Analytical Characterization of Common-mode Voltage in A Three-level ANPC Inverter

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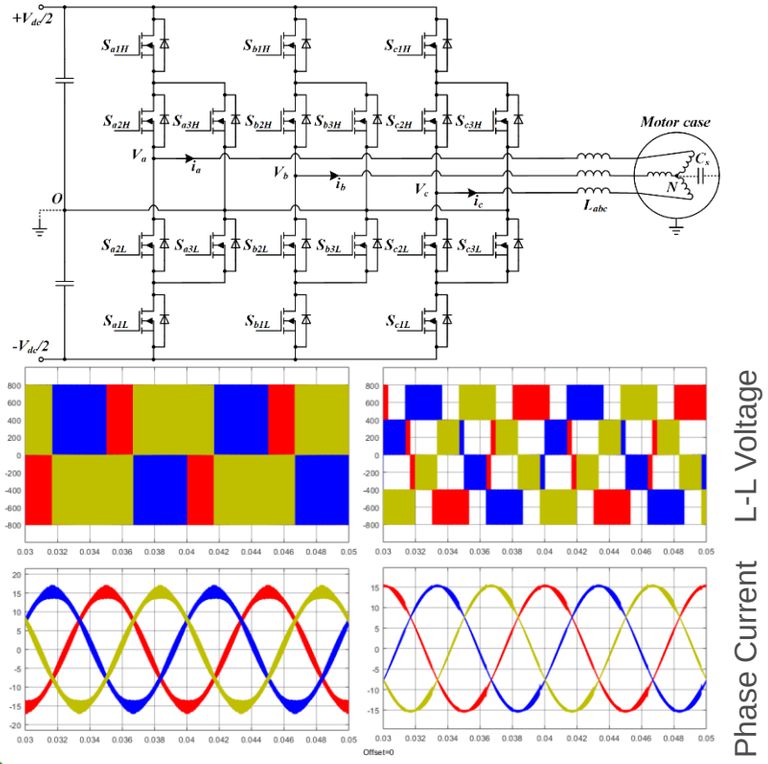
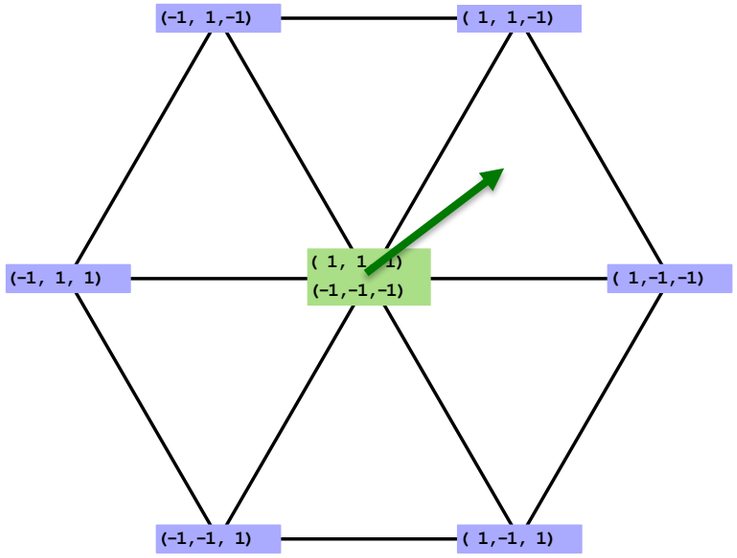
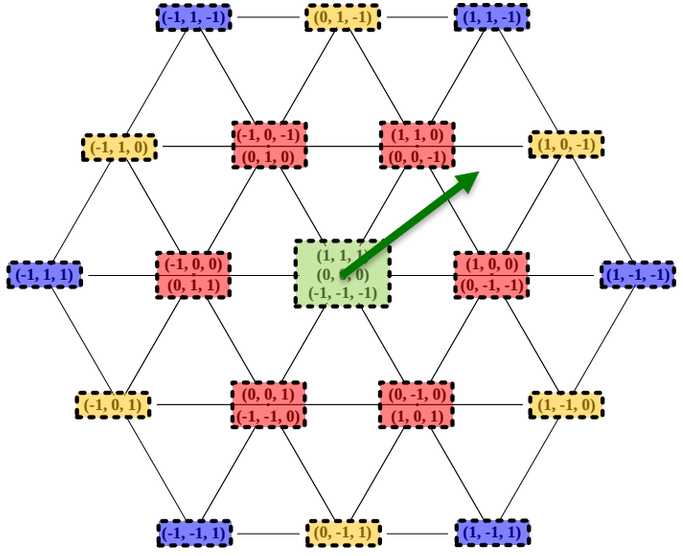
Three-level ANPC Realization

