Modular Multilevel Converters (MMC)

Fujin Deng

School of Electrical Engineering

fdeng@seu.edu.cn

東南大學電氣工程學院
SCHOOL OF ELECTRICAL ENGINEERING, SEU

OUTLINES

- Circuit, Topologies and operation Principles
- Modulation Schemes
- Capacitor Voltage Balancing Control

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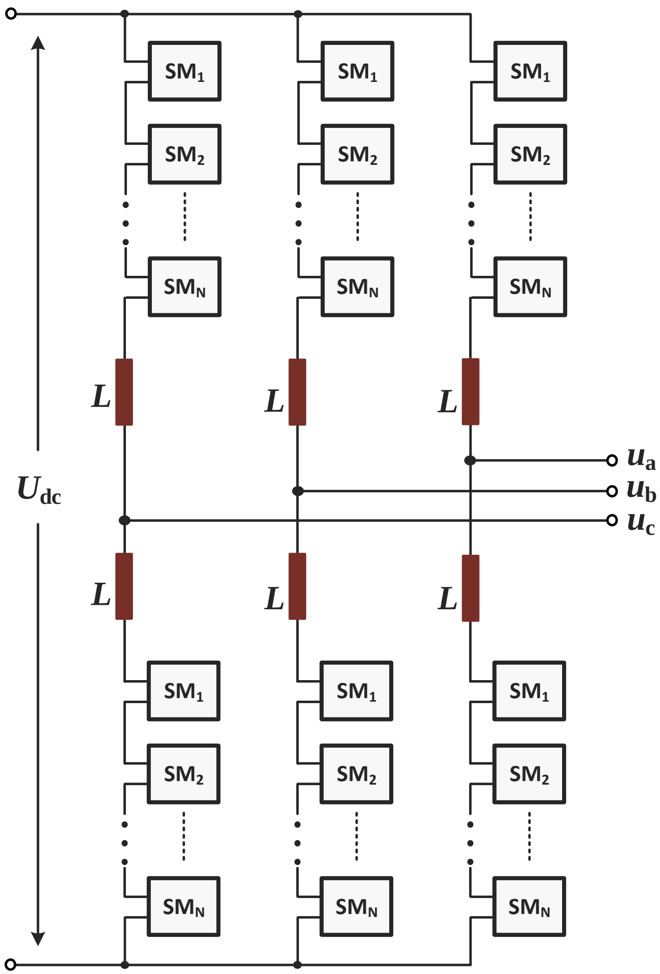
1-1 MMC Topology Features

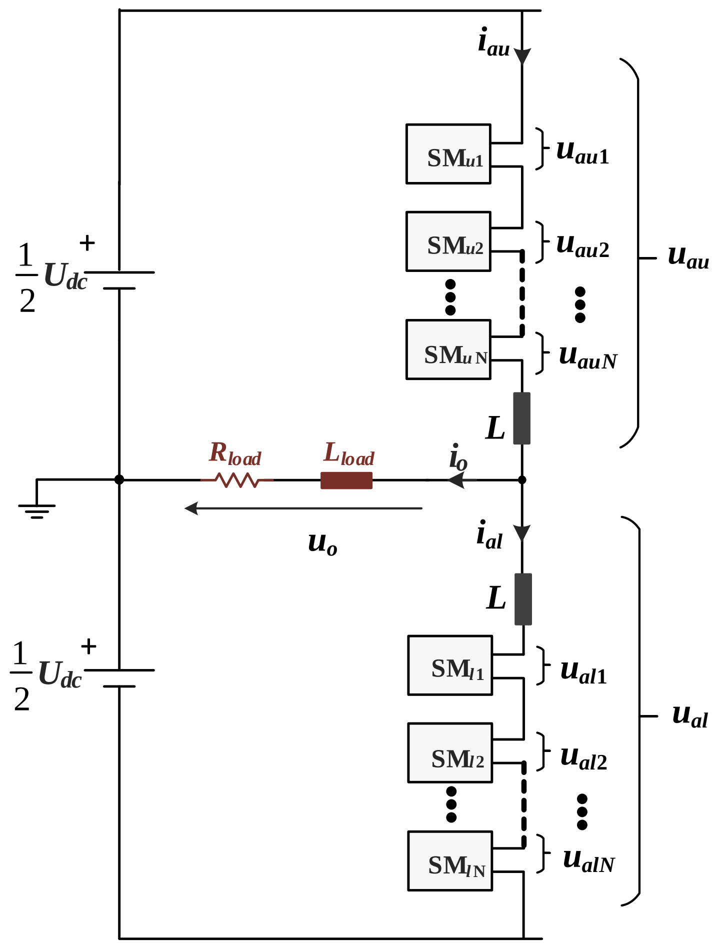
Circuit Structure

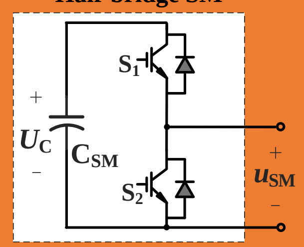


- Common DC link
- Three phases
- Six arms (upper and lower arms)
- Each arm consists of *N* series connected SMs and an arm inductor

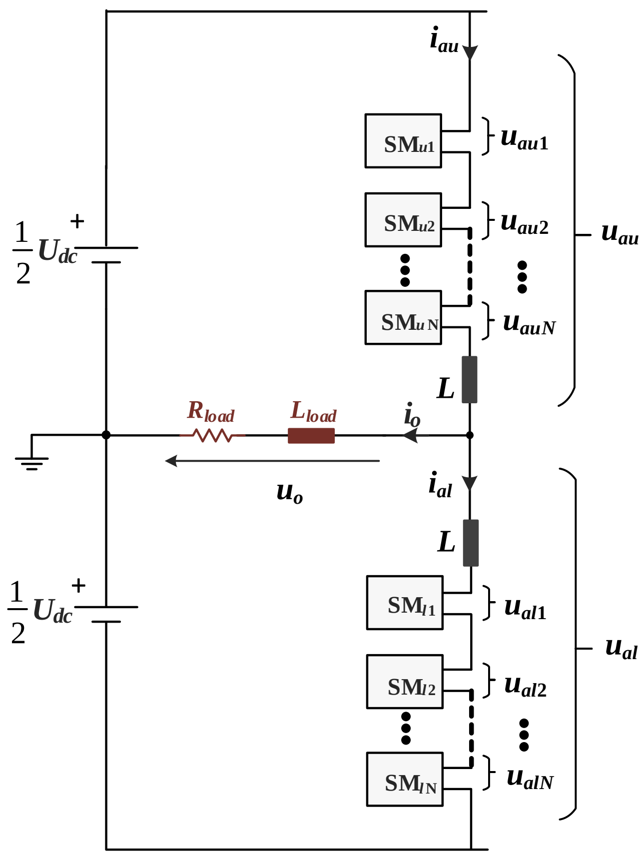
1-2 Operation Principles

SM Operation Principles



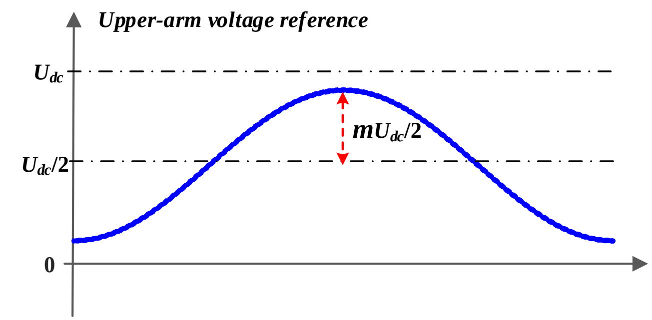
SM Type	States	Terminal voltage
Half-bridge SM 	S1 on, S2 off	$u_{sm}=U_C$
	S1 off, S2 on	$u_{sm}=0$

