Day-4
Custom Power
Compensating Devices

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Load Compensation using DSTATCOM

The primary goals of a DSTATCOM are

• to cancel the effect of poor load power factor such that the current drawn from the source has a near unity power factor.

• to cancel the effect of harmonic contents in loads such that current drawn from the source is nearly sinusoidal.

• to offset the effect of unbalanced loads such that the current drawn from the source is balanced.

In addition, it can also eliminate dc offset in loads.
Ideal DSTATCOM

- **Source voltage**: $v_s$, **source current**: $i_s$, **load**: $Z_I$
- **load current**: $i_I$
- **The DSTATCOM**: current sources $i_{fa}$, $i_{fb}$ & $i_{fc}$

Point of common coupling
DSTATCOM - Function

- Inject a set of currents such that the source currents are balanced and sinusoidal.
- If the load is unbalanced then the zero-sequence current circulates in the path joining the neutral of the load (n) and the compensator (n’) such that the current flowing through the neutral (N) is zero.
- Additionally power factor correction can also be performed such that the DSTATCOM supplies part or whole of the reactive power required by the load.
• Generate a set of reference currents $i_{fa}^*$, $i_{fb}^*$ and $i_{fc}^*$.
• These currents when injected into the system will simultaneously perform the following three tasks.

a) Force the zero-sequence source current to be zero, i.e.,

$$i_{sa} + i_{sb} + i_{sc} = 0$$

• This guarantees that the zero-sequence current flowing through the source neutral is zero in a 3-phase, 4-wire system.
b) Force the angle between the source voltage and current to be a specified value, i.e.,

\[ \angle(v_{sa}) = \angle(i_{sa}) + \phi \]

\[ \angle(v_{sb}) = \angle(i_{sb}) + \phi \]

\[ \angle(v_{sc}) = \angle(i_{sc}) + \phi \]

- In the above, \( \phi \) is pre-specified.
- If \( \phi = 0 \), the source voltage and load current are in phase. This will be called the unity power factor (upf) operation.
c) The DSTATCOM must not absorb/generate any real power in the steady state, i.e., it only supplies zero-mean oscillating power.
The power condition can be written as

\[ v_{sa} i_{sa} + v_{sb} i_{sb} + v_{sc} i_{sc} = p_{lav} \]

In the above, \( p_{lav} \) is the average power drawn by the load.

To calculate it online, 3 Hall-effect voltage and 3 current transformers are required.

A low-pass Butterworth (or Chebyshev) filter can be used. It will have longer settling time.

Alternatively, a moving average filter settles in just half (or full) cycle.
DSTATCOM – Reference Generation

- Since

\[ i_{fk} = i_{lk} - i_{sk}, \quad k = a, b, c \]

- The reference currents are

\[
\begin{align*}
i_{fa}^* &= i_{la} - \frac{v_{sa} + (v_{sb} - v_{sc})\beta}{v_{sa}^2 + v_{sb}^2 + v_{sc}^2} p_{lav} \\
i_{fb}^* &= i_{lb} - \frac{v_{sb} + (v_{sc} - v_{sa})\beta}{v_{sa}^2 + v_{sb}^2 + v_{sc}^2} p_{lav} \\
i_{fc}^* &= i_{lc} - \frac{v_{sc} + (v_{sa} - v_{sb})\beta}{v_{sa}^2 + v_{sb}^2 + v_{sc}^2} p_{lav}
\end{align*}
\]

\[ \beta \equiv \tan \phi / \sqrt{3} \]
In a similar way the algorithm can be applied to 3p, 3w systems with both star and delta connected loads.
A DSTATCOM is realized by a VSC. The VSC is supplied by a dc capacitor. The DSTATCOM must meet the following requirements:

- It should be able to inject distorted and negative-sequence currents.
- It must be able to provide a circulating path for the zero-sequence load current such that it does not travel towards the source.
- It must be able to regulate the voltage dc capacitor such that no external battery source is required.
DSTATCOM Structure

