Analysis of EMI Source in the Balanced Inverter with Desynchronization of Gate Signals

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Outline

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- The Balanced Inverter and Voltage Waveform Analysis
- Spectrum Analysis of Source CM Voltage of Single Phase with Fixed Duty Cycle
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- Spectrum Analysis of Source CM Voltage of Three Phase
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Motivation and Purpose

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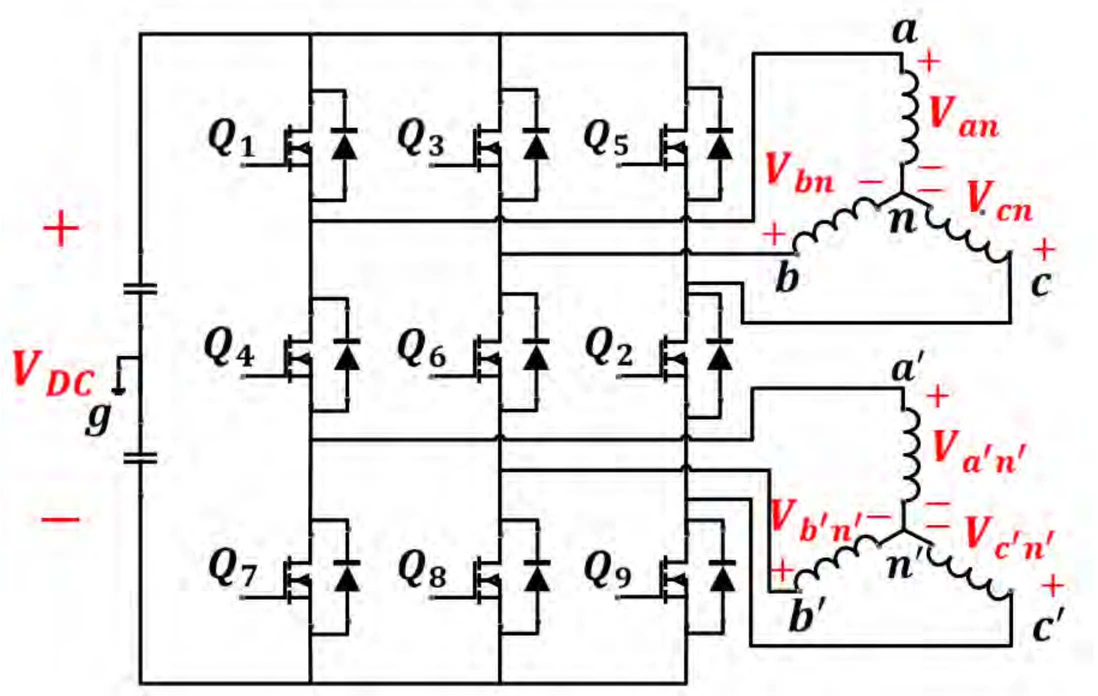
- Common-mode voltage issues will be aggravated for motor drive due to high dv/dt caused by WBG devices
- The balanced inverter is a novel topology and is recently introduced for eliminating the common mode emissions
- Benefits of balanced inverter:
    - Reduce overall cost, weight, and volume of the whole drive system
    - Simple control strategy