Arm Voltage References

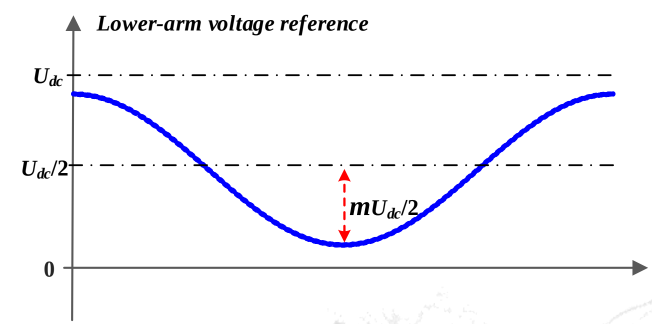


Suppose Modulation index is $m = \frac{2U_{om}}{U_{dc}}$

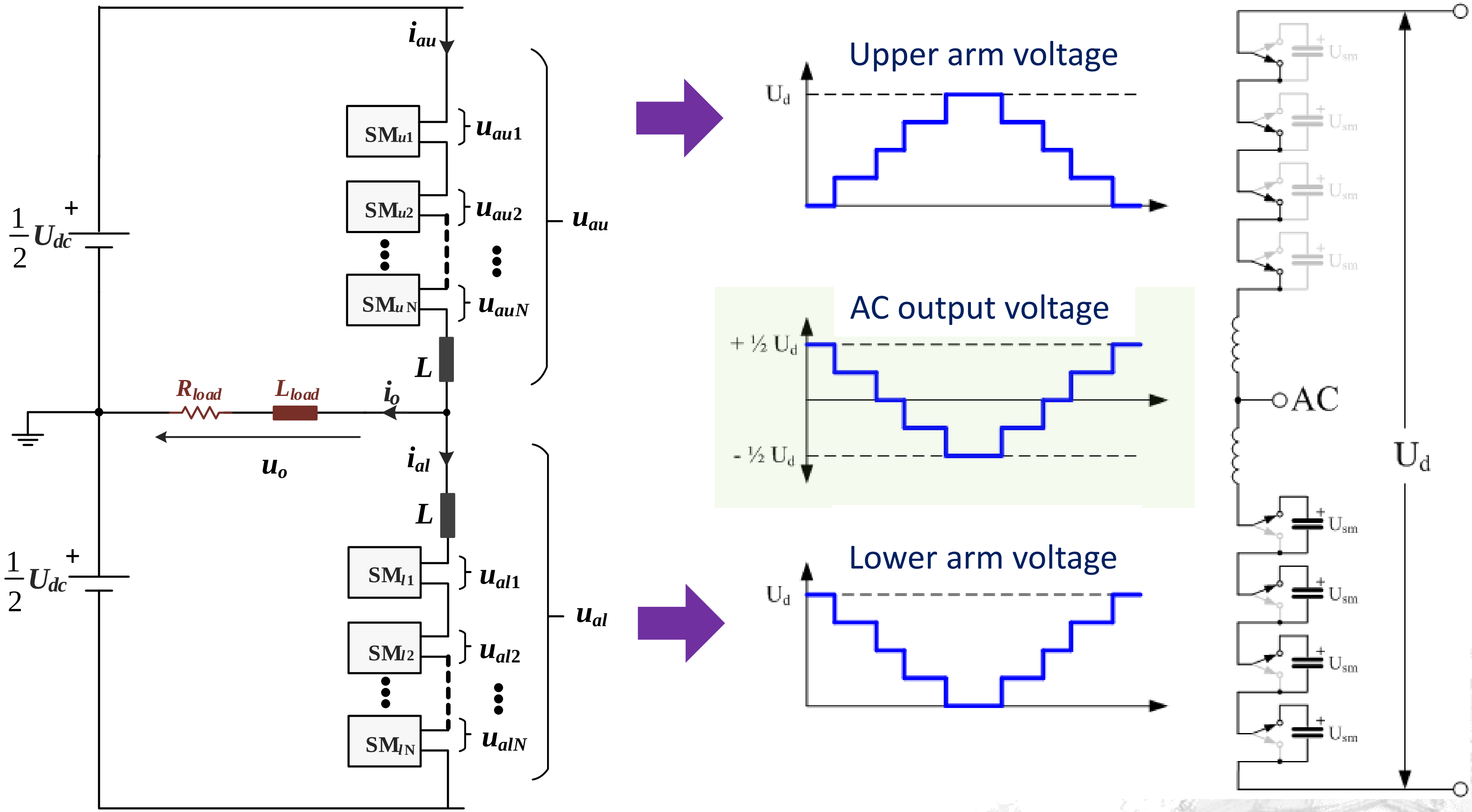
- Upper arm voltage reference: $u_{u\_ref} = \frac{U_{dc}}{2}(1 - m\cos\omega t)$



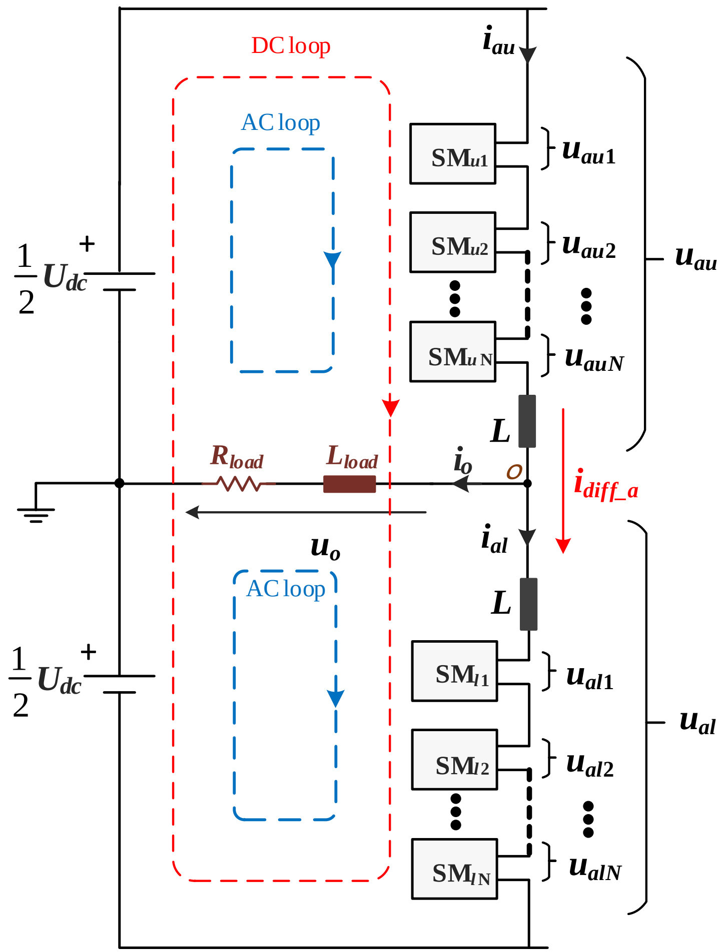
- Lower arm voltage reference: $u_{l\_ref} = \frac{U_{dc}}{2}(1 + m\cos\omega t)$



Arm Voltage References



MMC Model: Voltage Analysis



AC Loop Analysis

$$\begin{cases} u_o = -\sum_{i=1}^{n} u_{aui} - L\frac{di_{au}}{dt} + \frac{U_{dc}}{2} = -u_{au} + \frac{U_{dc}}{2} \\ u_o = \sum_{i=1}^{n} u_{ali} + L\frac{di_{al}}{dt} - \frac{U_{dc}}{2} = u_{al} - \frac{U_{dc}}{2} \end{cases}$$

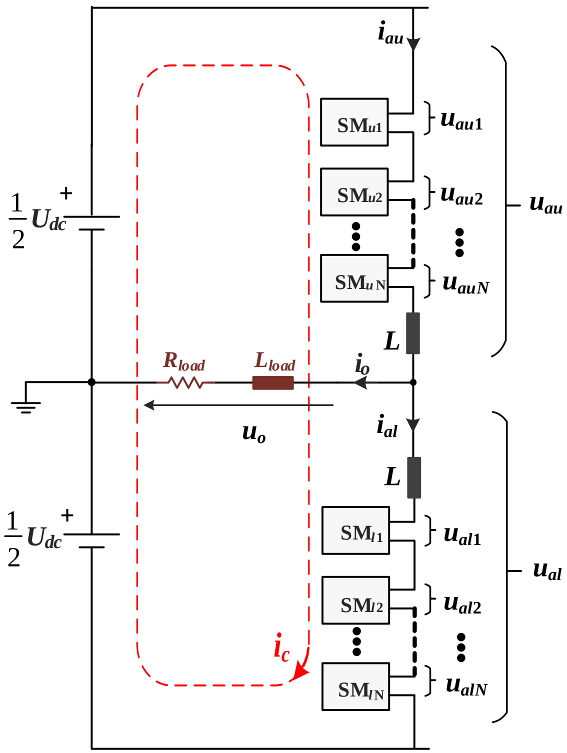
AC Voltage: $u_o = \frac{u_{al} - u_{au}}{2} = \frac{U_{dc}}{2} m\cos\omega t$

