Utility Applications of Power Electronics

ECE 529

Session 41
• Now determine what the STATCOM ac terminal voltage will be and the current at the terminals.

\[ V_{\text{low}} := \frac{V_{\text{mL}}}{10} \quad V_{\text{low}} = 36.94\text{-kV} \]

\[ X_{\text{xfmr\_low}} := 0.02\text{ohm} \quad L_{\text{xfmr\_low}} := \frac{X_{\text{xfmr\_low}}}{2\cdot\pi\cdot60\text{Hz}} \quad L_{\text{xfmr\_low}} = 0.05\text{-mH} \]

\[ Z_{\text{BLV}} := \frac{(34.5\text{kV})^2}{100\text{MVA}} \quad X_{\text{pu}} := \frac{X_{\text{xfmr\_low}}}{Z_{\text{BLV}}} \quad X_{\text{pu}} = 0.00168 \]

• In the steady-state, the STATCOM is equivalent to a voltage source behind an inductance (the transformer reactance). The fundamental component of the compensator voltage is in phase with the system voltage at the midpoint since no real power is transferred.

• We can take the equation for Q transferred across the transformer inductance (viewed from the line side, since the transformer absorbs Q too):

\[ Q_{\text{compensator}} = \frac{V_{\text{low}}^2 - V_{\text{low}}\cdot V_{\text{comp}}\cdot \cos(0\text{deg})}{X_{\text{xfmr\_low}}} \quad \text{Negative sign since} \quad Q \text{ going to power system} \]

\[ V_{\text{comp}} := \frac{Q_{\text{compensator}} \cdot X_{\text{xfmr\_low}} + V_{\text{low}}^2}{V_{\text{low}}\cdot \cos(0\text{deg})} \]

\[ V_{\text{comp}} = 37.31\text{-kV} \quad \text{line to line} \quad \frac{V_{\text{comp}}}{\sqrt{3}} = 21.54\text{-kV} \]

\[ \frac{V_{\text{comp}}}{34.5\text{kV}} = 1.08157\text{-pu} \]
Case 2: Without the step down transformer:

Results match calculation with small error for:
- Midpoint voltage
- Real power transfer
- Reactive power injection to midpoint bus

ATPDraw Simulation Results:

- Power circuit:
  1. STATCOM represented just as an ideal voltage source
  2. $P_{12}$ calculated in TACS as described in class
**Powerworld Simulation Results:**

Basecase, no compensation, verify calculations.

Case 1: With the step down transformer (preferred solution)

Results match calculation with small error for:
- Midpoint: voltage
- Real power transfer
- Midpoint: reactive power injection at STATCOM
- Reactive power injection to midpoint bus

Q at STATCOM VSC terminals
\[ V_{\text{comp}} = 40.543 \cdot \text{kV} \quad \text{line to line} \quad \frac{V_{\text{comp}}}{\sqrt{3}} = 23.408 \cdot \text{kV} \quad \text{Angle is: } \theta_m = -8.803 \cdot \text{deg} \]

\[ \frac{V_{\text{comp}}}{34.5 \text{kV}} = 1.17516 \cdot \text{pu} \]

And \( I_{\text{comp}} \) can be found from:

\[ I_{\text{comp}},\text{low} := \frac{Q_{\text{comp}}}{\sqrt{3} \cdot V_{m,\text{LV}}} \quad I_{\text{comp},\text{low}} = 10.938 \cdot \text{kA} \]

\[ Q_{\text{statcom}} := \sqrt{3} \cdot V_{\text{comp}} \cdot I_{\text{comp},\text{low}} \quad Q_{\text{statcom}} = 768.069 \cdot \text{MVAR} \]