- A common dc capacitor makes the distribution of power easier.
- The transformers provides isolation in addition to voltage step down.
DSTATCOM Structure

- Suitable for dc compensation.
- Two capacitors \((C_{dc1} \text{ and } C_{dc2})\) required.
- An additional chopper circuit containing \(S_{ch1}, S_{ch2}, R_p\) and \(L_p\) required.
DSTATCOM Structure

- Normally the switches $S_{ch1}$ are $S_{ch2}$ open.
- Suppose $V_{dc1}$ drops and $V_{dc2}$ rises.
- $S_{ch2}$ is closed.

- Current $I_p$ builds up in $L_p$ in the direction shown.
- Also the voltage $V_{dc2}$ falls.
- Once $I_p$ builds up to a desired level, $S_{ch2}$ is opened.
- The current $I_p$ discharges through $D_{ch1}$ charging the capacitor $C_{dc1}$.
- The voltage $V_{dc1}$ rises.
• **Zero sequence current is routed to path** \( n-n' \).
• **This must be supplied by the 4\(^{th}\) leg.**
• **Complexity and switching losses increase.**
DSTATCOM Control

- The dc voltage supplying the DSTATCOM must be held constant irrespective of the losses in the circuit.
- This can be accomplished by drawing power from the ac system to compensate for the losses.
- The power equation then must be modified to incorporate the losses as

\[ v_{sa}i_{sa} + v_{sb}i_{sb} + v_{sc}i_{sc} = P_{lav} + P_{loss} \]

- The reference current equations also get modified in which \( P_{lav} \) is replaced by the sum \( P_{lav} + P_{loss} \).
DSTATCOM Control

- Here $p_{loss}$ is generated by dc capacitor control loop.
- A PI controller is used for generating this

$$p_{loss} = K_P e + K_I \int e \, dt$$

$$e = V_{ref} - V_{dc,av}$$

- $V_{ref}$ is the reference dc voltage and $V_{dc,av}$ is the average dc voltage.
- Any deviation of the capacitor voltage from the reference is due to losses.
- The PI controller loop draws the loss from the ac system to hold the voltage constant.
• The reference currents are tracked in a hysteresis band.
• Simulation results of the DSTATCOM operation.
DSTATCOM Operation

Simulation

Experimental
The a load is supplied by a feeder.

The DSTATCOM is connected at PCC (terminal) at the end of the feeder.
• The reference generation algorithm assumes balanced supply.
• The left figure shows when the measured terminal voltages are used and the right figure shows when fundamental voltages are used.
DSTATCOM Connected to weak ac supply point

- To bypass the switch frequency harmonic generated, capacitor $C_f$ is used (left).
- The hysteresis tracking of $i_f$ results in an unstable feedback system (right).
- Alternate control strategy required.
One approach is state feedback control using linear quadratic regulator (LQR).

This will require on-line generation of all the reference states.

The LQR design is robust to parameter uncertainties.

The output feedback approach is simpler but cannot guarantee stability.
• With LQR control the source currents become sinusoidal.
• To achieve this, the PCC (terminal) voltages are forced to be sinusoidal.
DSTATCOM – Performance for Non-Stiff Systems

• The unbalance and harmonics in the source voltages get reflected in the source currents.
DSTATCOM in Voltage Control Mode

- The Thevenin equivalent of the system looking at Bus-3 is the same as those shown in Slides 245 or 247.
- We can then use a state feedback or output feedback controller to hold the voltage of Bus-3.
- Let us assume that we would like to correct the voltage of Bus-3.
• The magnitude of the bus voltage can be chosen arbitrarily.
• The phase angle ($\delta$) should be controlled to ensure the power flow.
• Note that the dc capacitor must be able to supply the DSTATCOM while maintaining its voltage by drawing power from the ac system.
• Two PI controllers are designed in an inner power and outer voltage loop configuration.
• The outer loop regulates the dc voltage as

$$p_{shref} = K_p \left( v_{dref} - v_{dcav} \right) + K_I \int \left( v_{dref} - v_{dcav} \right) dt$$
• The inner loop sets the angle by adjusting the power difference as

\[ \delta = C_P (p_{shref} - p_{shav}) + C_I \int (p_{shref} - p_{shav}) dt \]
Voltage Control Mode Results