DC Loop Analysis

$$U_{dc} = \sum_{i=1}^{N} u_{aui} + \sum_{i=1}^{N} u_{ali} + L\frac{di_{au}}{dt} + L\frac{di_{al}}{dt}$$
$$= \sum_{i=1}^{N} S_{aui}u_{caui} + \sum_{i=1}^{N} S_{aui}u_{cali} + 2L\frac{di_{diff\_a}}{dt}$$

Circulating Current: $i_{diff\_a} = \frac{i_{au} + i_{al}}{2}$

MMC Model: Arm Current Analysis



- AC current i_o is split equally between the upper and lower arms:

Arm currents:

$$\begin{cases} i_{au} = i_c + \frac{1}{2} i_o \\ i_{al} = i_c - \frac{1}{2} i_o \end{cases}$$

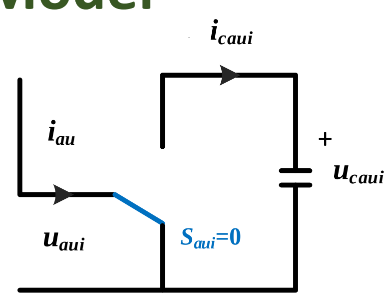
Circulating current is supposed to be suppressed

where i_c is phase dc current $i_c = \frac{1}{3} I_{dc}$

- Ideally, $i_o = I_{om} \cos(\omega t - \varphi)$

$$\Rightarrow \begin{cases} i_{au} = \frac{1}{3} I_{dc} + \frac{1}{2} I_{om} \cos(\omega t - \varphi) \\ i_{al} = \frac{1}{3} I_{dc} - \frac{1}{2} I_{om} \cos(\omega t - \varphi) \end{cases}$$

SM Model

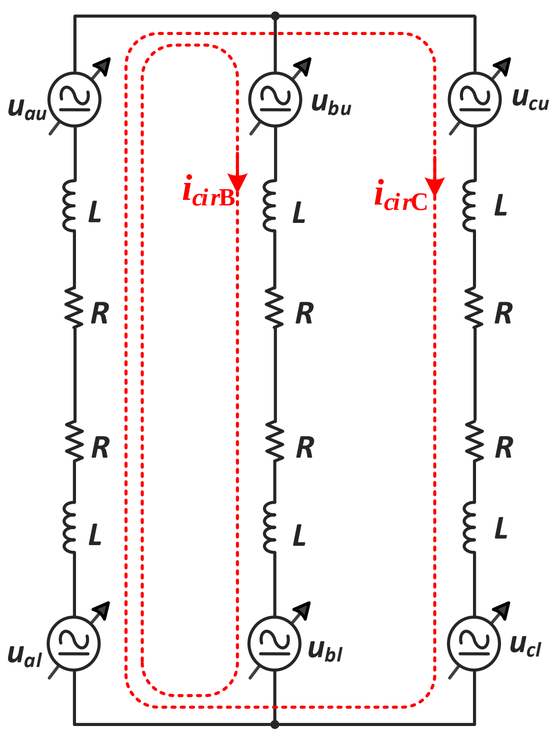


- The voltage and current relationship of *i*-th SM is

$$\begin{cases} i_{caui} = 0 \\ u_{aui} = 0 \end{cases}$$

MMC Model: Circulating Current Analysis

- Due to inner voltage unbalance among each phase of MMC
- Flow within the three phases units without affecting the dc and ac side voltages and currents
- In the following equivalent circuit, each arm of MMC is represented by a voltage source.



◆ **Upper and lower arm voltages**

$$\begin{cases} u_u = N \cdot y_u \dfrac{1}{C}\displaystyle\int y_u i_u dt \\ u_l = N \cdot y_l \dfrac{1}{C}\displaystyle\int y_l i_l dt \end{cases} \quad \text{with} \quad \begin{cases} y_u = \dfrac{1}{2}(1 - m\cos\omega t) \\ y_l = \dfrac{1}{2}(1 + m\cos\omega t) \end{cases}$$

$$u_u + u_l = \frac{N}{2C}\left[\int (y_u i_u + y_l i_l)dt - m\cos\omega t \int (y_u i_u - y_l i_l)dt\right] \quad (1)$$

◆ Upper and lower arm Current

(2)

$$\begin{cases} i_u = \displaystyle\sum_{n=0}^{\infty} i_{un} = \sum_{n=0}^{\infty} \hat{i}_{un} \cos(n\omega t + \phi_{un}) & (3) \\ i_l = \displaystyle\sum_{n=0}^{\infty} i_{ln} = \sum_{n=0}^{\infty} \hat{i}_{ln} \cos(n\omega t + \phi_{ln}) & (4) \end{cases}$$

Various harmonic components

- Substituting (2)~(4) into (1):

$$\begin{bmatrix} v_2 & z_2 & & & \\ x_4 & v_4 & z_4 & & \\ & x_6 & v_6 & z_6 & \\ & & \ddots & \ddots & \ddots \end{bmatrix} \times \begin{bmatrix} \hat{i}_2 e^{j\phi_2} \\ \hat{i}_4 e^{j\phi_4} \\ \hat{i}_6 e^{j\phi_6} \\ \vdots \end{bmatrix} = \begin{bmatrix} r \\ 0 \\ 0 \\ \vdots \end{bmatrix} \quad (5)$$

$$\begin{bmatrix} v_1 & z_1 & & & \\ x_3 & v_3 & z_3 & & \\ & x_5 & v_5 & z_5 & \\ & & \ddots & \ddots & \ddots \end{bmatrix} \times \begin{bmatrix} \hat{i}_1 e^{j\phi_1} \\ \hat{i}_3 e^{j\phi_3} \\ \hat{i}_5 e^{j\phi_5} \\ \vdots \end{bmatrix} = \begin{bmatrix} 0 \\ 0 \\ 0 \\ \vdots \end{bmatrix} \quad (6)$$

with
$$\begin{cases} x_n = -j\dfrac{m^2}{\omega 4(n-1)} \\ v_n = -j\dfrac{2(n^2-1)+n^2m^2}{2n\omega(n^2-1)} + \dfrac{2C}{N}(jn\omega L + R) \\ r = -j(\hat{I}_o \dfrac{3M}{8\omega_o} e^{-j\varphi} - \dfrac{M^2 I_{dc}}{6\omega}) \\ z_n = -j\dfrac{m^2}{\omega 4(n+1)} \end{cases}$$

- ❑ The dominated circulating current harmonic is second–order:

$$i_2 \approx Re\left\{ \frac{-j(\hat{I}_o \dfrac{3m}{8\omega} e^{-j\varphi} - \dfrac{m^2 I_{dc}}{6\omega})}{\dfrac{2C}{N}(j4\omega L + 2R) - j\dfrac{6+4m^2}{12\omega}} e^{j2\omega_o t} \right\}$$

- ✓ Only even-order harmonics
- ✓ No odd-order harmonics
- ✓ Increase arm current
- ✓ Require high power for devices
- ✓ Cause more power losses

Circulating current suppression is normally considered

1-4 Components Dimensioning

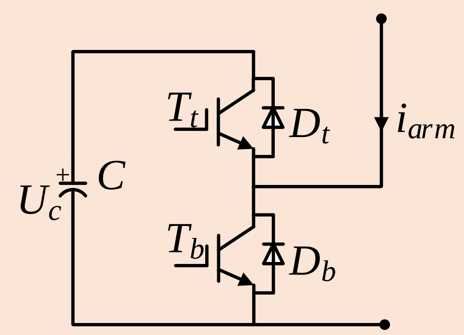
Device Voltage

- SM capacitor voltage is: $U_c = \frac{U_{dc}}{N}(1+\varepsilon)$ ε : capacitor voltage ripple percentage.