- Now try with out the lossess approximation:

\[ Q_{\text{HV,xfmr}} := Q_{\text{comp}} \]

\[ I_{\text{HV,side}} := -\left( \frac{Q_{\text{HV,xfmr}}}{3 \cdot V_{m,p}} \right) e^{j(\theta_m + 90 \deg)} \quad |I_{\text{HV,side}}| = 1093.761 \text{ A} \quad \text{arg}(I_{\text{HV,side}}) = -98.802 \cdot \text{deg} \]

\[ I_{\text{LV,side}} := \frac{V_{\text{HV}}}{V_{\text{LV}}} \quad |I_{\text{LV,side}}| = 10.938 \cdot \text{kA} \quad \text{arg}(I_{\text{LV,side}}) = -98.802 \cdot \text{deg} \]

\[ I_{\text{comp},\text{low}} - |I_{\text{LV,side}}| = 0 \cdot \text{A} \]

\[ V_{\text{L,STATCOM,LN}} := \left( \frac{V_{m,\text{LV}}}{\sqrt{3}} \right) e^{j \theta_m} + I_{\text{LV,side}} \left( R_{\text{xfmr,LV}} + j \cdot X_{\text{xfmr,low}} \right) \]

\[ |V_{\text{L,STATCOM,LN}}| = 23.408 \cdot \text{kV} \quad \text{arg}(V_{\text{L,STATCOM,LN}}) = -9.227 \cdot \text{deg} \]
\[ \left( \frac{V_{\text{comp}}}{\sqrt{3}} \right) e^{j\theta_m} = V_{t,\text{STATCOM}_LN} = (26.563 + 171.535i) V \]

\[ Q_{\text{statcom}_\text{alt}} := \text{Im}\left( 3 \cdot V_{t,\text{STATCOM}_LN} \cdot I_{LV\text{side}} \right) \quad Q_{\text{statcom}_\text{alt}} = 768.069\cdot\text{MVAR} \]

\[ (Q_{\text{statcom}}) - (Q_{\text{statcom}_\text{alt}}) = -2.384 \times 10^{-7} \text{ W} \]

- Calculate VDC:

\[ V_{\text{tpk}} := \sqrt{2} \cdot |V_{t,\text{STATCOM}_LN}| \quad V_{\text{tpk}} = 33.104\cdot\text{kV} \]

\[ \bullet \quad \text{We know:} \quad V_{\text{tpk}} = m \cdot \frac{V_{dc}}{2} \quad m_{\text{max}} := 0.8 \quad V_{dc_{\text{calc}}} := 2 \cdot \frac{V_{\text{tpk}}}{m_{\text{max}}} \quad V_{dc_{\text{calc}}} = 82760.6\cdot\text{V} \]

- Then if we round to nearest 10V:

\[ V_{dc} := 82.770\text{kV} \quad \frac{V_{dc}}{2} = 41.385\cdot\text{kV} \]

- Calculate PI controller gains

\[ \bullet \quad \text{Desired time constant:} \quad \tau_i := 0.005\text{sec} \]

We know that:

\[ \frac{k_i}{k_p} = \frac{R_S}{L_S} \quad \text{and} \quad \frac{k_p}{L_S} = \frac{1}{\tau_i} \]

So:

\[ k_p := \frac{L_{\text{xfrmrLV}}}{\tau_i} \quad k_p = 0.101 \Omega \quad k_i := k_p \cdot \left( \frac{R_{\text{xfrmrLV}}}{L_{\text{xfrmrLV}}} \right) \quad k_i = 3.174 \frac{1}{\text{F}} \]
- Find cross coupling cancellation term

\[ \Omega_L := 2 \cdot \pi \cdot 60 \text{Hz} (L_{xfrmLV}) \quad \Omega_L = 0.1904 \, \Omega \]

- Find \( V_{\text{base}} \) for PLL

\[ V_{\text{base}} := \sqrt[3]{\frac{2}{3}} \cdot V_{LV} \quad V_{\text{base}} = 28.169 \cdot \text{kV} \]
Sampling rate at 3840 (multiple of 60)