- The source is balanced but the load is unbalanced & distorted.
- The uncompensated bus voltage ($v_{ta}$) is distorted (top trace).
- The compensated bus voltage ($v_{ta}$) is distortion free (bottom trace).
Voltage Control Mode

Results

Load angle and power drawn from the ac system.
Voltage Control Mode Results

- The source voltages are unbalanced (top trace) and the load is both unbalanced and distorted.
- The DSTATCOM makes the bus voltages balanced (bottom trace).
Dynamic Voltage Restorer (DVR)

- In addition, it can also tightly regulate the voltage at the load bus.

- A DVR is a series connected device.

- It protects sensitive loads from sag, swell or source voltage distortion.
A fault in either locations shown will result in a voltage sag in the feeder supplying the load. The DVR adds a voltage in series to offset the sag.
DVR Installations

• In August 1996, Westinghouse Electric Corporation installed world’s first DVR in Duke Power Company’s 12.47 kV substation in Anderson, South Carolina to protect a automated rug manufacturing plant.

• The next commissioning of a DVR was done by Westinghouse in February 1997 in Powercor's 22 kV distribution system at Stanhope, Victoria, Australia. This was done to protect a diary milk processing plant.

• The saving that may result from the installation of this DVR is estimated at over $100,000 per year.

• The first ever platform mounted DVR was installed to protect Northern Lights Community College and several other smaller loads in Dawson Creek, British Columbia, Canada.
The Study System

The DVR is represented by voltage sources $v_{fa}$, $v_{fb}$, and $v_{fc}$.
The dc storage is one important issue in the DVR design. Schematic diagrams of (a) rectifier supported and (b) capacitor supported are shown. Other possibility is battery back up/support.
The DVR should not absorb any real power in the steady state.

Voltage injection must be in quadrature with line current.

Assume that source voltage and desired load voltage to be 1.0 per unit.

Then the injection must be such that $OA$ represent the source voltage.
• The compensator power is zero in the steady state.
• The DVR on the left has a filter capacitor in parallel with the transformer secondary.
• The DVR on the right has an LC filter connected in the primary side of the transformer.
Without active power exchange with the ac system, the capacity of the DVR to compensate a deep sag gets limited.
Rectifier Supported DVR

- Power flow is unidirectional, i.e., from the rectifier to DVR and not the other way round.
- Difficult for the DVR to absorb power transiently.
- During deep sag, if the rectifier output capacitor voltage exceeds the peak of the input ac voltage, the rectifier will cut off.
- The rectifier generates harmonics at its input terminals.
- **Solutions:** Use UPQC.
Unified Power Quality Conditioner (UPQC)
A UPQC has a shunt inverter and a series inverter, both connected together through a dc storage capacitor.

The dc capacitor facilitates power exchange between the two inverters.

The UPQC can independently or jointly perform the tasks of both the series and shunt compensators.

No much research done.

Whether the device justifies its high cost.

Possibly the star of the future.
Custom Power Park

Diagram showing the connection between Substation 1, Substation 2, SSTs, Standby Generator, DSTATCOM, DVR, CP Control Center, and various connections leading to Custom Power Park A, AA, and AAA.
- STS is GTO based.
- B1, B2 are SCBs, while B3, B4 are mechanical.
Loads L-2 and L-3 and the CPP bus voltage are balanced sinusoidal irrespective of L-1 being unbalanced and distorted.
Thank you