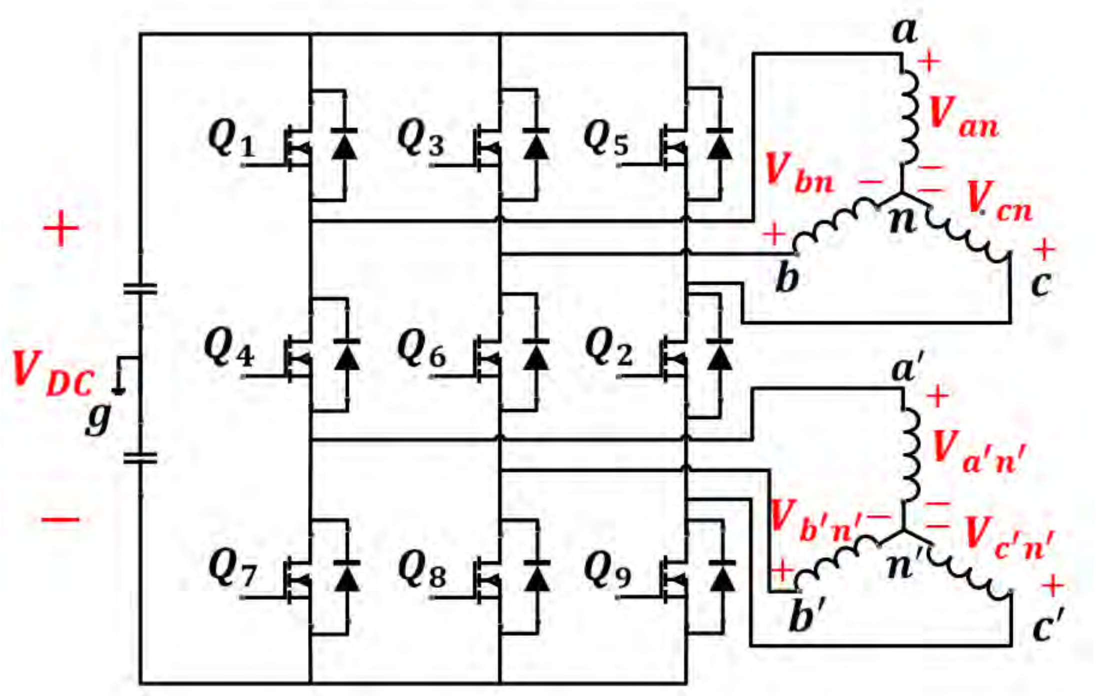


The balanced inverter

Balanced inverter is a novel solution to CM EMI

Motivation and Purpose

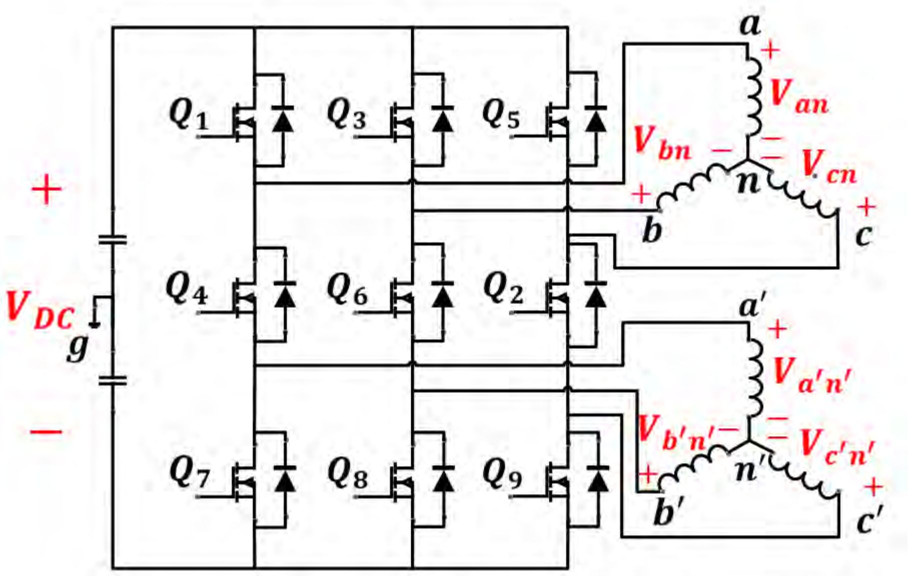
- Performance of the balanced inverter suffers the nonideal conditions of hardware realization
- Previous research has presented influences of several nonideal conditions
  - Gate Signals mismatch
  - Unbalanced load impedances
  - Unsymmetrical parasitic inductance distribution
- Purpose of this paper
  - Propose an analytical model for estimating the CM EMI performance under nonideal conditions