- To have comparable travel time as petrol-driven vehicles, extreme fast charging is promoted. This requires at least 800 V DC-link voltage, which also increase the efficiency.
- Three-level is preferred for the lower cost of devices with lower voltage blocking capability, especially wide bandgap devices like GaN HEMTs.





2L Vector Plane



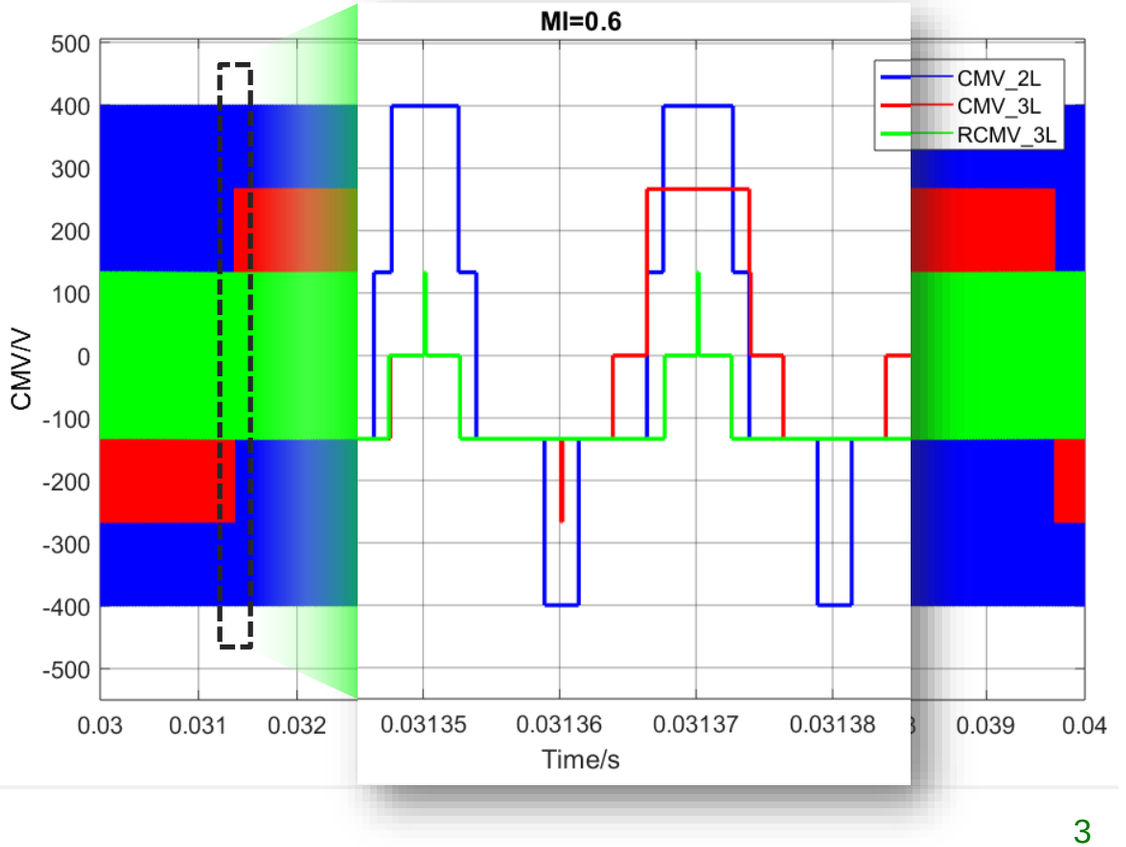
3L Vector Plane

Three-level ANPC Common-mode Voltage

- Since higher battery voltage directly increase the CMV, combined with higher switching speed, CM current is also larger, causing potentially bigger mechanical damage to the motor.
- By properly assigning the space vector combination, the CMV can be reduced even more.