345 kV System

Subtract 90 deg from angles so PlotXY phasors calculate with bus 1 at 0 degrees

Voltage trans VT for measur
Real power at the point of interconnect and dc power)

\[ P_{\text{ave}} = 0 \text{ MW} \]
\[ P_{3\text{ph}} = -2.6 \text{ MW} \]

A bit lower than calculated earlier:
\[ P_{\text{loss}} = 5.696 \text{ MW} \]
Introduction to High Voltage Direct Current (HVDC) Transmission

- Update to Edison's Vision
- AC Power Generation at Conventional Voltage
  » Step Voltage Up to High Levels
- Convert From AC to DC and Back
  » DC Voltages Pole to Ground up to 800 kV
  » Currents up to about 3000A → 5000 to 7000 A
- Most Systems Presently Point to Point
  » Some systems with 3 – 5 converter terminals
  » Multiterminal Grids

HVDC Transmission
Spring 2023
A Little History

- First "Static" Var Compensator (Germany, late 1930's)
  » saturated reactors in combination with capacitors, into the 1960's
- First HVDC project: Berlin-Charlottenburg 1942
  » Equipment to Moscow 1951
- Gotland 1954 (first successful operating project)
- Pacific HVDC Intertie 1970 (one of last Mercury Arc Valve)
- Thyristor Controlled Reactors (TCR), GE, 1970
- HVDC projects move to Thyristors in early 1970's
- Voltage source converters late 1990s

Berlin Mercury Arc Valves 1942

HVDC Transmission 3 Spring 2023
Gotland Mercury Arc Valve

HVDC Power Transmission

- No distance limitation for stability
- No distance limit for underground/sea cables
- Controlled power flow
- High power transfer, fewer lines,
  » Narrower ROW
  » Lower losses
- Potentially a firewall against cascading outages
Basic Concepts with HVDC

- Overhead Lines
  - Bulk Power Transfer Over Long Distances
  - Possibly Connecting Asynchronous Systems
- Underwater or Underground Cables
- Back-to-back interconnections
  - Asynchronous systems – same or different frequency

Fast Control Available

- Control Power Flow on DC Link (point to point)
  - Control DC Voltage
  - Control DC Current
- Damp AC Power Systems Oscillations
- VSC HVDC Converters Can Directly Control AC Side Voltage or Reactive Power
  - LCC HVDC Converters Can to an Extent
LCC versus VSC HVDC

- Most existing systems use line commutated converters (LCC)
- VSCs have advantages in several applications
  » Independent control of real and reactive power injection
  » Provide dynamic voltage support to the ac system
  » Less harmonic filters requirement
  » Easier for multiterminal HVDC
- Also disadvantages
  » Losses
  » Lower Vdc and MW ratings (so far)
  » DC faults
  » Most new projects are VSC

LCC HVDC Transmission

- Common Applications
  - Long-distance, bulk-power transmission
  - Sea and land cable transmission
  - Asynchronous interconnections
  - Power flow control
  - Congestion relief
- Ratings
  - Power range up to 4000 MW at ± 500 kV
  - Power range up to 4800 MW at ± 600 kV
  - Voltage range increasing to ± 800 kV with power range up to 8000 MW
Generator Outlet Transmission

- More power on fewer lines
- Improved stability
- Lower installed cost
- Reduced losses
- Double circuit (bipolar line)
- Reduced ROW
- One line vs. two

Asynchronous Interconnections

- Economic
  - Firm transactions
  - Shared reserves
  - Increase diversity
  - Economy energy trade

- Reliability
  - Emergency power support
  - Mutual assistance
  - Isolate disturbances
  - 'Fire-wall' against cascading outages
  - Reserve sharing

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HVDC in North America

Asynchronous borders

Offshore wind
Interconnections

- Firm capacity
- Bypass congestion
- Avoid loop flow
- No limit due to parallel paths
- Interconnect diverse regions

LCC Operating Configurations and Modes

Monopole, ground return
Monopole, metallic return
Monopole, midpoint grounded
Back-up-Back

Bipole
Bipole, Series-Connected Converters

Multimodul

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