Instability of Voltage Source Converters in weak AC grid conditions: a case study

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Introduction (1)

- Worldwide growth of number of HVDC links using Voltage Source Converters (VSC)
- VSCs can operate with weaker AC grids than Line Commutated Converters
  - i.e. with smaller values of \( \frac{\text{AC system short-circuit capacity}}{\text{VSC nominal power}} \)
- However, VSCs can be subject to small-signal instability when connected to a weak AC grid
Introduction (2)

• Improved controls of VSC have been proposed to extend the range of stable operation

• This presentation: a case study of destabilization of a VSC after a severe drop of short-circuit capacity
  – relying on a simple system with generic VSC model
  – combining small-signal and large-disturbance analyses
System and disturbance

after fault clearing by line opening:

\[ P_{\text{max}}^{st} = \frac{V \cdot E_{\text{th}}}{X} = \frac{1 \cdot 1}{2} = 0.5 \text{ pu} (= S_{sc}) \]
Instability driven by power electronics

does not fall in one of the “classical” categories (angle, frequency, voltage) “ruled” by synchronous machines and loads
Response to fault and line tripping

- In terms of pre-fault power, $P_{max}^{st}$ is the "static" stability limit
  - no post-disturbance equilibrium; static power flow equations infeasible
- but the "dynamic" stability limit can be smaller:

\[ P_{max}^{st} \]

- same initial operating point
- same disturbance
- different controller settings
VSC model (1)

Current controllers (in dq frame)

Phase reactor dynamics (in xy frame)

Phase Locked Loop (PLL)

\[ I = i_x + j i_y \]

\[ V = v_x + j v_y \]
VSC model (2)

Active power control outer loop

\[ P_{\text{ref}} \]

\[ v_x i_x + v_y i_y \]

\[ \sqrt{v_x^2 + v_y^2} \]

Terminal voltage control outer loop

\[ V_{\text{ref}} \]

\[ K_{vi} \]

\[ K_{pi} \]

\[ I_{max}^d \]

\[ I_{max}^q \]
Small-signal analysis: simplified model

\[
\frac{d}{dt} i_d = \frac{1}{T_e} (i_d^{ref} - i_d)
\]
\[
\frac{d}{dt} i_q = \frac{1}{T_e} (i_q^{ref} - i_q)
\]
\[
\frac{d}{dt} \theta = K_{pll} (-v_x \sin \theta + v_y \cos \theta)
\]
\[
\frac{d}{dt} i_d^{ref} = K_{pi} (P^o - v_x i_x - v_y i_y)
\]
\[
\frac{d}{dt} i_q^{ref} = -K_{vi} (V^o - \sqrt{v_x^2 + v_y^2})
\]
\[
0 = -i_x + i_d \cos \theta - i_q \sin \theta
\]
\[
0 = -i_y + i_q \cos \theta + i_d \sin \theta
\]
\[
0 = -v_x + E_{th} - X_{th} i_y
\]
\[
0 = -v_y + X_{th} i_x
\]

PLL

active power control

terminal voltage control
dq → xy reference

network (Thévenin equiv.)
Small-signal analysis: simplified model linearized

\[
\begin{align*}
\begin{bmatrix}
\Delta i_d \\
\Delta i_q \\
\Delta \theta \\
\Delta i_d^{\text{ref}} \\
\Delta i_q^{\text{ref}}
\end{bmatrix}
&= \begin{bmatrix}
\frac{-1}{T_e} & 0 & 0 & \frac{1}{T_e} & 0 \\
0 & \frac{-1}{T_e} & 0 & 0 & \frac{1}{T_e} \\
0 & 0 & A_{\theta \theta} & 0 & 0 \\
0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 \\
\end{bmatrix}
\begin{bmatrix}
\Delta i_d \\
\Delta i_q \\
\Delta \theta \\
\Delta i_d^{\text{ref}} \\
\Delta i_q^{\text{ref}}
\end{bmatrix}
\end{align*}
\]