$$V_{CM} = \frac{\left(V_{ao} + V_{bo} + V_{co}\right)}{3}$$

Vector Types	Space Vectors	CMV
Zero voltage vectors	(0, 0, 0)	0
	(1, 1, 1) (-1, -1, -1)	$\lvert V_{dc}/2 \rvert$
Small voltage vectors	(1, 1, 0) (1, 0, 1) (0, 1, 1) (-1, -1, 0) (-1, 0, -1) (0, -1, -1)	$\lvert V_{dc}/3 \rvert$
	(1, 0, 0) (0, 1, 0) (0, 0, 1) (-1, 0, 0) (0, -1, 0) (0, 0, -1)	$\lvert V_{dc}/6 \rvert$
Medium voltage vectors	(1, 0, -1) (0, 1, -1) (-1, 1, 0) (-1, 0, 1) (0, -1, 1) (1, -1, 0)	0
Large voltage vectors	(1, -1,-1) (1, 1, -1) (-1, 1, -1) (-1, 1, 1) (-1, -1, 1) (1, -1, 1)	$\lvert V_{dc}/6 \rvert$



Double Fourier Integral Analysis

- Double Fourier integral analysis can provide analytical solutions to identify harmonic components of the PWM signal.
- Functions x(t) and y(t) are the time variation of high-frequency carrier waveform and low-frequency modulation waveform.

$$x(t)=\omega_s t+\theta_s$$

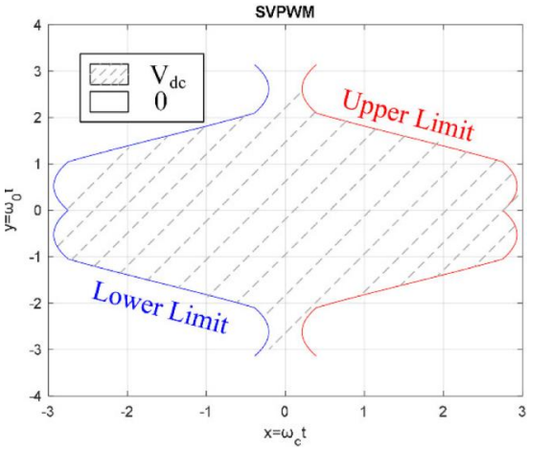
$$y(t)=\omega_0 t+\theta_0$$

Switching funtion:

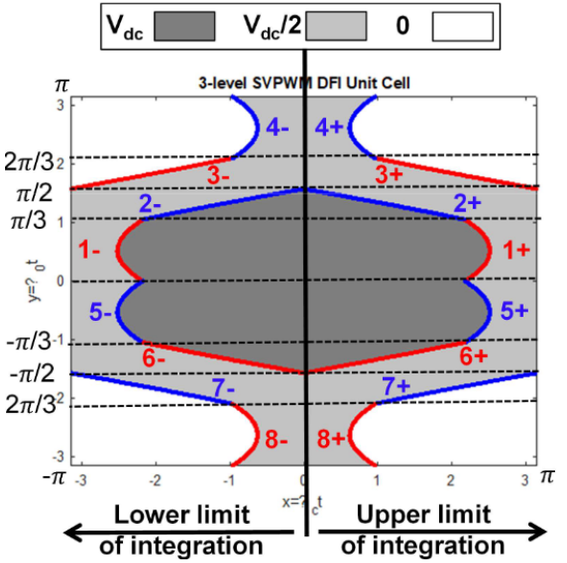
$$f(x,y)=\frac{A_{00}}{2}+\sum_{n=1}^{\infty}\left\{A_{0n}\cos\left(n\left(\omega_0 t+\theta_0\right)\right)+B_{0n}\sin\left(n\left(\omega_0 t+\theta_0\right)\right)\right\}$$

$$+\sum_{m=1}^{\infty}\left\{A_{m0}\cos\left(m\left(\omega_s t+\theta_s\right)\right)+B_{m0}\sin\left(m\left(\omega_s t+\theta_s\right)\right)\right\}$$

$$+\sum_{m=1}^{\infty}\sum_{\substack{n=-\infty \\ n\neq 0}}^{\infty}\left\{A_{mn}\cos\left(m\left(\omega_s t+\theta_s\right)+n\left(\omega_0 t+\theta_0\right)\right)+B_{mn}\sin\left(m\left(\omega_s t+\theta_s\right)+n\left(\omega_0 t+\theta_0\right)\right)\right\}$$