Device Current

- Arm current amplitude is: $I_{peak} = \frac{1}{3} I_{dc} + \frac{1}{2} I_{om}$
- Arm current RSM value is: $I_{rms} = \sqrt{\frac{1}{9} {I_{dc}}^2 + \frac{1}{4} {I_{om}}^2}$

Half-Bridge SM



Arm inductors

- Design Principle1： Limit rate of rise of the arm current when DC side short-circuit

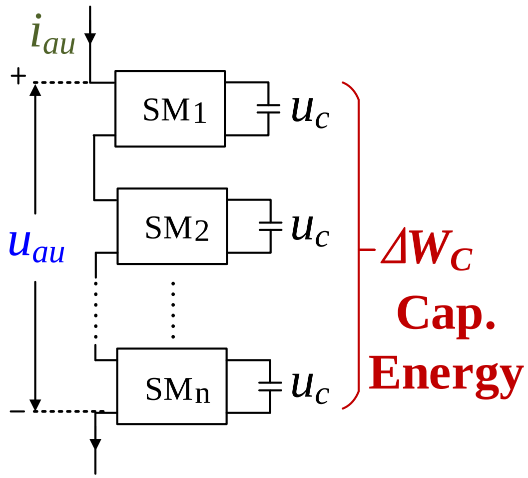
$$L \geq \frac{U_{dc}}{2\frac{di_{ju}}{dt}}$$

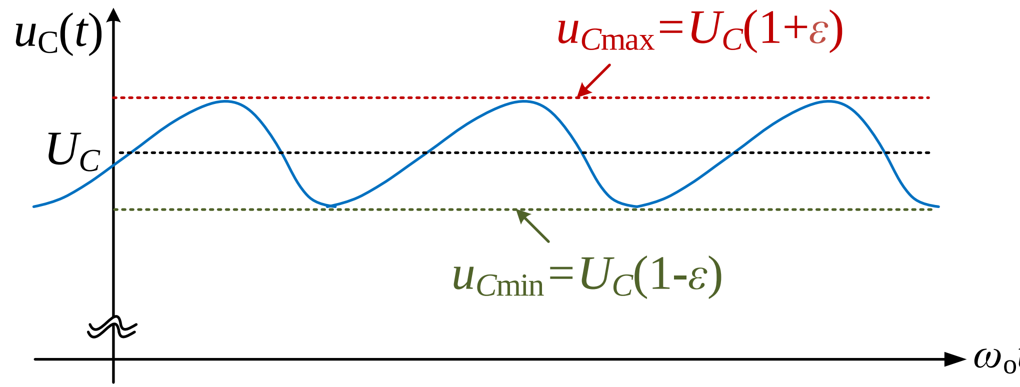
- Design Principle2： Limit second-frequency circuiting current within three phases

$$L \geq \frac{U_{dc}}{8\omega^2 C U_C}\left(\frac{P}{3I_{2m}} + U_{dc}\right)$$

SM Capacitance

- Principle: keep the capacitor voltage within reasonable limit $\pm\varepsilon$.





- Maximum and minimum capacitor voltages are

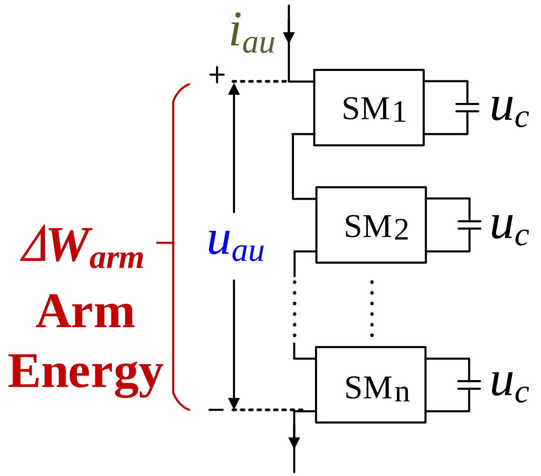
$$\begin{cases} u_{C\max} = U_C\left(1+\varepsilon\right) \\ u_{C\min} = U_C\left(1-\varepsilon\right) \end{cases}$$

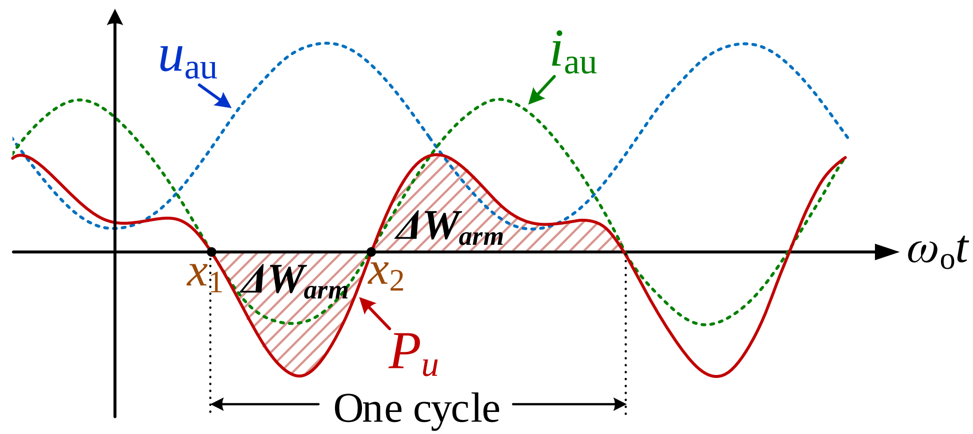
- Arm maximum capacitor energy variation ΔW_C is

$$\Delta W_C = N\frac{1}{2}C\left[\left(u_{C\max}\right)^2-\left(u_{C\min}\right)^2\right]=2N\varepsilon C U_C{}^2$$

[1] C. Oates, "Modular multilevel converter design for VSC HVDC applications," *IEEE J. Emerging Sel. Topics Power Electron.*, vol. 3, no. 2, pp. 505–515, 2015.

SM Capacitance





- Arm instantaneous power $P_u(t)$

$$p_u(t) = u_{ju}(t) i_{ju}(t) = \frac{1}{2} U_{dc}[1\text{-}m\cos(\omega_o t)] \times \frac{1}{3} I_{dc}[1 + \frac{2}{m\cos\varphi}\cos(\omega_o t - \varphi)]$$

- Maximum energy variation of an arm ΔW_{arm} is

$$\Delta W_{arm} = \int_{x_1}^{x_2} p_u(t)\,dt = \int_{x_1}^{x_2} u_{au}(t) i_{au}(t)\,dt = \frac{U_{om} I_{om}}{mN\omega\cos\varphi}\left[1 - \left(\frac{m\cos\varphi}{2}\right)^2\right]^{3/2}$$

Energy Balancing: $\boxed{\Delta W_{arm} = \Delta W_c}$ $\Rightarrow$ $\boxed{C_{SM} \geq \frac{\Delta W_{arm}}{2\varepsilon U_C^{\,2}}}$

[1] C. Oates, "Modular multilevel converter design for VSC HVDC applications," *IEEE J. Emerging Sel. Topics Power Electron.*, vol. 3, no. 2, pp. 505–515, 2015.

