Substation Engineering

Compensation Equipment (Part 1 of 2)

Milav Dabgar

Compensation Equipment (Part 1)

- Reactive Power Compensation
- Shunt and Series Capacitors

Lecture Agenda

- What is Reactive Power?
- The Need for Compensation
- Types of Compensation (Series vs Shunt)
- Shunt Capacitors: Operation and Benefits
- Location of Shunt Capacitors
- Series Capacitors: Operation and Benefits
- Increasing Power Transfer Capability
- Challenges with Series Capacitors (SSR)

Understanding Reactive Power (Q)

- In AC systems, power has two components: Active (P, in MW) and Reactive (Q, in MVAR).
- Active power does real work (spins motors, lights lamps).
- Reactive power sustains the electromagnetic fields of inductive equipment (transformers, induction motors).
- Q continuously oscillates between the source and the load.
- It does no useful work but occupies capacity in the transmission lines.

Why is Reactive Power Problematic?

- 1. Increased Line Losses: Flow of Q increases the total current (I). Since losses are I^2R, more Q means higher thermal losses.
- 2. Voltage Drop: Reactive current flowing through the line reactance (X) causes a significant voltage drop ($\Delta V \approx Q*X/V$).
- 3. Reduced Capacity: The apparent power limit (MVA) of transformers and lines gets filled up by Q, leaving less room for real power (P).
- 4. Poor Power Factor: Requires generators to operate at lower power factors.

The Need for Compensation

- Instead of transmitting Q from the generator, we 'compensate' or generate it locally near the load.
- Objectives of Compensation:
- - Improve voltage profile across the network.
- - Improve Power Factor (PF).
- - Reduce I^2R losses in transmission lines.
- - Increase the active power transfer capability of existing lines.

Types of Compensation Methods

- Compensation equipment is classified by how it is connected to the network:
- 1. Shunt Compensation: Connected in parallel with the load/line.
- - E.g., Shunt Capacitors, Shunt Reactors.
- 2. Series Compensation: Connected in series with the transmission line.
- - E.g., Series Capacitors.
- We can also classify them as Passive (fixed/switched capacitors) or Active/Dynamic (SVC, STATCOM).

Shunt Capacitors: Function

- Most industrial loads (motors) are highly inductive (lagging PF).
- Shunt capacitors draw leading reactive current.
- This leading current locally cancels out the lagging reactive current demanded by the load.
- Result: The generator only needs to supply active power (P), and power factor near the source becomes close to unity.

Diagram/Visual: Phasor diagram showing inductive load current (lagging) and capacitor current (leading) summing to a smaller total current.

Advantages of Shunt Capacitors

- Cost-effective and simple to install.
- Improves voltage at the load bus (boosts sagging voltages).
- Reduces kVA demand on the supplying transformers.
- They can be switched in and out in steps (using circuit breakers) depending on the load demand.
- Zero active power consumption (ideally).

Location of Shunt Capacitors

- The closer the capacitor is to the inductive load, the better.
- 1. Load Level: Directly at the motor terminals (best, but expensive).
- 2. Plant Level: At the main LV busbar of an industry (common).
- 3. Substation Level: Large capacitor banks connected to the MV/HV busbars of a distribution substation.
- Substation banks correct the PF of an entire feeder.

Series Compensation Overview

- Used on very long Extra High Voltage (EHV) transmission lines.
- Long lines have high inductive reactance (X_L), which restricts power flow.
- A capacitor is connected in series with the line phase conductor.
- The capacitive reactance (X_C) cancels out a portion of the line's inductive reactance (X_L).
- Net line reactance becomes: $X_{net} = X_L - X_C$.

Power Transfer Capability

- Power flow equation: $P = (Vs * Vr * \sin(\delta)) / X\_net$
- By reducing X_net using series capacitors, the maximum power P_max increases significantly.
- Degree of Compensation (k) = X_C / X_L.
- Usually, k is kept between 20% to 70%.
- Allows utilities to push more megawatts through existing right-of-ways without building new towers.

Voltage Stability with Series Capacitors

- Unlike shunt capacitors which provide a fixed voltage boost regardless of load, series capacitors are self-regulating.
- Voltage boost = I * X_C.
- When load current (I) increases, the voltage boost automatically increases.
- Excellent for improving voltage stability on long lines subjected to rapid load changes.

Challenges with Series Capacitors: SSR

- Sub-Synchronous Resonance (SSR).
- The series capacitor forms an LC resonant circuit with the line inductance.
- This electrical resonance can interact with the mechanical torsional frequencies of nearby turbine-generator shafts.
- If resonance occurs, it can physically snap the generator shaft.
- Requires complex damping and bypass schemes (e.g., spark gaps, MOVs) to protect the equipment during faults.

Comparison: Shunt vs Series Capacitors

Feature	Shunt Capacitor	Series Capacitor
Connection	Parallel to load/bus	Series with line
Primary Purpose	Power Factor correction	Increase power transfer limit
Voltage Boost	Fixed (if unswitched)	Proportional to load current
Application	Distribution & Transmission	Long EHV Transmission lines
Fault Current Effect	Little effect	Increases short-circuit levels

Equipment layout of Series Capacitors

- Because it is in series with the line, the entire capacitor bank sits at line voltage (e.g., 400kV).
- The banks are mounted on fully insulated platforms.
- Requires an intricate bypass circuit (Bypass breaker, Metal Oxide Varistor) to protect the capacitor from blowing up during a line fault.

Diagram/Visual: Diagram showing the main capacitor in parallel with an MOV, a spark gap, and a bypass breaker.

Summary of Lecture 29

- Reactive power increases losses and causes voltage drops.
- Compensation generates reactive power locally.
- Shunt capacitors improve power factor and support voltage.
- Series capacitors reduce line reactance, boosting power transfer limits.
- SSR is a major mechanical risk associated with series compensation.

Next Lecture Preview

- In Part 2, we will explore:
- Shunt Reactors (to prevent overvoltage).
- Synchronous Condensers (rotating compensation).
- Static Var Compensators (SVC).
- STATCOM (Advanced dynamic compensation).