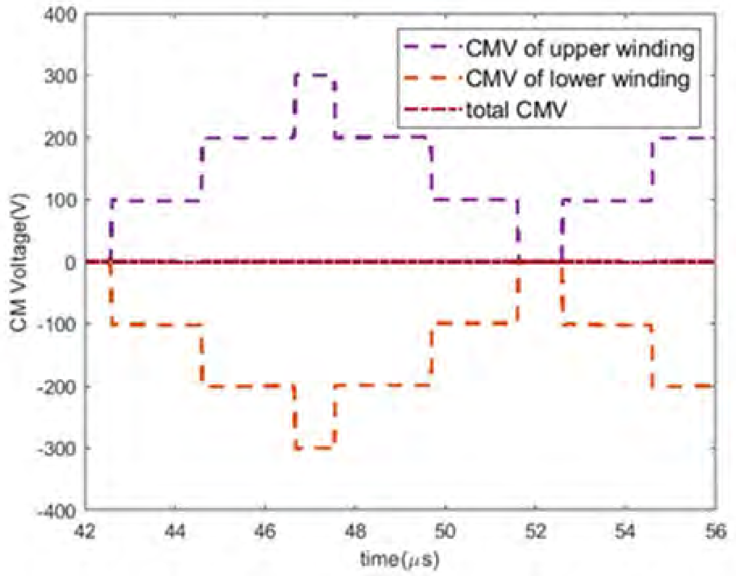
The balanced inverter

This research will be beneficial for optimal operation of the balanced inverter

The Balanced Inverter and Voltage Waveform Analysis



The balanced inverter



CMV cancellation in balanced inverter under ideal condition

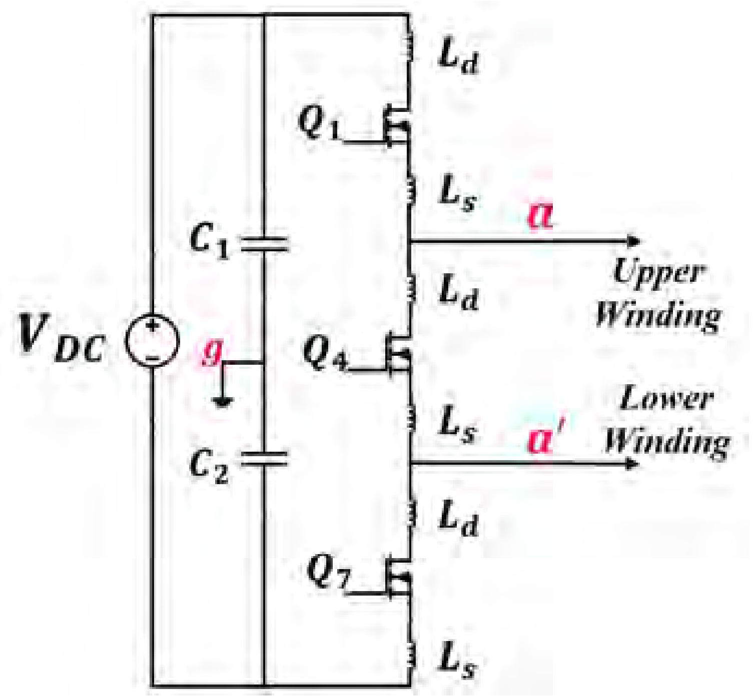
- Three switches in one phase leg, and nine switches in total
- The two windings in the same phase are symmetrical and are series-connected in opposite polarities in stator

The CMV of upper and lower output will be cancelled
The CMV of balanced inverter will be zero theoretically

