Three-Phase Voltage-Source Converters

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Outline
- Basic Operation & Applications
- Pulse-Width Modulation
- AC-Side Current Control
- DC-Link Voltage Regulation

Three-Phase VSC Circuit
- A Versatile Interface between DC and Three-Phase AC
- Middle of DC Link is Usually Used as Reference Point
- Inductive Elements at AC Terminals Required
- Bidirectional Power Flow Capabilities

Applications in Power Systems
- Renewable Energy Integration into the Grid
  - Including Energy Storage
- High-Voltage DC Transmission
- Reactive Power Compensation
  - Including Harmonics as Active Power Filter
- Dynamic Voltage Restorer (DVR)
- Unified Power Flow Controller (UPFC)
- Other FACTS Devices

Carrier-Based PWM
- Modulation Index; Carrier Frequency $f_c = \frac{f_s}{2\pi}$, with an Initial Phase $\theta_c$

Phase and Line-Line Voltages
- Phase Voltages have 2 Levels
- Line-Line Voltages have 3 Levels
Assume Balanced AC with a Floating Neutral Point, \( V_N \):

\[ I_a(t) + I_b(t) + I_c(t) = 0 \]

\[ V_a(t) = V_b(t) = V_c(t) \]

Common-Mode Voltage:

\[ V_{cm} = \frac{V_A + V_B + V_C}{3} \]

- Defined as the Common Component of Output Voltages
  - Same as the Line Neutral Voltage
  - Also called Zero-Sequence Voltage

\[ v_{cm}(t) = V_{cm} = \frac{1}{2} M \cos(\omega t + \theta) + \frac{1}{2} M \sin(\omega t + \theta) \]

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Carrier and Its Harmonics

\[ v_{cm}(t) = M \cos(\omega t + \theta) + \frac{1}{2} \sum_{n=1,3,5,...}^{\infty} \frac{4}{n\pi} M \sin(n \frac{\omega t + \theta}{2}) \cos(n \alpha t + \phi) \]

Sideband Components Centered around the Carrier Frequency and its Harmonics

\[ v_{cm}(t) = \frac{1}{2} M \cos(\omega t + \theta) + \frac{1}{2} M \sin(\omega t + \theta) \]
Effects of CM Voltage

- Common-Mode (Ground) Current – EMI Problem
- Motor Bearing Current – Motor Reliability

Possible Solutions:
- Common-Mode Voltage Filtering
- CM Voltage Reduction by Circuit Topology and PWM Techniques
- Ceramic Bearing (High Performance Systems e.g. Aerospace)

Maximum Output Voltage

- Maximum Output Voltage – Achieved when $M = 1$
- Overmodulation – Nonlinear Gain – Saturation – Increased Harmonics

3rd Harmonic Injection

- 3rd Harmonics (of the Fundamental) are of Zero-Sequence
  - Identical for All Three Phases: $3\times120° = 360°$
  - Adding the Same 3rd-Order Harmonic to the References
    - Doesn’t Affect Load Phase Voltages
    - Allows the Fundamental Amplitude to be Higher than the Carrier

Triplen Harmonics Injection

All triplen harmonics are zero-sequence components, hence can be injected without affecting the load phase voltage. A special case is a triangular wave.

Limits for Harmonics Injection

$v_{ref}(t)$ must fall in the shadowed area in order to avoid distortion

Maximal Output Voltage

$v_{ref} = \frac{V}{\sqrt{3}}$
Maximal Output Voltage

\[ V_{\text{max}} = \frac{V_{pk}}{\sqrt{3}} \]

Different Injection Methods

\[ V_f = \frac{V_{pk}}{\sqrt{3}} \]

Harmonic Injection

Overmodulation

Linear Region

\[ V_{\text{linear}} \]

Different Injection Methods

\[ V_f = \frac{V_{pk}}{4} \]