2L Integral Bounds

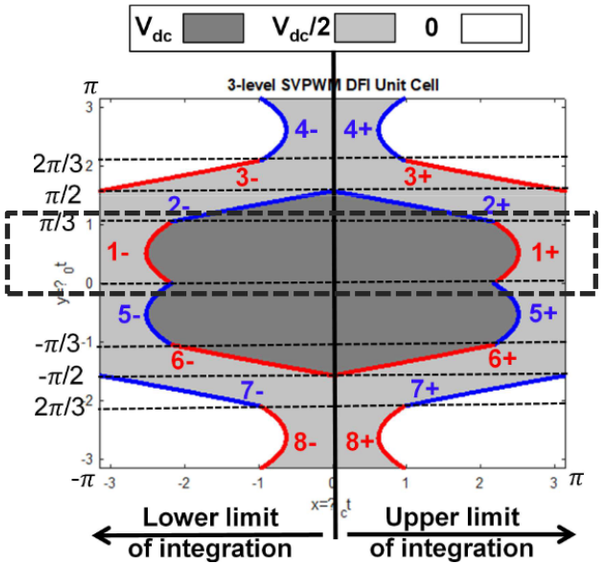


3L Integral Bounds

Continuous SVM

Three-level DFI

- There are 8 sections for each fundamental cycle. Especially, in sections 1, 2, 5, and 6, there are three integration areas. In sections 3, 4, 7, and 8, there is only one.
- The carrier harmonics and sideband components of the CMV can be calculated and compared to the simulation at f0=100 Hz, fs=10 kHz, 200V DC bus voltage.



3L Integral Bounds

$$A_{mn}+jB_{mn}=\frac{1}{2\pi}\int_{-\pi}^{\pi}\int_{\substack{lowerlimit\\insectori}}^{\substack{upperlimit\\insectori}} Ue^{j(mx+ny)}dxdy$$

$$=\int_{-\pi}^{-\frac{2\pi}{3}}\int_{8-}^{8+}\frac{V_{dc}}{2}e^{j(mx+ny)}V_{dc}dxdy+\int_{-\frac{2\pi}{3}}^{-\frac{\pi}{3}}\int_{7-}^{7+}\frac{V_{dc}}{2}e^{j(mx+ny)}V_{dc}dxdy$$

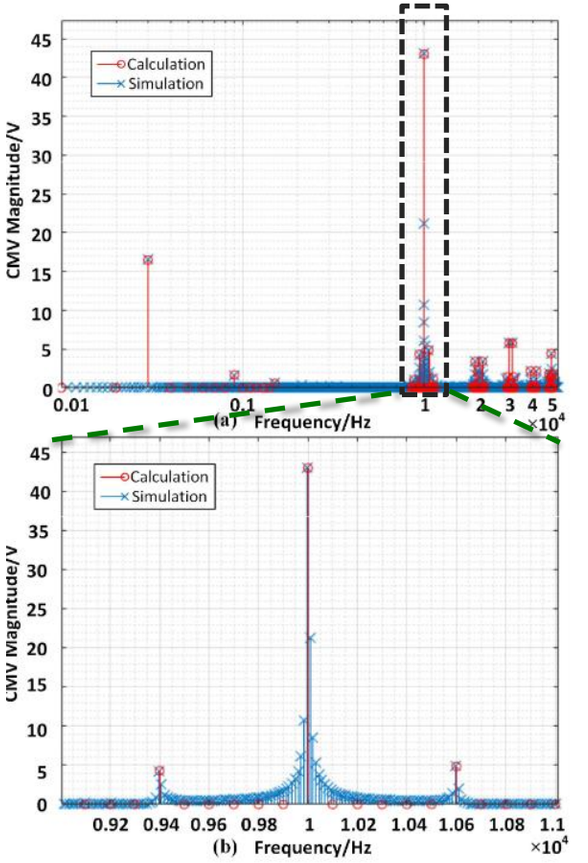
$$+\int_{-\frac{\pi}{2}}^{-\frac{\pi}{3}}\int_{-\pi}^{6-}\frac{V_{dc}}{2}e^{j(mx+ny)}V_{dc}dxdy+\int_{-\frac{\pi}{2}}^{-\frac{\pi}{3}}\int_{6-}^{6+}V_{dc}e^{j(mx+ny)}V_{dc}dxdy+\int_{-\frac{\pi}{2}}^{-\frac{\pi}{3}}\int_{6+}^{\pi}\frac{V_{dc}}{2}e^{j(mx+ny)}V_{dc}dxdy$$

