Harmonic Stability in Power Electronic Based Power Systems

HARMONY SYMPOSIUM 2015, AALBORG, DENMARK

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Outline

- Challenge in power electronic based power system
- Harmonic instability
  - Basic concept, historical review, phenomena
- Basic analysis
  - Current control, grid synchronization
- Conclusions
Challenge

Harmonic Coupling and Controller Interaction

- Nonlinear characteristic of passive components under square wave condition
- More resonances in converter-filters and cables
- Interactions of harmonic and inter-harmonic components
Basic Concept

Harmonic Instability in Voltage Source Converters (VSCs)

Harmonic Instability differs from Harmonic Resonance in its dependence on Control Dynamics!

- $\text{Re}\{Y_o\} > 0$, stable but may be resonant
- $\text{Re}\{Y_o\} = 0$, resonant, zero damping
- $\text{Re}\{Y_o\} < 0$, unstable, negative damping
Harmonic Instability is a Waveform-Distortion Instability

Harmonic instability between controlled static convertors and a.c. networks

J. D. Ainsworth, B.Sc.(Eng.), C.Eng., M.I.E.E.

(first paper 1967)

Irregular valve firing pulses due to a positive feedback of distorted ac voltage
Harmonic Instability Phenomena in LCC-HVDC Systems

- Harmonic instability occurs with low Short-Circuit Ratio (SCR)

\[
SCR = \frac{\text{short-circuit power of ac system (VA)}}{\text{dc power rating of converter (W)}}
\]

- Composite resonance
  - Coupling of ac- and dc-side impedance
  - Converter- and system-related resonance

Harmonic Instability is Magnified Resonance (Frequency Coupling)

Harmonic Resonance

Harmonic Instability

Harmonic stability also named as resonance stability in electrical railway systems
Instability Phenomena

An Example of Harmonic Instability with Single VSC
Instability Phenomena

An Example of Harmonic Instability with Three Paralleled VSCs

Stable

Critically-Damped Resonance
Basic Analysis

How do control loops affect output admittance of converter?

Assumption
- Constant dc-link voltage

Focus
- Converter current control
- Phase-Locked Loop (PLL)
Current Control

Converter Current Control

- \( L \)-filter plant and open-loop gain
  \[ Y_{lp} = \frac{1}{Z_{L1}}, \quad T_1 = G_c G_d Y_{lp} \]

- Closed-loop gain and output admittance
  \[ G_{cl} = \frac{T_1}{1+T_1}, \quad Y_{cl} = \frac{Y_{lo}}{1+T_1} = \frac{1}{Y_{lo} + \frac{1}{Y_{ld}}}, \quad Y_{ld} = \frac{1}{G_c G_d} \]

- Stability depends on
  - \( G_{cl} \): stable open-circuit behavior
  - \( Y_{cl} \): \( \text{Re}\{Y_{cl}\} \geq 0 \)
Current Control

Output Admittance Evaluation

- Including proportional gain $k_p$ only for PR current controller

\[ Y_{1d} = \frac{1}{G_c G_d} = \frac{1}{k_p} e^{j1.5\omega T_s} = \frac{1}{k_p} \left[ \cos(1.5T_s \omega) + j \sin(1.5T_s \omega) \right] \]

\[ \text{Re}\{Y_{1d}(j\omega)\} < 0 \Rightarrow \omega \in (\omega_s/6, \omega_s/2) \]

$T_s$: computation delay; $0.5T_s$: PWM delay

Time delay ($1.5T_s$) plays a key role in destabilizing current control
Stability of Converter Current Control at PoC

- Reducing time delay for stability improvement

\[ G_d(s) = e^{-1.5 T_s s} \Rightarrow \omega \in (\omega_s / 6, \omega_s / 2] \]

\[ G_d(s) = e^{-T_s s} \Rightarrow \omega \in (\omega_s / 4, \omega_s / 2] \]

- \( T_s \): computation delay
- \( 0.5 T_s \): PWM delay

\( 0.5 T_s \): reduced computation delay with interrupt shift
Grid Synchronization

Experimental Verification

In Summary

- Harmonic stability describes dynamic interactions in the form of waveform distortion
  - Either harmonic or inter-harmonic interactions
  - Both above and below the fundamental frequency
- Harmonic stability extends small-signal stability to frequency-coupled stability
- Harmonic stability differs from harmonic resonance in its dependence on control system
- Harmonic stability includes switching frequency oscillation
Thank You! Questions?

“THE HIDDEN HARMONY IS BETTER THAN THE OBVIOUS”

- P. PICASSO

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