Effects on Phase Voltages

- Phase Voltages Contain Additional Harmonics under Harmonic Injection
  -Injected Harmonics and Sideband Components
  -Identical in All Three Phases
  -Hence Causal in Line-Line Voltages
- These Harmonics Become Part of Common-Mode Voltage
  -Relatively Low Frequency and Magnitude Compared to the CM Voltage Generated by PWM
- Phase Voltage Spectra can also be Obtained by Double Fourier Series Analysis
  -Closed-Form Results have been Reported in the Literature
- Optimal Harmonic Injection

AC Current Control

- DC-AC Converter (Inverter) Current Control
  -Torque Control in Motor Drives
  -Active and Reactive Power Control in Grid-Connected DG
  -Current-Mode Control in UPS and Standalone DG
- AC-DC Converter (Rectifier) Current Control
  -Unity Input Power Factor
  -Regulation of DC Voltage

Example Current Waveforms

Active Power Generation (DG)
Reactive Power Compensation
DG with Reactive Compensation
Rectification (PFC)
Active Power Filtering
UPS (with Nonlinear Loads)
Current Control Principles

\[ i_a = \frac{V_a - V_{sa}}{Z_1} \]

\[ i_b = \frac{V_b - V_{sb}}{Z_1} \]

\[ i_c = \frac{V_c - V_{sc}}{Z_1} \]

Single Phase

Three Phase

Averaged Modeling

\[ d_a, d_b, \text{ and } d_c \text{ is the Duty Ratio of the Upper Switch in Phase } a, b, \text{ and } c, \text{ Respectively} \]

\[ \text{Averaging Removes Switching Ripple} \]

\[ \text{Resulting Model is in General Valid at Frequencies Lower than Half the Switching (Carrier) Frequency} \]

Basic Control Structure

- Objective: Control Phase Currents \( i_a, i_b, \text{ and } i_c \) to Follow Given References \( i_{a,ref}, i_{b,ref}, \text{ and } i_{c,ref} \)

- Assumption: Terminal Voltages \( V_{sa}, V_{sb}, \text{ and } V_{sc} \) are Known

- Current Responses Governed by

\[ \begin{align*}
\frac{di_a}{dt} &= -V_{sa} - V_{ja} - V_{ja,ref} + \frac{1}{L_s} \int (i_{a,ref} - i_a) dt \\
\frac{di_b}{dt} &= -V_{sb} - V_{jb} - V_{jb,ref} + \frac{1}{L_s} \int (i_{b,ref} - i_b) dt \\
\frac{di_c}{dt} &= -V_{sc} - V_{jc} - V_{jc,ref} + \frac{1}{L_s} \int (i_{c,ref} - i_c) dt 
\end{align*} \]

Feedforward Control

- One Linear (PI) Regulator per Phase
- Simple, Robust
- Limited Performance
  - Existence of Control Error

\[ V(s) = F(s) + H(s) \]

\[ F(s) = \frac{1}{s} \]

\[ H(s) = \frac{1}{s} \]

Feedback + Feedforward

\[ \begin{align*}
V(s) &= \frac{1}{s} L_s \int (i_{a,ref} - i_a) dt \\
F(s) &= \frac{1}{s} L_s \int (i_{b,ref} - i_b) dt \\
H(s) &= \frac{1}{s} L_s \int (i_{c,ref} - i_c) dt 
\end{align*} \]
Nonlinear (Hysteretic) Control

- Features
  - Direct Generation of Switch Gate Signals
  - No Need for PWM
  - Simple, Robust
  - Stable Operation, Fast Response
  - Variable Switching Frequencies
  - Not Suitable for Digital Control

- Possible Improvement
  - Variable Hysteretic Bands to Reduce Switching Frequency Variation
  - Space Vector-Based Hysteretic Control

Practical Control Methods

- Control in DQ Reference Frame
  - Balanced Three-Phase References Become DC in DQ Frame
  - No Steady-State Tracking Error

- Resonant Feedback Compensation
  - Compensator has a Resonance at the Line Frequency
  - Improve Tracking of Inductor Current at the Line Frequency