$$+\int_{-\frac{\pi}{2}}^{-\frac{\pi}{3}}\int_{-\pi}^{5-}\frac{V_{dc}}{2}e^{j(mx+ny)}V_{dc}dxdy+\int_{-\frac{\pi}{2}}^{-\frac{\pi}{3}}\int_{5-}^{5+}V_{dc}e^{j(mx+ny)}V_{dc}dxdy+\int_{-\frac{\pi}{2}}^{-\frac{\pi}{3}}\int_{5+}^{\pi}\frac{V_{dc}}{2}e^{j(mx+ny)}V_{dc}dxdy$$

$$+\int_{-\frac{\pi}{2}}^{-\frac{\pi}{3}}\int_{-\pi}^{1-}\frac{V_{dc}}{2}e^{j(mx+ny)}V_{dc}dxdy+\int_{-\frac{\pi}{2}}^{-\frac{\pi}{3}}\int_{1-}^{1+}V_{dc}e^{j(mx+ny)}V_{dc}dxdy+\int_{-\frac{\pi}{2}}^{-\frac{\pi}{3}}\int_{1+}^{\pi}\frac{V_{dc}}{2}e^{j(mx+ny)}V_{dc}dxdy$$

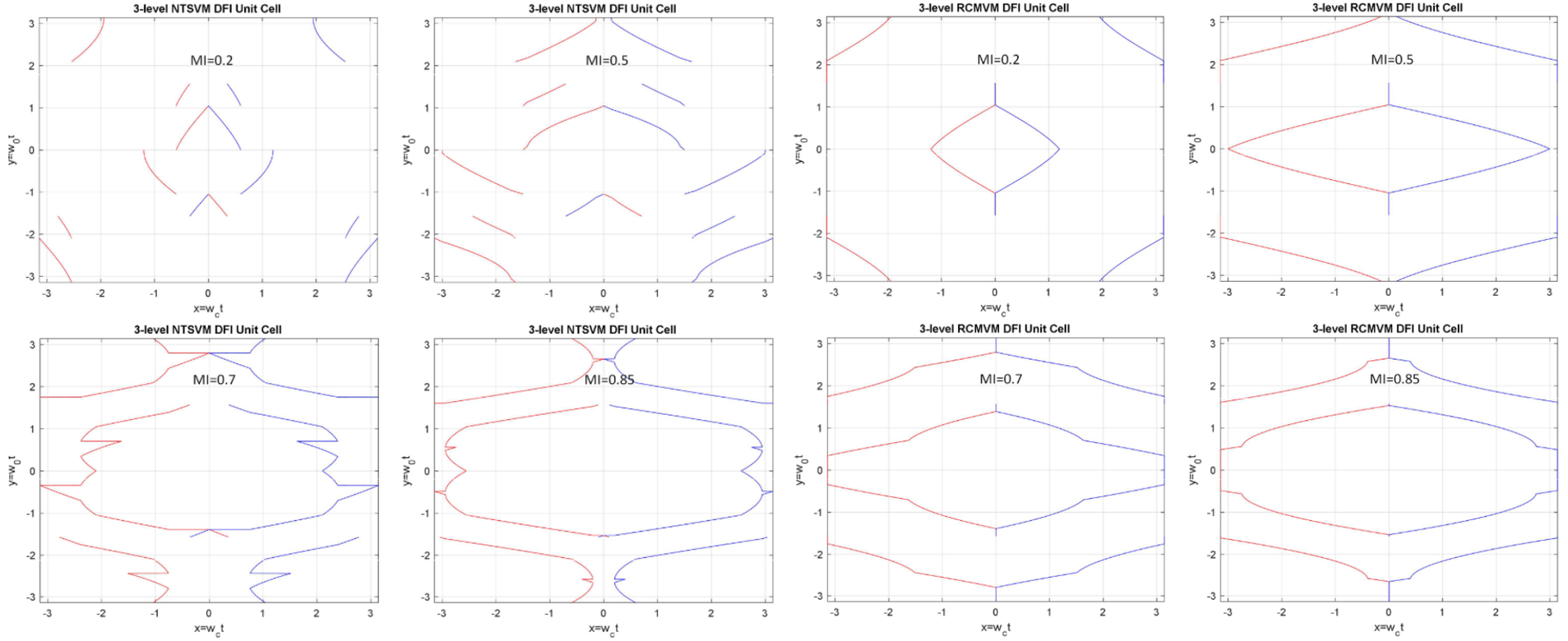
$$+\int_{-\frac{\pi}{2}}^{-\frac{\pi}{3}}\int_{-\pi}^{2-}\frac{V_{dc}}{2}e^{j(mx+ny)}V_{dc}dxdy+\int_{-\frac{\pi}{2}}^{-\frac{\pi}{3}}\int_{12-}^{2+}V_{dc}e^{j(mx+ny)}V_{dc}dxdy+\int_{-\frac{\pi}{2}}^{-\frac{\pi}{3}}\int_{2+}^{\pi}\frac{V_{dc}}{2}e^{j(mx+ny)}V_{dc}dxdy$$