\[
\begin{bmatrix}
-1 & 0 & 0 & 0 & 0 \\
0 & -1 & 0 & 0 & 0 \\
0 & 0 & -X_{th} & -1 & 0 \\
0 & 0 & 0 & -1 & 0 \\
0 & 0 & 0 & 0 & -1 \\
\end{bmatrix}
\]

\[
J_{dyn} = A - B \ D^{-1} \ C
\]

\[
A_{\theta \theta} = K_{p\theta}(1 - v_0^x \cos \theta^0 - v_0^y \sin \theta^0) \\
A_{\theta x} = -K_{p\theta} \sin \theta^0 \\
A_{\theta y} = K_{p\theta} \cos \theta^0 \\
A_{x \theta} = -i_0^d \sin \theta^0 - i_0^q \cos \theta^0 \\
A_{y \theta} = -i_0^q \sin \theta^0 + i_0^d \cos \theta^0
\]
Small-signal analysis: results (1)

Locus of dominant eigenvalues when varying initial power $P^\circ$; $X_{th} = 2$ pu

- $P_{max}^{st} = 0.5$ pu
- $P_{max}^{dyn} = 0.44$ pu
- $K_{vi} = 15$
- $K_{pll} = 60$
- $K_{pi} = 30$
Small-signal analysis: results (2)

Locus of dominant eigenvalues when varying initial power $P^\circ; \ X_{th} = 2 \text{ pu}$

$P_{max}^{dyn} = 0.49 \text{ pu}$

$K_{vi} = 15 \quad K_{pll} = 60 \quad K_{pi} = 30$

$K_{vi} = 60 \quad K_{pll} = 60 \quad K_{pi} = 30$

stability improved by making voltage control faster than power control
Small-signal analysis : results (3)

Locus of dominant eigenvalues when varying initial power $P^\circ$; $X_{th} = 2$ pu

$K_{vi} = 15$  $K_{pll} = 60$  $K_{pi} = 30$
$K_{vi} = 60$  $K_{pll} = 60$  $K_{pi} = 30$
$K_{vi} = 15$  $K_{pll} = 600$  $K_{pi} = 30$

making the PLL faster deteriorates stability
VSC model for large voltage disturbances (1)

\[ V = \sqrt{v_x^2 + v_y^2} \]

\[ V_{\text{ref}} \rightarrow \frac{K_{vi}}{s} \rightarrow i_{q_{\text{ref}}} \]

\[ I_{d_{\text{max}}} \rightarrow \sqrt{1 - (i_d_{\text{ref}})^2} \]

if \( V > 0.9 \text{ pu} \)

\[ P_{\text{ref}} \]

\[ v_x i_x + v_y i_y \]

\[ -I_{d_{\text{max}}} \]

\[ K_{pi} \]

\[ 1 \text{ pu} \]
VSC model for large voltage disturbances (2)

\[
P_{\text{ref}} = v_x i_x + v_y i_y
\]

\[
\sqrt{1 - (i_q^{\text{ref}})^2}
\]

\[
V = \sqrt{v_x^2 + v_y^2}
\]

1 pu

value of \(i_q^{\text{ref}}\) when \(V\) drops below 0.9 pu

if \(V < 0.9\) pu
VSC model for large voltage disturbances (3)

\[ V = \sqrt{v_x^2 + v_y^2} \]

After voltage has recovered above 0.9 pu, at \( t = t_r \)

\[ \min \left( 1., 0.2(t - t_r) \right) \]
Large disturbances validating small-signal analysis

Very good agreement between small-signal analysis and large-disturbance time simulation