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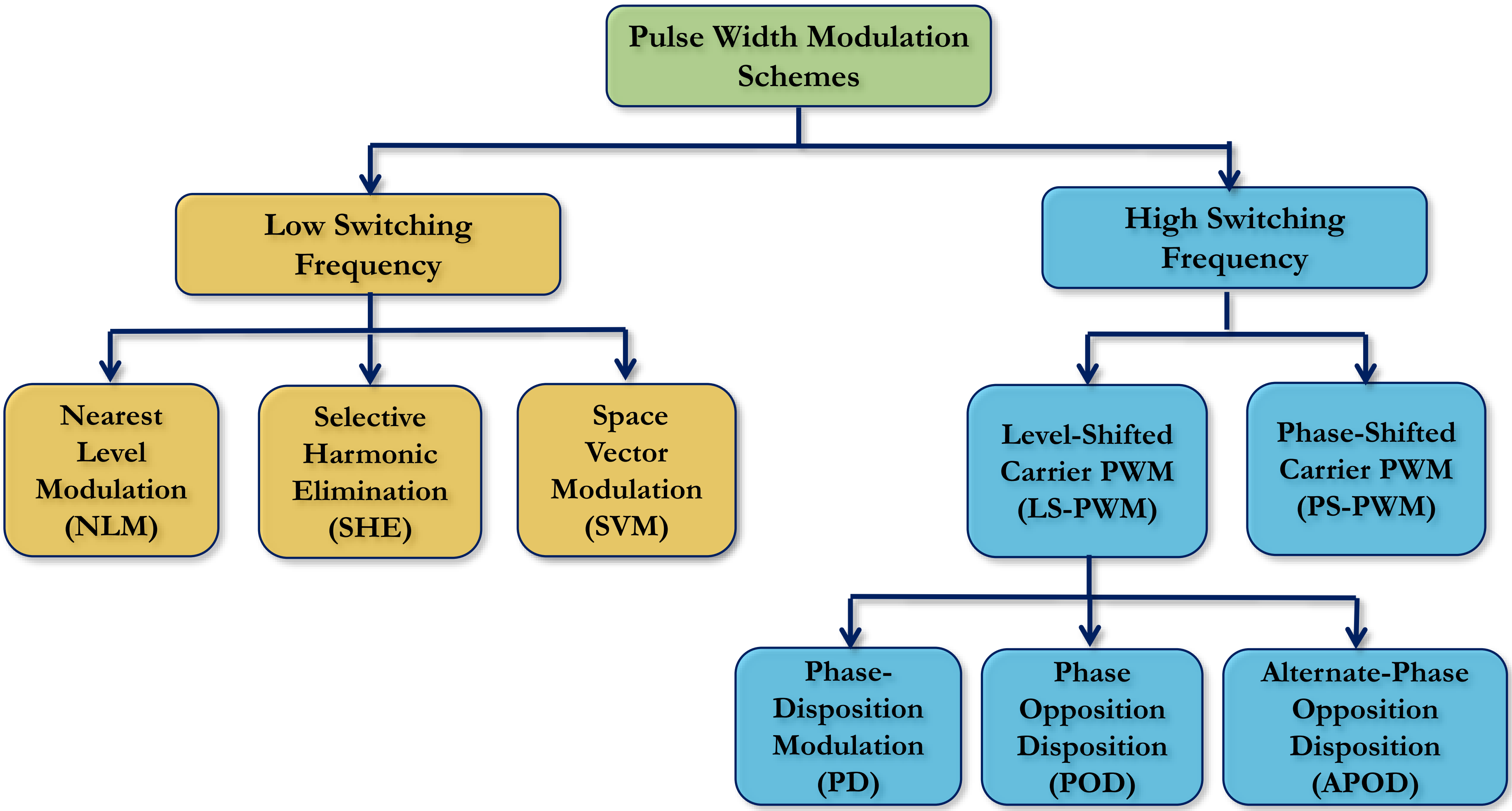
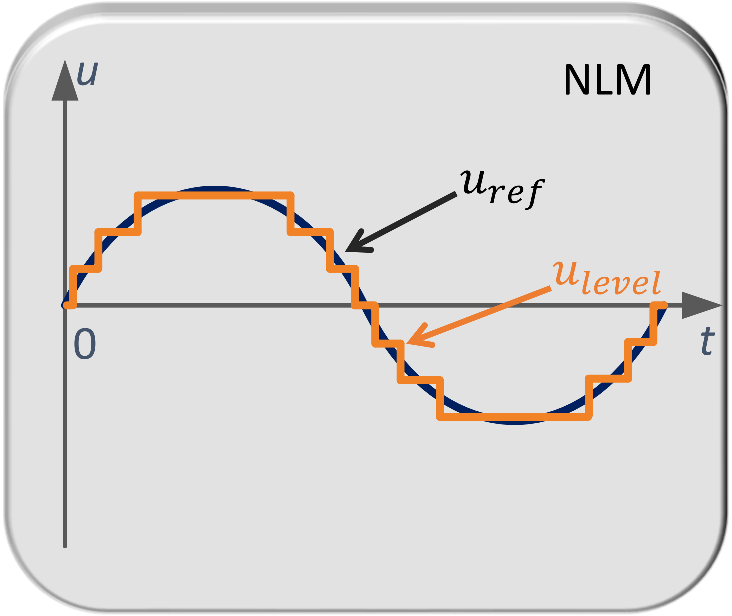
- Circuit, Topologies and operation Principles
- **Modulation Schemes**
- Capacitor Voltage Balancing Control

Modulation Techniques



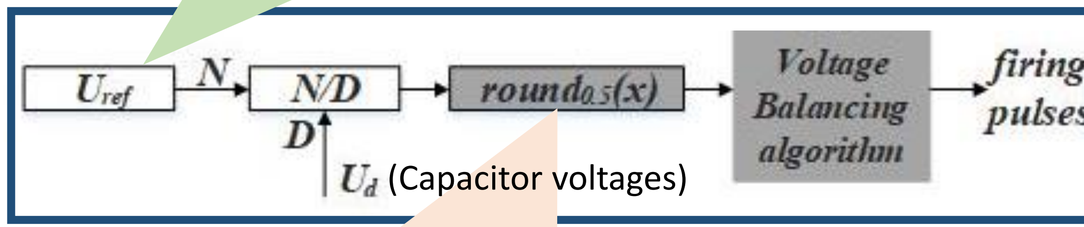
2–1 Low Switching-Frequency Modulation

1. NLM - Nearest Level Modulation



Upper and lower arm reference voltages:

$$\begin{cases} u_{ref\_upper} = \dfrac{U_{dc}}{2}[1 - m\cos(\omega t)] \\ u_{ref\_lower} = \dfrac{U_{dc}}{2}[1 + m\cos(\omega t)] \end{cases}$$

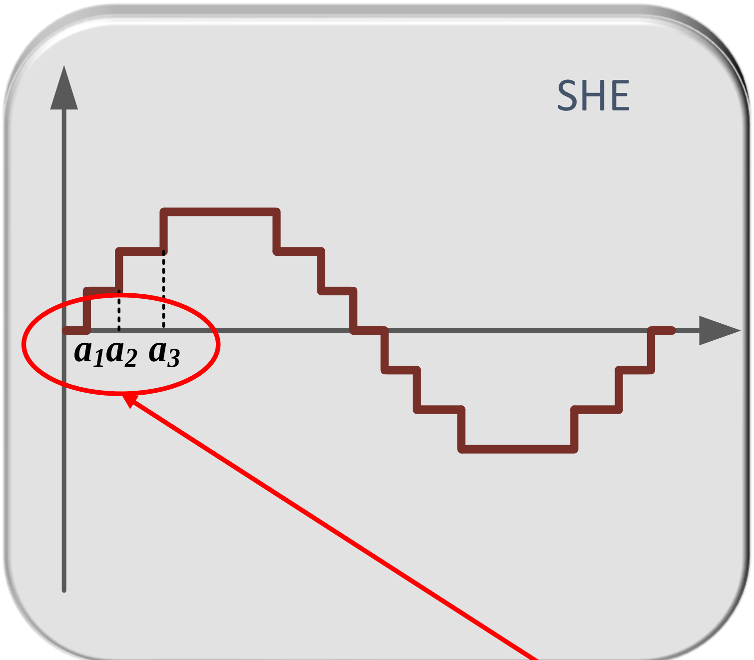


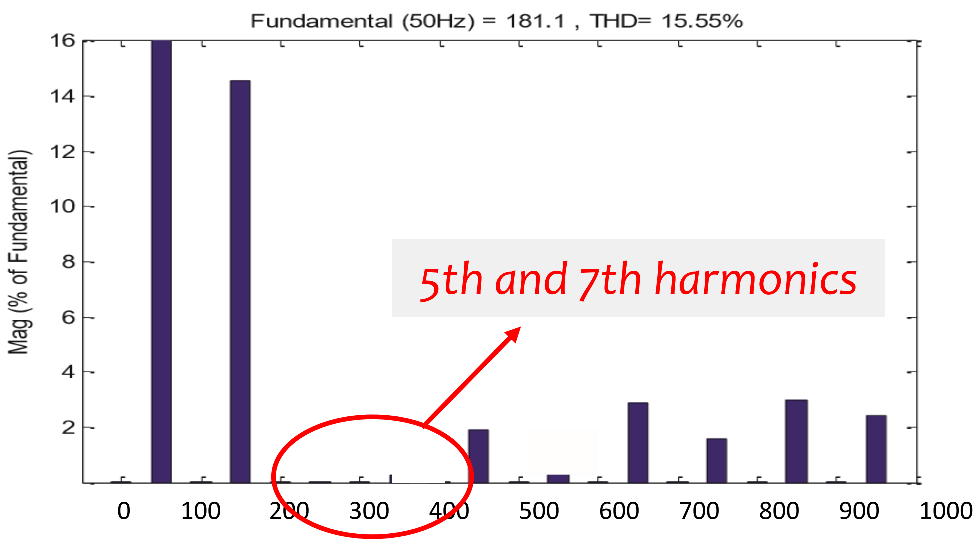
- ✓ Low switching frequency
- ✓ low losses
- ✓ For the case with large number of SMs
- ✓ High distortion (particular at the flat) when number of SM is not large enough

