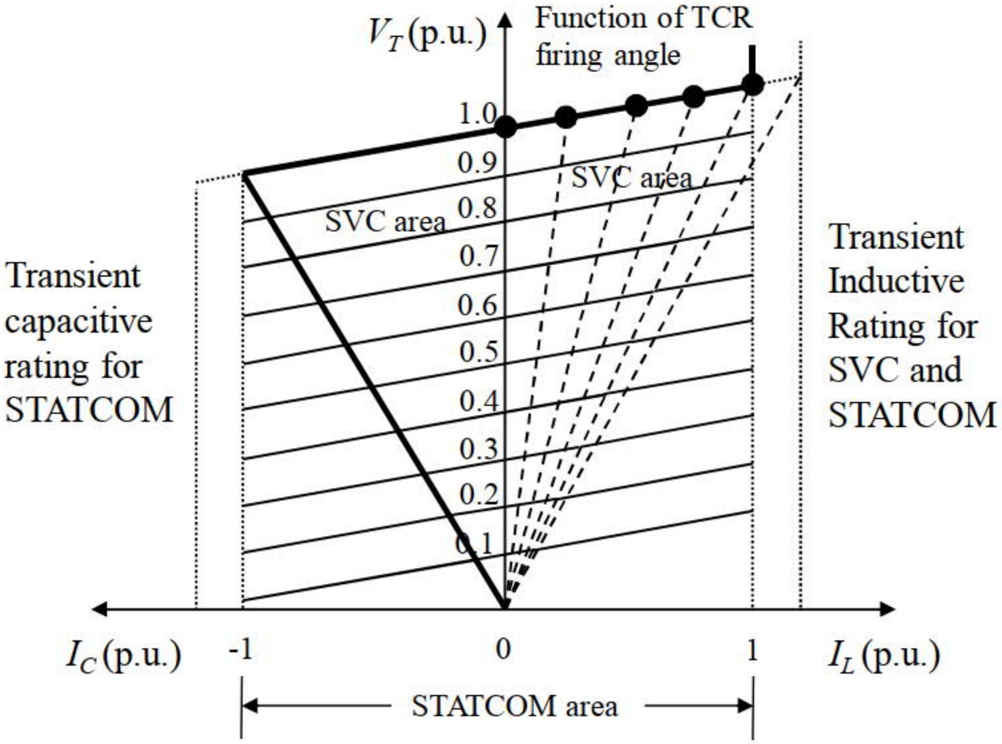
- Alternative newer, more sophisticated solution for SVC
- Behaves more like a synchronous generator
- Capacitor bank connected to the DC-side of an inverter
  - Can control the reactive power injection without being impaired by low voltage



