ECE 529
Utility Applications of Power Electronics
Session 27
VSC Applications

- Flexible AC Transmission Systems (FACTS)
  - VSC, Thyristor
- PV
- Wind Turbines
- Storage
- HVDC with VSC → DC Circuit Breakers (Multiterminal Systems)
  → LCC
- Harmonic Filters
  → Distribution

- Fault injection
- Grid Forming
Distribution Problem Areas

- Usually fall under power (voltage) quality:
  - Voltage sags due to faults, motor starting
  - Voltage flicker
  - Interruptions
  - Harmonics

Traditional Solutions

- Reactive compensation (distribution)
  - Shunt capacitors/reactors
  - Synchronous condensers
  - Passive harmonic filters
- Reactive compensation (transmission)
  - Shunt compensation (capacitors, synchronous condensers)
  - Series capacitors (SSR issues in some cases)

Also subsynchronous control interactions with power converters → Type 3 wind turbines
## Traditional Solutions

- Transmission system fixes
  - Automatic Generation Control
  - Excitation control/Power System Stabilizers
  - Phase shifting transformers
  - Faster protection (trip/reclose)
  - Operational limits
  - Reconductor lines
  - Increase voltage levels
  - Build more lines
  - Special stability controls

## Power Electronic Applications?

- Specialized applications where traditional technologies inadequate
- Apply where power converters matter
  - Fast, dynamic compensation is needed
    - Avoid steady-state AC compensation
  - Conversion ac/dc or between frequencies
    - For transmission
    - Due to nature of generation or energy storage
Transmission Applications

- Static VAR Compensators
  - 1: Reactive compensator—faster response
  - 2: Started with saturated reactors in 1930's developed in Germany, Dr. E. Friedlander
    - Still used in 1960's
  - 3: First thyristor based devices in 1970's
  - 4: Used at transmission and distribution level

VSC → inject current to

Flexible AC Transmission Systems (FACTS)
- 1: Shunt compensation (L-N or L-L)
- 2: Series compensation
- 3: Phase angle regulator
- 4: Combined #1, #2, and #3
- 5: Speed of response
- 6: Enhanced capabilities
- Drawbacks: Cost, complexity

Spring 2017
For the simple 2 bus system shown in the figure look at steady-state reactive compensation

\[ |V1| = 132 \text{ kV (line to line)} \]

| at an angle of 0 degrees

\[ |V2| = 132 \text{ kV (line to line)} \]

| at an angle of -20 degrees

Define Constants

Sending and Receiving End Voltages

\[ V_{1L} := 132 \text{kV} \]

\[ V_{2L} := 132 \text{kV} \]

\[ V_{1p} := \frac{V_{1L}}{\sqrt{3}} \]

\[ V_{2p} := \frac{V_{2L}}{\sqrt{3}} \]

\[ V_{1p} = 76.21 \text{kV} \]

\[ V_{2p} = 76.21 \text{kV} \]

Sending and Receiving End Angles

\[ \theta_1 := 0 \text{deg} \]

\[ \theta_2 := -20.14 \text{deg} \]

Line Reactance

\[ X_{\text{line}} := 10 \text{ohm} \]

Define Unit for MVar

\[ \text{MVar} := \text{MW} \]
\[ X_{c_{\text{max}}} := 0.6 \cdot X_{\text{line}} \]

\[ P_{12_{\text{max}}} := \frac{3 \cdot V_{1p} \cdot V_{2p} \cdot \sin(\theta_1 - \theta_2)}{X_{\text{line}} - X_{c_{\text{max}}}} \]

\[ P_{12_{\text{max}}} = 1499.84 \text{ MW} \]

**Advantages**
1) Effective way to increase power transfer
2) Can vary compensation by switching multiple banks in series/parallel combinations
3) Insensitive to location
4) Relatively inexpensive (compared to other options)
5) Doesn't result in overvoltages at either bus when line lightly loaded

**Disadvantages**
1) Potential series resonance problems
2) Possible subsynchronous resonance (SSR)
3) Stepwise variation in compensation only
4) Slow response if need to change \( X_c \) (can't damp slow oscillations)
5) Overvoltage protection needed for capacitor in event of fault on line
6) Impact on distance protection schemes

**B.** Instead of series compensation add phase angle control. What phase, \( \alpha \), does the compensator need to produce? Let's say that \( \alpha_{\text{max}} = 30^\circ \), what is \( P_{12_{\text{max}}} \)?