- Number of inserted SMs in upper and lower arms

$$\begin{cases} N_{upper} = round_{0.5}\left\{\dfrac{U_{dc}}{2U_d}[1 - m\cos(\omega t)]\right\} \\ N_{lower} = round_{0.5}\left\{\dfrac{U_{dc}}{2U_d}[1 + m\cos(\omega t)]\right\} \end{cases}$$

2. SHE - Selective Harmonic Elimination





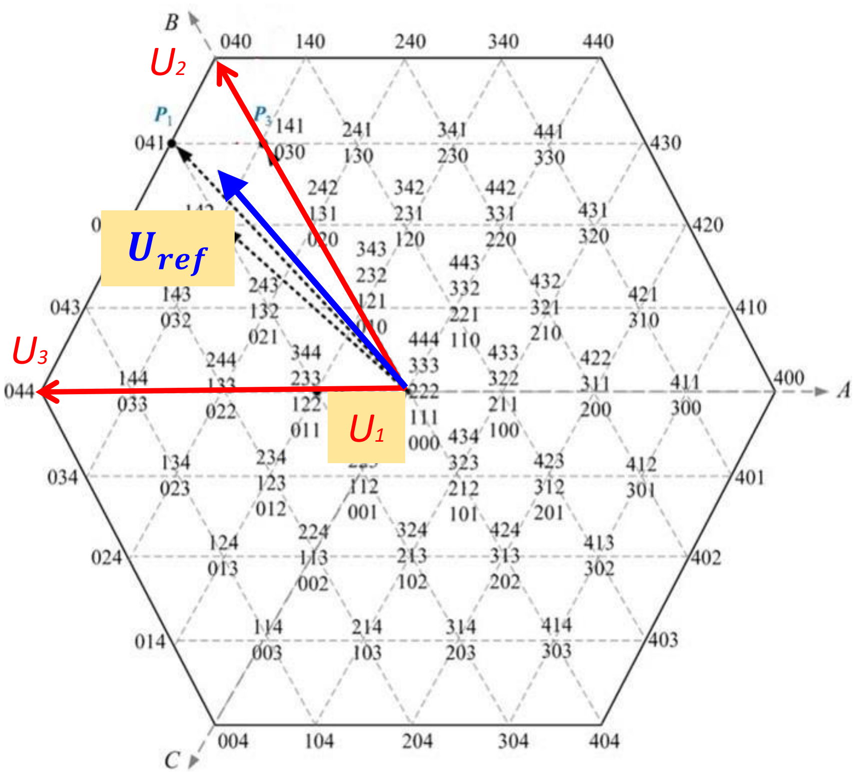
Harmonic spectrum using SHE

SHE Algorithm:

$$\left.\begin{aligned}\frac{2U_{dc}}{\pi}(1-2\cos a_1+2\cos a_2-2\cos a_3)&=U_{ref}\\ \frac{2U_{dc}}{5\pi}(1-2\cos 5a_1+2\cos 5a_2-2\cos 5a_3)&=0\\ \frac{2U_{dc}}{7\pi}(1-2\cos 7a_1+2\cos 7a_2-2\cos 7a_3)&=0\end{aligned}\right\}\Rightarrow \boxed{a_1,a_2,a_3}$$

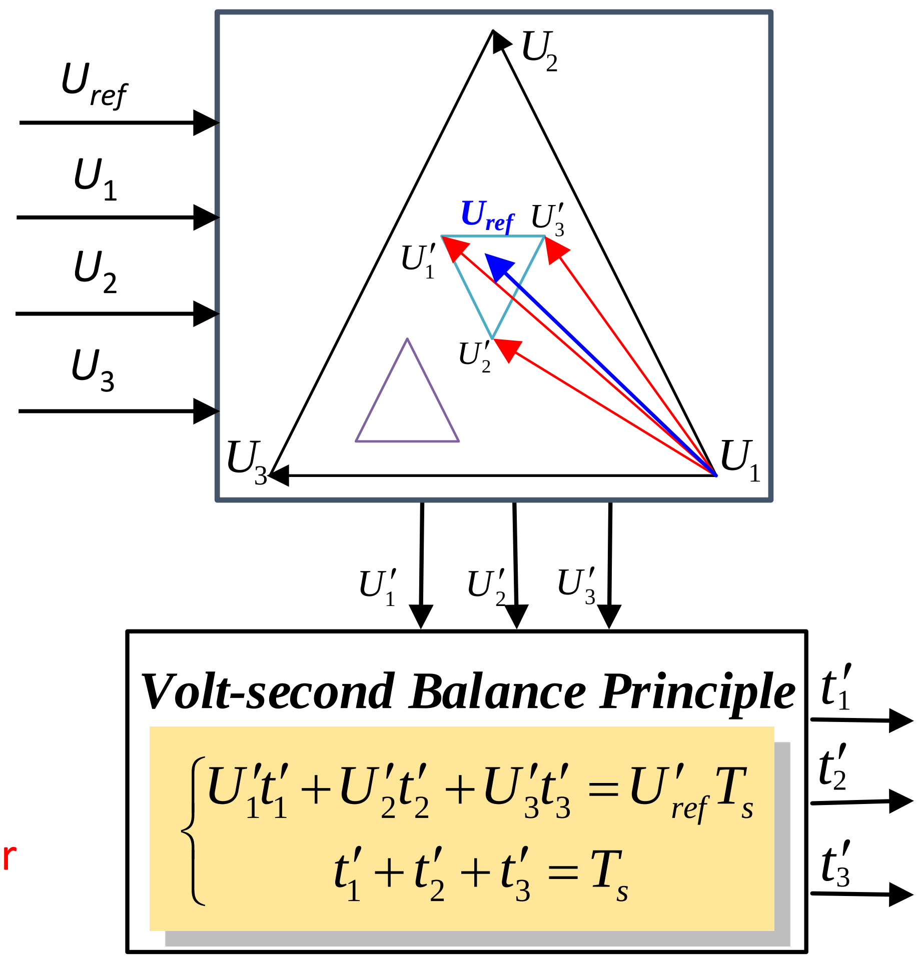
- ✓ Low switching frequency
- ✓ Improve harmonic performance
- ✓ High complexity for switching angles as the SM number increases