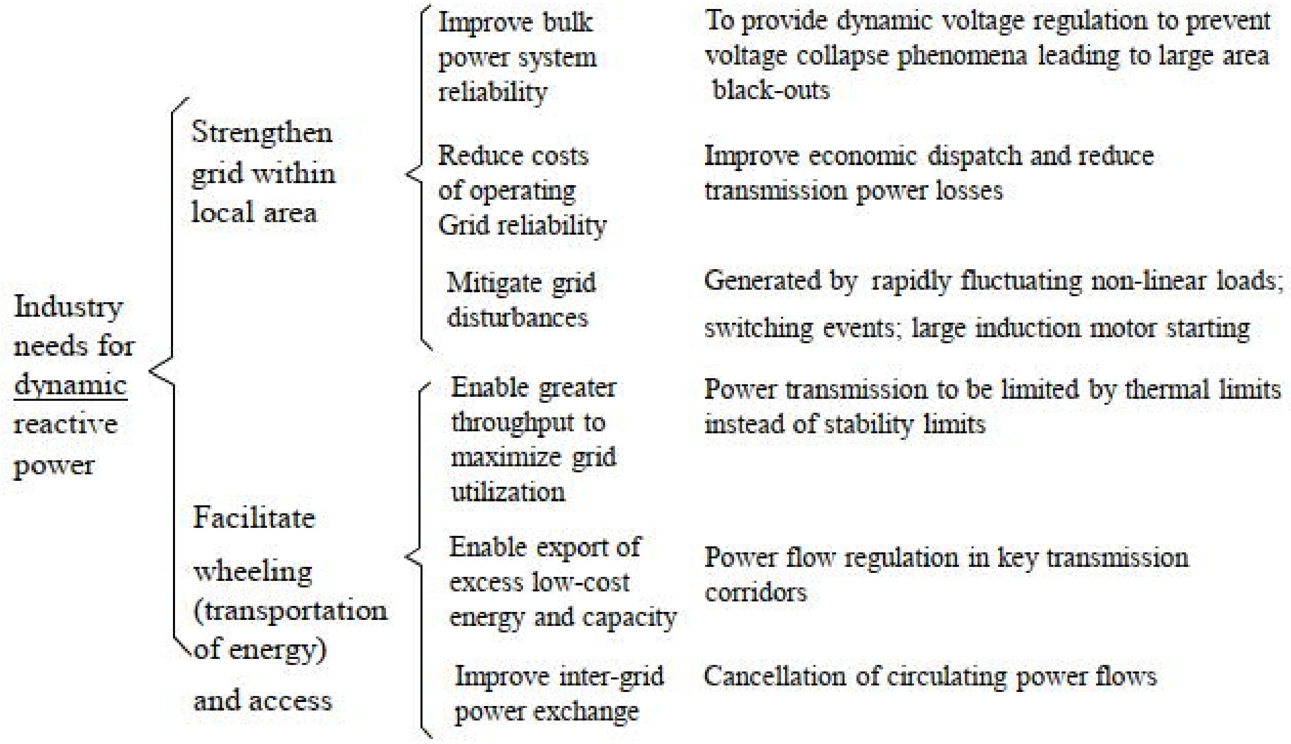


Statcom – SVC comparison

- Statcom injection current is not limited by the power grid voltage



Needs for Dynamic Reactive Power



- Industry needs for dynamic reactive power
  - Strengthen grid within local area
    - Improve bulk power system reliability: To provide dynamic voltage regulation to prevent voltage collapse phenomena leading to large area black-outs
    - Reduce costs of operating Grid reliability: Improve economic dispatch and reduce transmission power losses
    - Mitigate grid disturbances: Generated by rapidly fluctuating non-linear loads; switching events; large induction motor starting
  - Facilitate wheeling (transportation of energy) and access
    - Enable greater throughput to maximize grid utilization: Power transmission to be limited by thermal limits instead of stability limits
    - Enable export of excess low-cost energy and capacity: Power flow regulation in key transmission corridors
    - Improve inter-grid power exchange: Cancellation of circulating power flows

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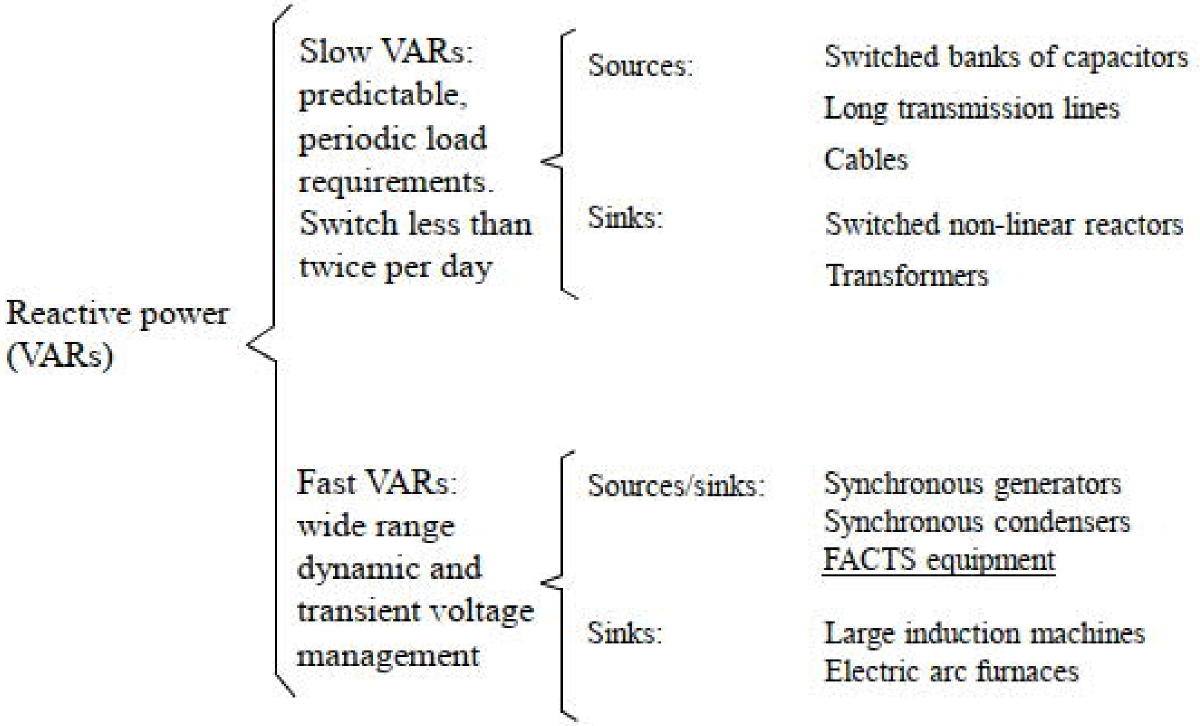
Optimum Mix of Reactive Power Sources/Sinks



- Reactive power (VARs)
  - Slow VARs: predictable, periodic load requirements. Switch less than twice per day
    - Sources:
      - Switched banks of capacitors
      - Long transmission lines
      - Cables
    - Sinks:
      - Switched non-linear reactors
      - Transformers
  - Fast VARs: wide range dynamic and transient voltage management
    - Sources/sinks:
      - Synchronous generators
      - Synchronous condensers
      - FACTS equipment
    - Sinks:
      - Large induction machines
      - Electric arc furnaces

Overall

- The power generation and consumption must be equal at all times
- Frequency is a global variable affected by active power
  - Inertia damps the frequency fluctuation in the power grid
    - Stored energy in the rotating mass of the generators
  - Droop-control of the generators
- Voltage is local variable affected by reactive power
  - Reactive power is not economical to transfer and must be generated locally
    - Grid compensation
  - Large generators are usually restricted to feeding active power to the grid in normal operation
    - Ability to support grid voltage during faults
- **Increase in solar and wind power are changing the dynamics of the power grid**
  - New requirements for the power electronics connecting them to the grid