$$+\int_{-\pi}^{-\frac{2\pi}{3}}\int_{3-}^{3+}\frac{V_{dc}}{2}e^{j(mx+ny)}V_{dc}dxdy+\int_{-\frac{2\pi}{3}}^{-\frac{\pi}{2}}\int_{4-}^{4+}\frac{V_{dc}}{2}e^{j(mx+ny)}V_{dc}dxdy$$



DFI Bounds of Other 3L Modulations

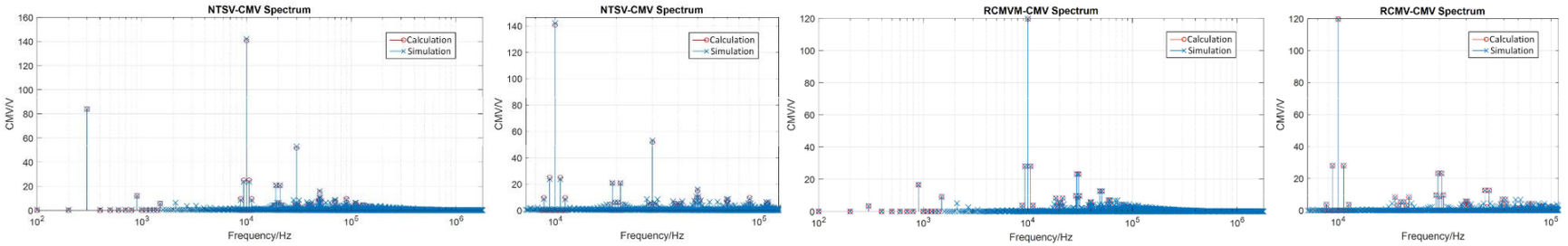
- NTSVM is nearest three vector modulation. It uses three nearby vectors to compose the reference. RCMVM is reduced common-mode voltage modulation. It always uses low CMV vectors instead.
- By deriving the switching function, the DFI bounds with different MI can be plotted as below.

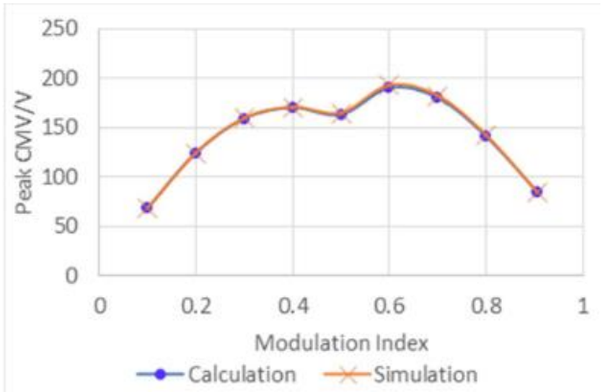


NTSVM RCMVM

Result Comparison

- Analytical CMV spectrum and the simulation result are compared below.
- At given DC bus voltage of 800 V, MI=0.8, fs=10 kHz and f0=100 Hz, the result shows very accurate agreement. (left and middle)
- This result is then compared to preliminary experiment test. (right)