3. SVPWM - Space-Vector PWM $100Hz < f_{sw} < 2000Hz$



Space vector states for 5-level MMC converter

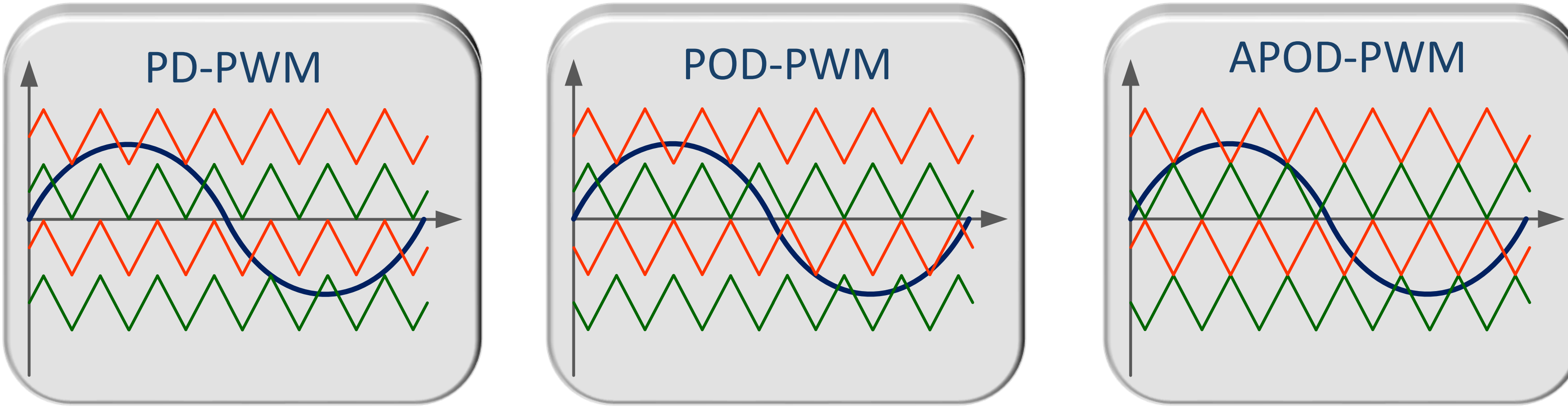
Determining the Sector



Calculate the action time

2–2 High Switching-Frequency Modulation

1. LS-PWM - Level Shifted PWM



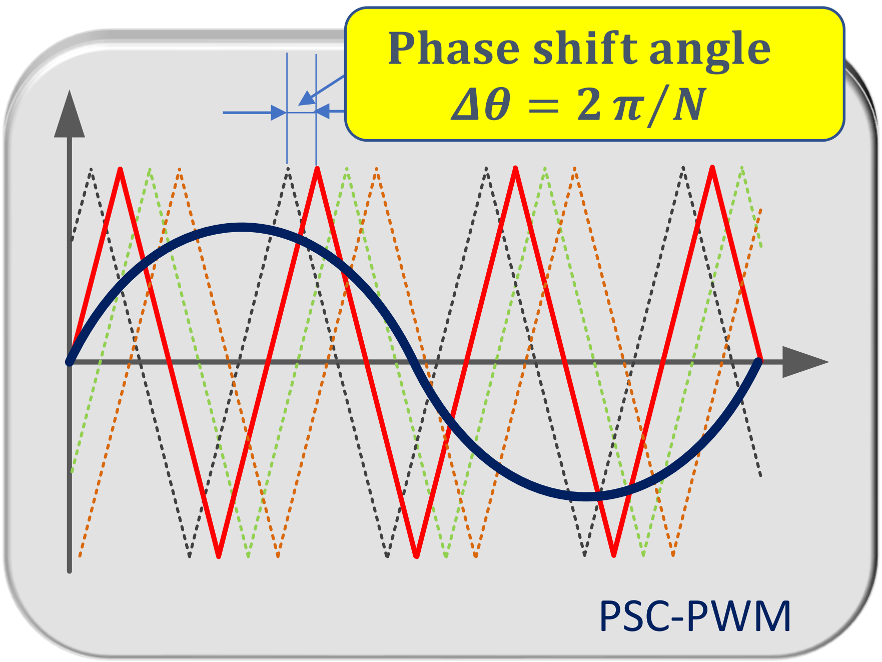
Level number	2N+1 Level			N+1 Level		
Modulation mode	PD-PWM	POD-PWM	APOD-PWM	PD-PWM	POD-PWM	APOD-PWM
Equivalent switching frequency	f_{cs}	f_{cs}	f_{cs}	f_{cs}	f_{cs}	f_{cs}
Harmonic distribution	$2f_{cs}$	$2f_{cs}$	$2f_{cs}$	f_{cs}	f_{cs}	f_{cs}

SM number N is odd

SM number N is even

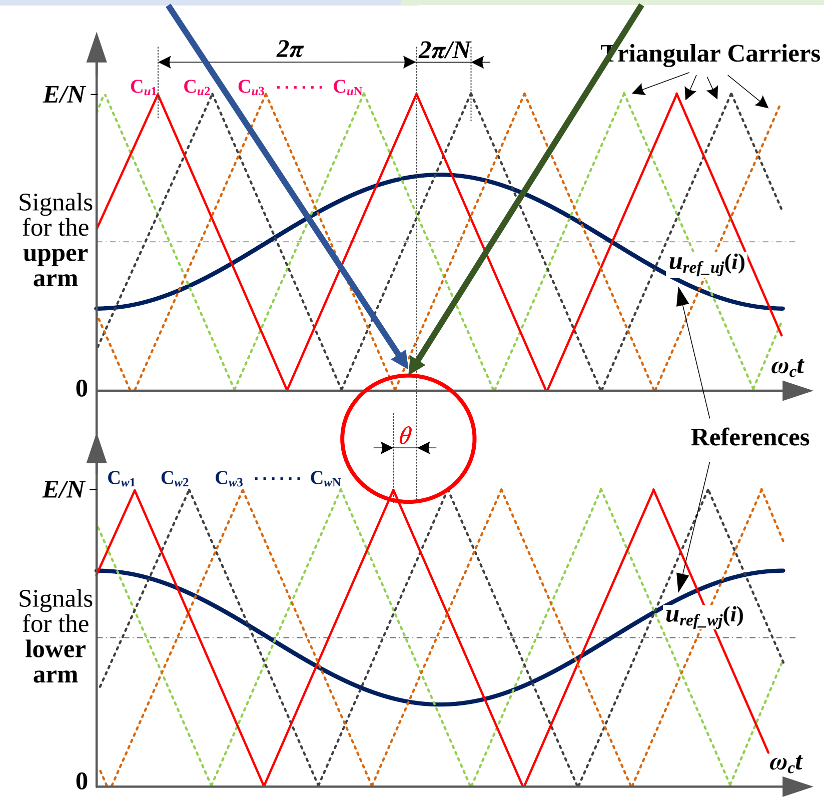
- ✓ Low output harmonics
- ✓ Harmonic features varies with modulation index

2. PSC - PWM-Phase-Shifted Carrier PWM



- Equivalent switching frequency is $N \times f_c$
- Equivalent switching frequency is $2N \times f_c$

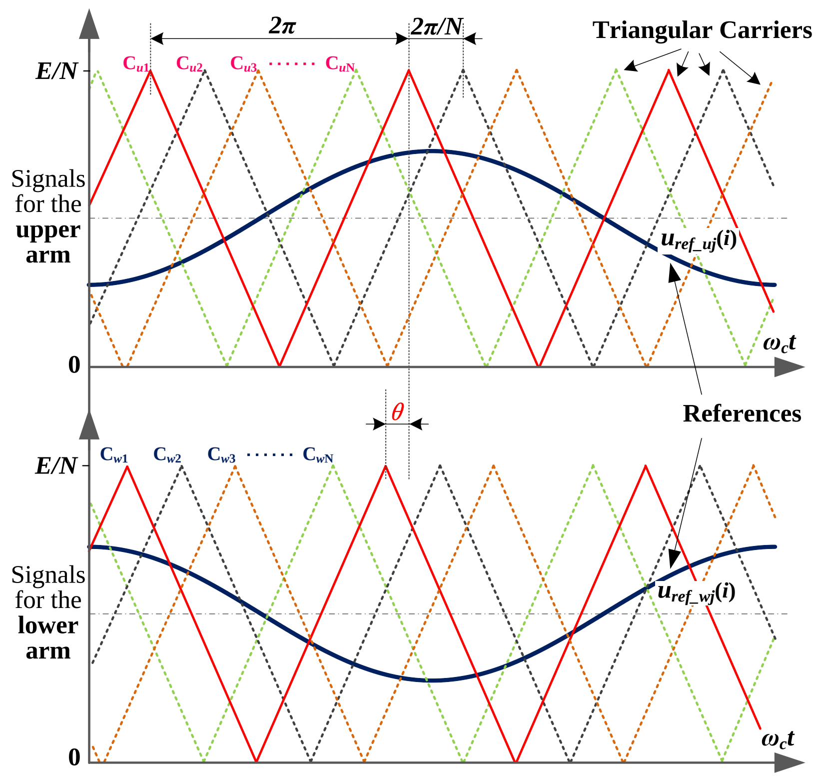
without θ interleaving | with θ interleaving



- ✓ **High switching frequency**
- ✓ **low THD**
- ✓ **Harmonic features are irrespective with modulation index**
- ✓ **Suitable for the case with few SMs (Medium Voltage Applications)**