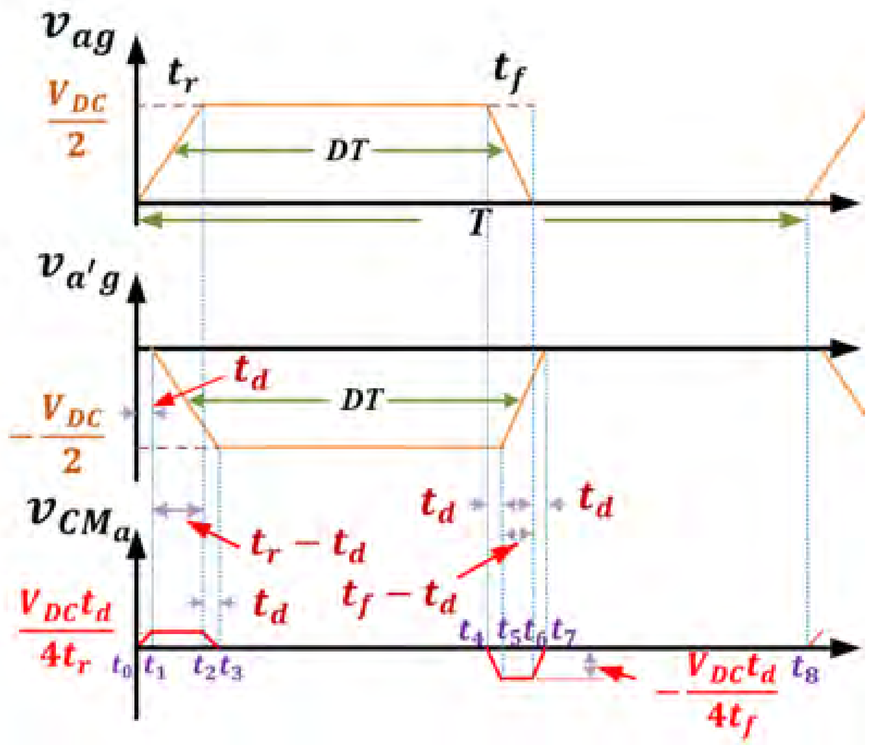
The Balanced Inverter and Voltage Waveform Analysis

- Due to the different delay propagation of each gate driver, the gate signal of each switch will be desynchronized

The CMV of the balanced inverter will not always be maintained as zero when gate signals mismatch exists



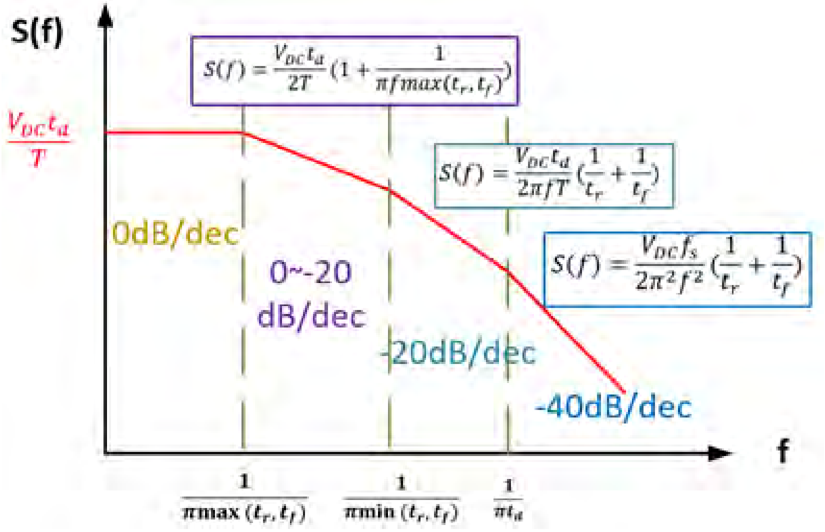
The simplified model of Phase leg A of balanced inverter