NTSVM
<===

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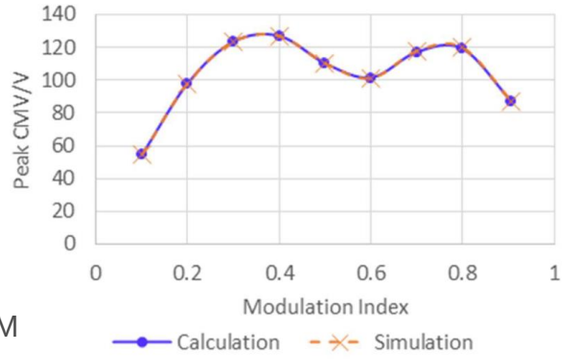
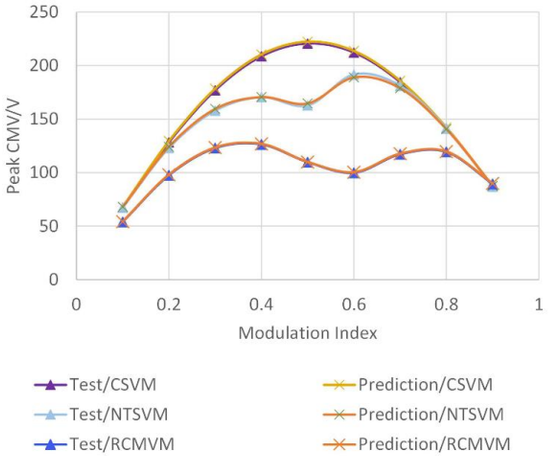
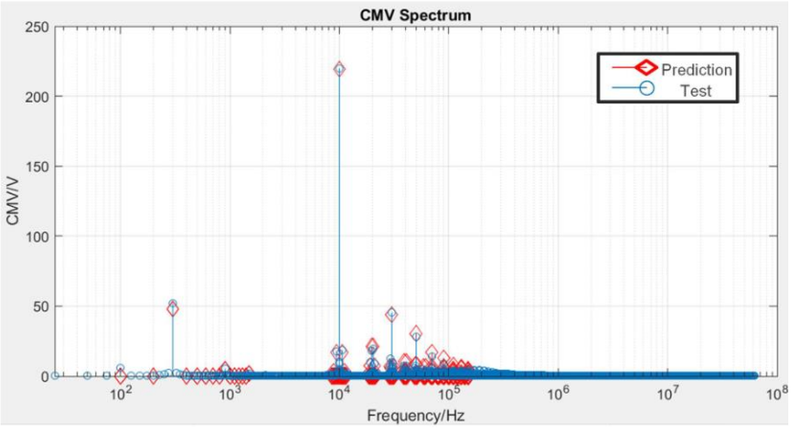
RCMVM