- active power recovers with a ramp
- system “smoothly” brought to its final equilibrium point
- \( \Rightarrow \) stability limit not influenced by nonlinearities

\[
P_{max}^{dyn} = 0.44 \text{ pu}
\]

\[
K_{vi} = 15 \quad K_{pll} = 60 \quad K_{pi} = 30
\]
Milder disturbance with a 10 Ω fault resistance
V drops below 0.9 pu, but not as much
⇒ the injected reactive current is smaller
⇒ there is room for the whole active current (not reduced)
⇒ the pre-disturbance active power is forced immediately
Large disturbances: effective stability limit

\[ K_{vi} = 15 \]
\[ K_{pll} = 60 \]
\[ K_{pi} = 30 \]

lower effective stability limit \((0.38 < 0.44)\) pu
Summary

• Power electronics-driven instability after a fault resulting in severe decrease of short-circuit capacity of AC system.

• In terms of pre-disturbance power, “static” stability limit $P_{max}^{st}$:
  - $P > P_{max}^{st}$ infeasible; can be detected by static calculation.

• “Dynamic” stability limit can be more severe: $P_{max}^{dyn} < P_{max}^{st}$:
  - Determined by small-signal / eigenvalue analysis.
  - Making V control faster than P control increases $P_{max}^{dyn}$.
  - Making the PLL faster decreases stability.

• Same limit found by large-disturbance time simulations:
  - Due to the ramp recovery of active power after fault clearing.

• But fast instability if active current not reduced during fault:
  - Milder disturbance $\Rightarrow$ lower reactive current support $\Rightarrow$ active current not limited.
  - (Limit case: drop of short-circuit capacity without fault !)
More issues to investigate...

• Adequacy of modelling
  – generic VSC model used in this case study
  – additional controls installed by manufacturers?
  – combination of phasor-mode and detailed models appropriate?

• Other forms of instabilities?
  – harmonics, etc.

• Possibility of detecting the instability from local measurements?
  – relying on internal signals readily available inside the converter

• Possibility of keeping the HVDC link in operation with a reduced power transfer?
Thank you for your attention!

*Discussions on modelling with Prof. Xavier Kestelyn, ENSAM, Lille (France) are gratefully acknowledged.*
Appendix. PLL and reference frame

\[(x, y) : \text{reference axes on which time-varying phasors are projected in network equations.}\]

PLL aims at aligning \(d\) axis with \(V_m\). In steady state:

\[
\begin{align*}
    v_q &= 0 \quad \theta = \theta_r \quad i_d = i_p \quad P = v_d i_d \quad i_q = -i_Q \quad Q = -v_d i_q
\end{align*}
\]

\[
\begin{bmatrix}
    i_x \\
    i_y \\
\end{bmatrix} = \begin{bmatrix}
    \cos \theta & -\sin \theta \\
    \sin \theta & \cos \theta
\end{bmatrix} \begin{bmatrix}
    i_d \\
    i_d
\end{bmatrix} = \begin{bmatrix}
    \cos \theta & \sin \theta \\
    -\sin \theta & \cos \theta
\end{bmatrix} \begin{bmatrix}
    i_x \\
    i_y
\end{bmatrix}
\]

\[
R_{dq\rightarrow xy}(\theta) = \begin{bmatrix}
    \cos \theta & -\sin \theta \\
    \sin \theta & \cos \theta
\end{bmatrix}
\]

\[
R_{xy\rightarrow dq}(\theta) = \begin{bmatrix}
    \cos \theta & \sin \theta \\
    -\sin \theta & \cos \theta
\end{bmatrix}
\]
Appendix. Data

VSC

- $S_N = 1000$ MVA
- $V_N^{ac} = 400$ kV
- $V_N^{dc} = \pm 320$ kV
- $R = 0.01$ pu
- $L = 0.2$ pu

Controls

- Inner Loops:
  - $K_P = 0.127$ pu/pu
  - $K_I = 2$ pu/(pu.s)
  → response time ~ 5 ms
- PLL:
  - $K_{pll} = 60$ rad/(pu.s)
- Outer loops:
  - $K_{PI} = 30$ pu/s
  - $K_{VI} = 0.01$ pu/s
  - $K_V = 2.5$ pu/pu