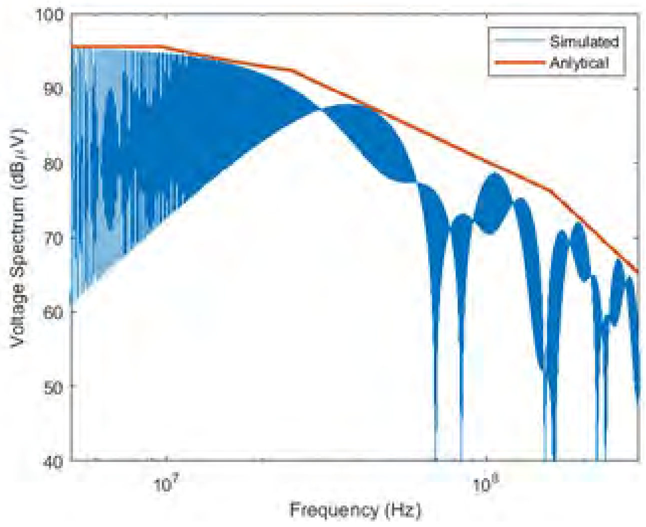
Voltage waveforms of Phase A in balanced inverter with gate signal desynchronization

Spectrum Analysis of Source CM Voltage of Single Phase with Fixed Duty Cycle

$$S(n) = \frac{V_{DC}T}{8n^2\pi^2 t_r t_f}\left| \begin{array}{c} t_f\left[\left(1-e^{-j2n\pi t_d/T}\right)+e^{-\frac{j2n\pi t_r}{T}}\left(e^{-j2n\pi t_d/T}-1\right)\right] \\ -t_r\left[\left(1-e^{-j2n\pi t_d/T}\right)+e^{-\frac{j2n\pi t_f}{T}}\left(e^{-j2n\pi t_d/T}-1\right)\right]e^{-jn\pi(2DT+t_r-t_f)/T} \end{array}\right|$$



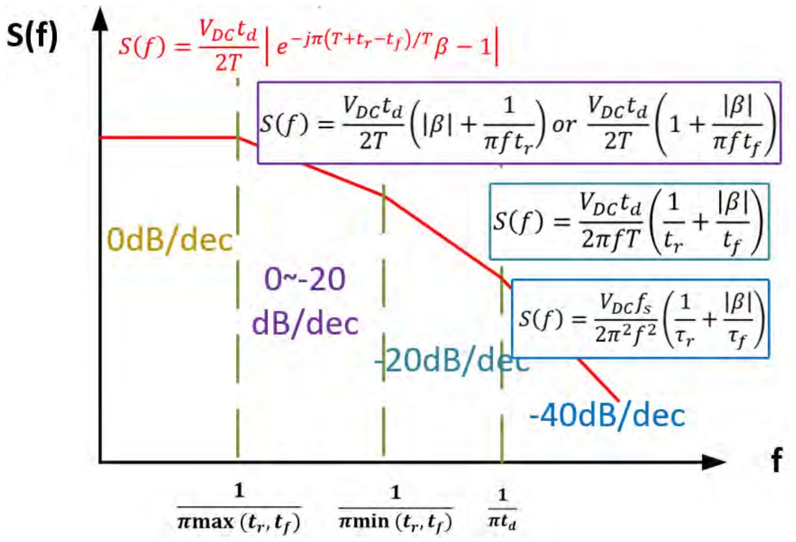
Analytical approximation of the spectral envelope of CMV