Ripple Current and L Selection

- Inductor Currents Contain Ripple Components at the Switching Frequency

- Amplitude \( \propto (\Delta f) \)
  - Varies over a Line Cycle

- Effects of Current Ripple
  - Contribute to System Harmonics
  - Increase Converter Losses

- Inductor Design Considerations
  - Performance vs. Cost & Size

DC-Link Voltage Control

- Applications Requiring Control of the DC-Link Voltage
  - Power Factor Corrected Rectifiers
  - Active Power Filters
  - Static VAR Compensators
  - Grid Interface for Fuel Cells, Solar, and Wind Power

- Power Balance:

\[
I_v = \frac{1}{v_{dc}} \left( \frac{dL}{dt} + \frac{dL_{cap}}{dt} \right)
\]

\[
\text{Power Balance: } I_v v_{dc} = \tau_a \frac{dL}{dt} + \frac{dL_{cap}}{dt}
\]

\[
V_{dc} \text{ Response to Phase Currents}
\]

- Assume Balanced Sinusoidal Source Voltages

- Only Active Component of Phase Currents Affects Average of \( V_{dc} \)

- Reactive Component doesn’t Affect \( V_{dc} \)

- Unbalanced Fundamental Components (Active or Reactive) Lead to 2nd Harmonic in \( V_{dc} \)

- Balanced \( (3\Delta \pm 1) \) Harmonic Currents Generates 6th Harmonic in \( V_{dc} \)

\[
v_a(t) = V_p \cos(\omega t), \quad v_b(t) = V_p \cos(\omega t - 2\pi/3), \quad v_c(t) = V_p \cos(\omega t + 4\pi/3)
\]

\[
\cos x \cos x = \frac{1}{2} \left( \cos 2x + 2 \right)
\]

\[
\sin x \sin x = \frac{1}{2} \left( \cos 2x - 2 \right)
\]

\[
\sin x \cos x = \frac{1}{2} \left( \sin 2x + \cos 2x \right)
\]

\[
\cos x + \cos x = \frac{2}{2} \cos x
\]

\[
\sin x + \sin x = \frac{2}{2} \sin x
\]
Voltage Dynamics and Control

Assume Active Component of Phase Current $i_p = g$.

$g$ is the Control Variable
- Represents Voltage Compensator Output
- Dynamics Described by a Nonlinear Model
  - Linearization about a Steady-State Operation Point

$$\frac{d}{dt} \frac{V}{V_{rms}} \cdot \frac{1}{\frac{1}{V_{rms}} - i_p} = \frac{1}{\frac{1}{V_{rms}} - i_p} \cdot \frac{1}{V_{rms}}$$

$V_{rms}$ = Input Phase RMS Voltage

$vi_d = 0$

$2 \cdot \text{rms} 0$ $3$

$iv_g V iv dt$

vdC $	ext{dcdc} \cdot T$

$iv$

Assume Active Component of Phase Current $V_{rms} = \text{Input Phase RMS Voltage}$

$\sum K K i_p + V_{ref} - v_d$

$\sum i_d$ $i_{ref}$

Reference Currents Required for System Control Functions

Reading & HW Assignments

- Holmes and Lipo, Pulse Width Modulation for Power Converters, Chapters 5&6

- Consider A Three-Phase Solar Inverter Switched at 20 kHz and with a 350 V DC Input. The Inverter is Connected to a 120 V (Phase RMS) Grid through a 1 mH (per Phase) Inductor, and Supplies 10 kW Active Power to the Grid. Calculate
  - The Modulation Index $M$
  - The Amplitude of Phase Harmonic Current at $20 \text{ kHz}$, $20 \text{ kHz} \pm 60 \text{ Hz}$, $20 \text{ kHz} \pm 120 \text{ Hz}$, $20 \text{ kHz} \pm 180 \text{ Hz}$; and $40 \text{ kHz}$, $40 \text{ kHz} \pm 60 \text{ Hz}$, $40 \text{ kHz} \pm 120 \text{ Hz}$, $40 \text{ kHz} \pm 180 \text{ Hz}$