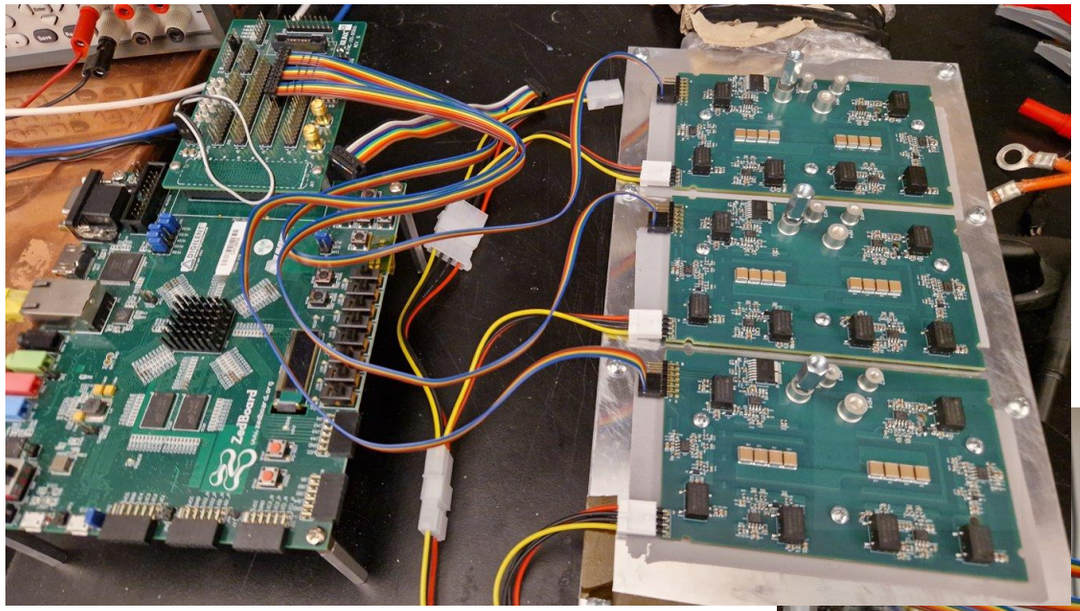




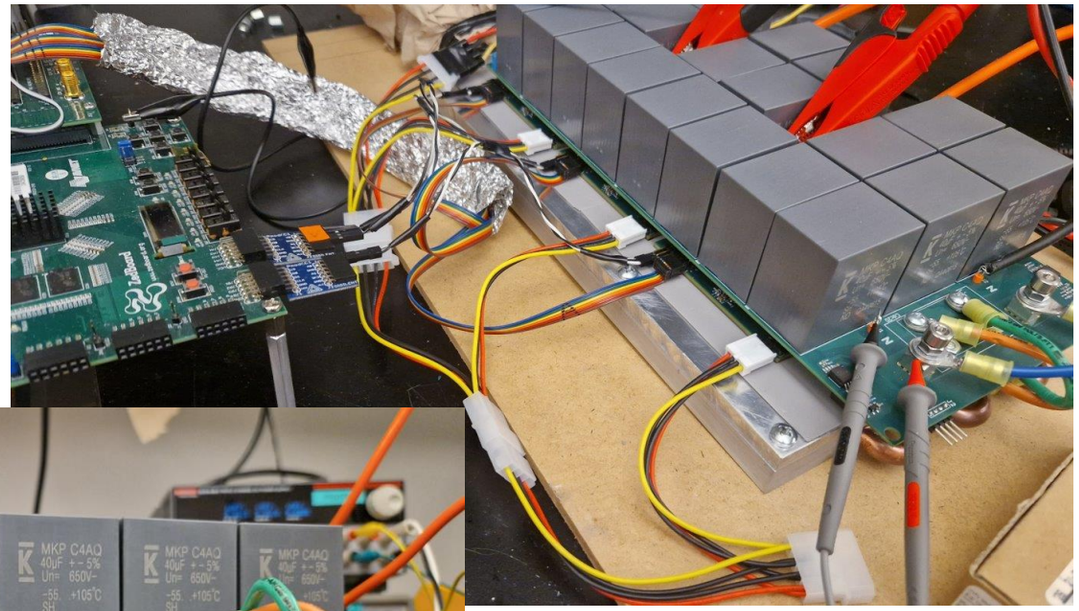
Experiment Result (200 V) vs. Prediction

Test Platform

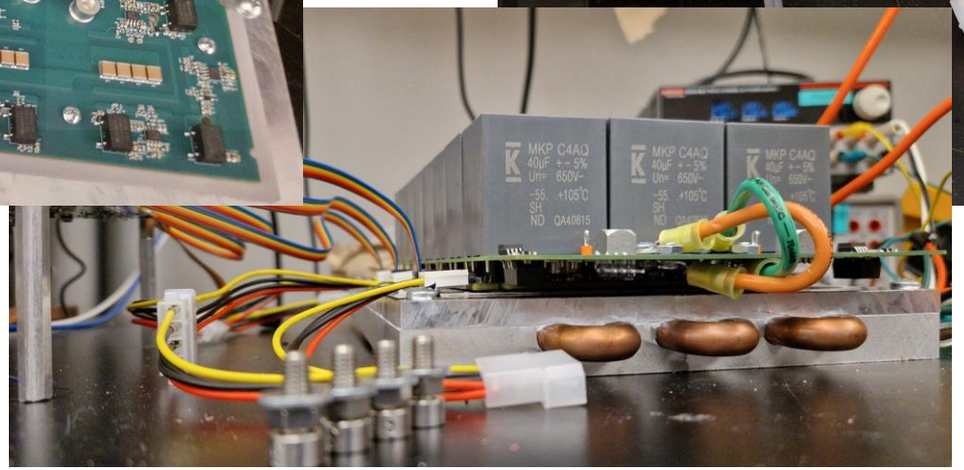
- Currently, we have built an 800 V, 75 kVA three-level all GaN inverter, with a power density of 25 kVA/L. Tests are conducting to gradually reach full power.
- More tests are on the way to prove the accuracy of our analytical calculation.



Modular Design Sitting on the Cold Plate



Complete Inverter Connected with FPGA



Low Profile Design

Acknowledgements

This work was supported by *.