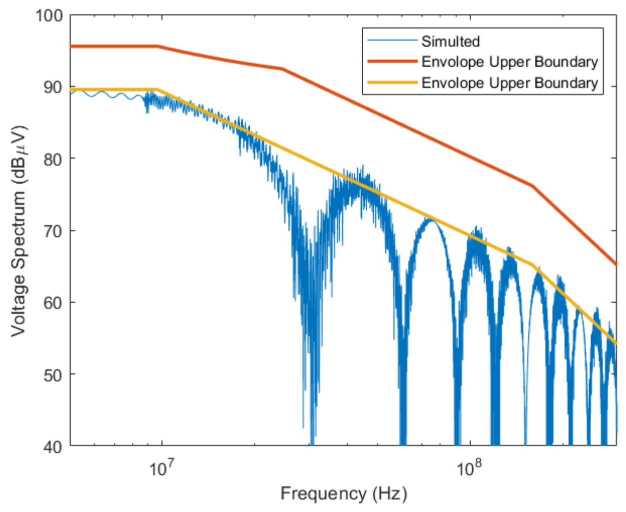
Spectrum comparison between simulation and analysis

Gate signal synchronization along with switching frequency and DC voltage determine the upper bound of the spectral envelope in the low-frequency region

Spectrum Analysis of Source CM Voltage of Single Phase with SPWM



Analytical approximation of the spectral envelope of CMV



Spectrum comparison between simulation and analysis

The simulated spectral envelope sits between the two analytical boundaries

$$S(k) = \frac{V_{DC}T}{8n^2\pi^2 t_r t_f}\left| \begin{matrix} t_f\left[\left(1 - e^{-j2k\pi t_d/T}\right) + e^{-\frac{j2k\pi t_r}{T}}\left(e^{-j2k\pi t_d/T} - 1\right)\right] \\ -t_r\left[\left(1 - e^{-j2k\pi t_d/T}\right) + e^{-\frac{j2k\pi t_f}{T}}\left(e^{-j2k\pi t_d/T} - 1\right)\right] e^{-jk\pi(T+t_r-t_f)/T}\frac{1}{\alpha}\sum_{i=0}^{\alpha-1} e^{-jk\pi M_0 \sin\left(\frac{2\pi i}{\alpha}\right)} \end{matrix} \right|$$

Spectrum Analysis of Source CM Voltage of Three Phase

$$S(k) = \frac{V_{DC}T}{8n^2\pi^2 t_r t_f}\left| \begin{matrix} t_f\left[\left(1 - e^{-j2k\pi t_d/T}\right) + e^{-\frac{j2k\pi t_r}{T}}\left(e^{-j2k\pi t_d/T} - 1\right)\right] \\ -t_r\left[\left(1 - e^{-j2k\pi t_d/T}\right) + e^{-\frac{j2k\pi t_f}{T}}\left(e^{-j2k\pi t_d/T} - 1\right)\right] e^{-jk\pi\left(T+t_r-t_f\right)/T} \frac{\beta_a + \beta_b + \beta_c}{3} \end{matrix} \right|$$

$$\beta_a = \frac{\sum_{i=0}^{\alpha-1} e^{-jkn\pi M_0 \sin\left(\frac{2\pi i}{\alpha}\right)}}{\alpha} \qquad \beta_b = \frac{\sum_{i=0}^{\alpha-1} e^{-jkn\pi M_0 \sin\left(\frac{2\pi i}{\alpha} - \frac{2}{3}\pi\right)}}{\alpha} \qquad \beta_c = \frac{\sum_{i=0}^{\alpha-1} e^{-jkn\pi M_0 \sin\left(\frac{2\pi i}{\alpha} + \frac{2}{3}\pi\right)}}{\alpha}$$

$$\beta_a = \beta_b = \beta_c = \beta$$

The spectrum of source CM voltage of three phases is the same as the spectrum of source CM voltage of phase A

Conclusion

- A promising model for estimating the source CMV under nonideal conditions has been proposed for the balanced inverter
- Under non-ideal conditions caused by gate signal desynchronization, the source CMV voltage consists of a trapezoidal waveform that grows in amplitude as the desynchronization worsens
- This analytical model shows that gate signal synchronization delay time t_d along with switching frequency and DC voltage determine the upper bound of the spectral envelope of the source EMI in the low-frequency region

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Thank You !

Q & A