![Diagram](attachment:image.png)

- \( |V_1| = 132 \text{ kV (line to line)} \) at an angle of 0 degrees
- \( |V_2| = 132 \text{ kV (line to line)} \) at an angle of -20.1 degrees
(a) Compute $P_{12}$

$$P_{12} := \left( \frac{3 \cdot V_{1p} \cdot V_{2p}}{X_{\text{line}}} \right) \sin (\theta_1 - \theta_2)$$

$$P_{12} = 599.93\, \text{MW} \quad \text{For all intensive purposes: } 600\, \text{MW}$$

(b) Next increase $P_{12}$ to 700 MW. Consider the following options to do so. Give a written evaluation of each form of compensation.

A. Add series capacitance. What size capacitor is needed? What is the percent compensation? If the max compensation is 60%, what is $P_{12\, \text{max}}$?

Assume $\theta_{V2}$ doesn't change...

$$X_{\text{total}} := \frac{3 \cdot V_{1p} \cdot V_{2p} \cdot \sin (\theta_1 - \theta_2)}{700\, \text{MW}}$$

$$X_{\text{total}} = 8.57\, \text{ohm}$$

$$X_{\text{cap}} := X_{\text{line}} - X_{\text{total}} \quad X_{\text{cap}} = 1.43\, \text{ohm}$$

$$\text{PercentCompensation} := \frac{X_{\text{cap}}}{X_{\text{line}}} \quad \text{PercentCompensation} = 14.3\, \%$$

Cap := \frac{1}{2 \cdot \pi \cdot 60\, \text{Hz} \cdot X_{\text{cap}}} \quad \text{Cap} = 1855.6\, \mu\text{F}$$
Total Angle: \( \alpha = \arcsin \left( \frac{700 \text{MW} \cdot X_{\text{line}}}{3 \cdot V_{p} \cdot V_{2p}} \right) \)

\( \alpha = 3.55^\circ \)

\( P_{12, \text{max}} = 1337.49 \text{ MW} \)

Advantages:
1) Effective control of power flow in a given line
2) Can locate at substation at the end of a line
3) Unlikely to create resonance problems

Disadvantages:
1) Potential stability problems at large angles
2) Somewhat sensitive to location
3) Stepwise variation in compensation only
4) Slow response if need to change \( \alpha \) (can't damp slow oscillations)

Unified Power Flow Controller (UPFC)
C. We next look at adding midpoint compensation. Let's just call it an ideal compensator right now. What midpoint voltage is needed? How much reactive power does the compensator provide? Do you consider this a feasible solution?

\[ |V1| = 132 \text{kV (line to line)} \]
\[ \text{at an angle of 0 degrees} \]
\[ |V2| = 132 \text{kV (line to line)} \]
\[ \text{at an angle of -20.1} \]

\[ X_{\text{half}} := \frac{X_{\text{line}}}{2} \]
\[ X_{\text{half}} = 5 \cdot \text{ohm} \]

Lossless line, so the following relationships hold:

- \[ P_{12\text{req}} := 700\text{MW} \]
- \[ P_{1m} := P_{12\text{req}} \]
- \[ P_{m2} := P_{12\text{req}} \]

\[ \theta_m := \frac{\theta_2 - \theta_1}{2} \]

\[ V_{mp} := \frac{P_{1m} \cdot X_{\text{half}}}{3 \cdot V_{1p} \cdot \sin(\theta_1 - \theta_m)} \]
\[ V_{mp} = 87.55 \text{kV} \]
\[ V_{mL} := \sqrt{3} \cdot V_{mL} \quad V_{mL} = 151.64 \cdot \text{kV} \]

\[ \text{OverVolt} := \frac{V_{mL}}{V_{1L}} \quad \text{OverVolt} = 114.88 \cdot \% \]

\[ Q_{m1} := \frac{\left( V_{mL} \right)^2}{X_{\text{half}}} - \left( \frac{V_{mL} \cdot V_{1L} \cdot \cos(\theta_m - \theta_1)}{X_{\text{half}}} \right) \]

\[ Q_{m2} := \frac{\left( V_{mL} \right)^2}{X_{\text{half}}} - \left( \frac{V_{mL} \cdot V_{2L} \cdot \cos(\theta_m - \theta_2)}{X_{\text{half}}} \right) \]

\[ Q_{\text{compensator}} := Q_{m1} + Q_{m2} \]

\[ Q_{\text{compensator}} = 1314.91 \cdot \text{MVAr} \]

This is almost double P12, so this is not a reasonable solution in this case.

**Advantages**
1) Local reactive support
2) Will not create resonance problems unless use fixed capacitors
3) Continuously variable is use synchronous condensor

**Disadvantages**
1) Sensitive to location
2) Relatively slow response if rotating machine
3) Not as effective as series capacitor or phase shifting transformer
4) High cost