❑ Harmonic analysis of MMCs under PSC-PWM

θ is displacement angle between the upper and lower arm carriers



- Output voltage of MMC:

$$u_{oj} = \frac{1}{2} ME\cos(\omega_o t + \varphi_j) + \sum_{m=1}^{\infty}\sum_{n=-\infty}^{\infty} \frac{(-1)^n 2E}{m\pi N} J_{2n+1-Nm}\left(\frac{MNm\pi}{2}\right) \times \cos[Nm\omega_c t + Q] \cos\left[\frac{Nm(\theta-\pi)}{2}\right]$$

- Circulating current of MMC:

$$i_{cj} = \frac{I_{dc}}{3} - \sum_{m=1}^{\infty}\sum_{n=-\infty}^{\infty} \frac{(-1)^n E \times J_{2n+1-Nm}\left(\frac{MNm\pi}{2}\right)}{m\pi N L_0\left(Nm\omega_c + (2n+1-Nm)\omega_o\right)} \times \cos[Nm\omega_c t + Q] \sin\left[\frac{Nm(\theta-\pi)}{2}\right]$$

✓ Both contain *N*-multiples of carrier-frequency harmonics and associated sideband components

✓ Magnitudes of the *Nm*th carrier group harmonics of output voltage and circulating current are a function of θ

[1] B. Li, "Analysis of the Phase-Shifted Carrier Modulation for Modular Multilevel Converters," IEEE Trans. on Power Electronics, vol. 30, no. 1, pp. 297–310, Jan. 2015.

❑ Phase-shift Angle θ Selection

➢ To Minimize Output Voltage Harmonics

$$\theta=\begin{cases}0 & N \text{ is odd}\\ \dfrac{\pi}{N} & N \text{ is even}\end{cases}$$

The output voltage harmonics becomes:

$$\hat{V}_{Nm} = K_{Nm} \times \left|\cos\left[\frac{Nm(\theta-\pi)}{2}\right]\right| = 0$$

✓ But circulating current harmonics are at their maximums:

$$\hat{I}_{Nm} = H_{Nm} \quad (m=1, 3, 5, \ldots)$$

Contradiction

➢ To Minimize Circulating Current Harmonics

$$\theta=\begin{cases}\dfrac{\pi}{N} & N \text{ is odd}\\ 0 & N \text{ is even}\end{cases}$$

All switching harmonics in circulating currents are completely eliminated:

$$\hat{I}_{Nm} = H_{Nm} \times \left|\sin\left[\frac{Nm(\theta-\pi)}{2}\right]\right| = 0$$

✓ But the output voltage harmonics are at their maximums

$$\hat{V}_{Nm} = K_{Nm} \quad (m=1, 2, 3, \ldots)$$

3. Improved PS-PWM

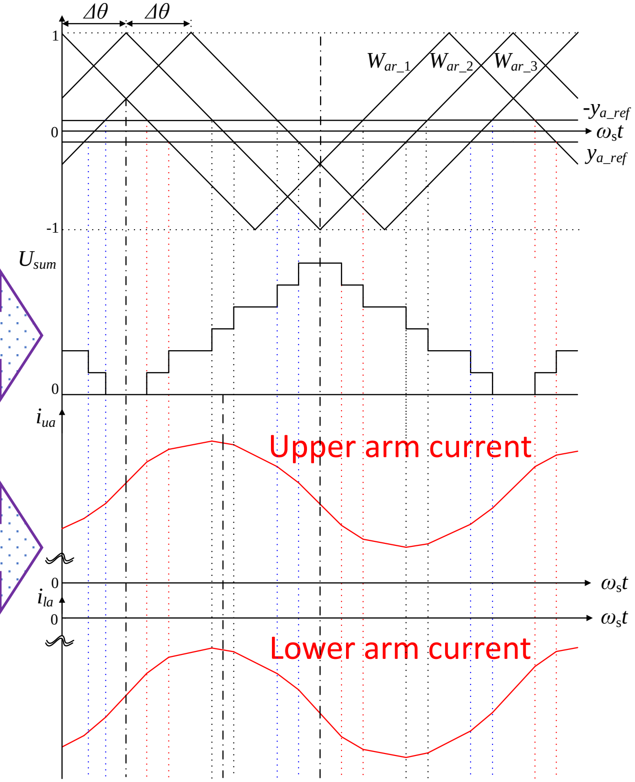
$$0 < \Delta\theta < 2\pi/N$$

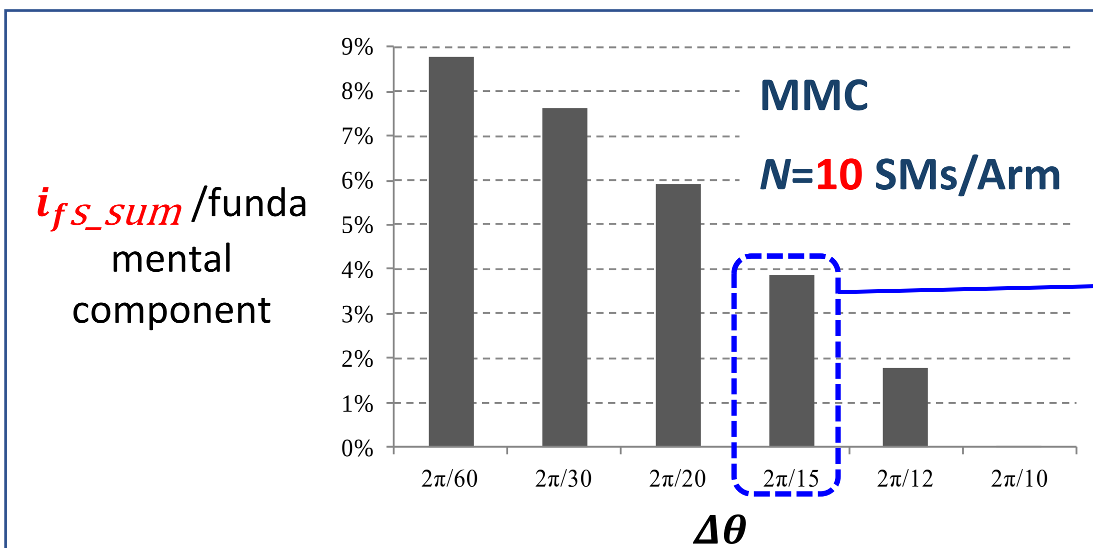
- High-frequency Voltage

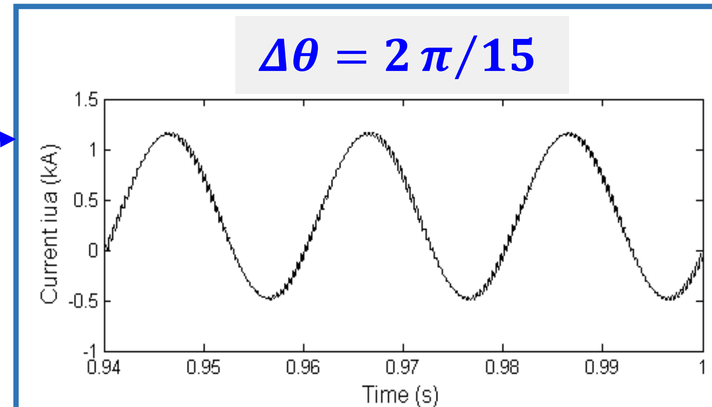
$$u_{fs\_sum}(t) = -\frac{4V_c}{\pi}\frac{\sin\frac{n\Delta\theta}{2}}{\sin\frac{\Delta\theta}{2}}\cos\left(\frac{\Delta\theta_u-\Delta\theta_l}{4}\right)\cos\left(\omega_s t-\frac{n-1}{2}\Delta\theta\right)$$

- High-frequency Current

$$i_{fs\_sum}(t) = \frac{2V_c}{\pi\omega_s L_s}\frac{\sin\frac{n\Delta\theta}{2}}{\sin\frac{\Delta\theta}{2}}\cos\left(\frac{\Delta\theta_u-\Delta\theta_l}{4}\right)\cos\left(\omega_s t-\frac{n-1}{2}\Delta\theta-\frac{\pi}{2}\right)$$







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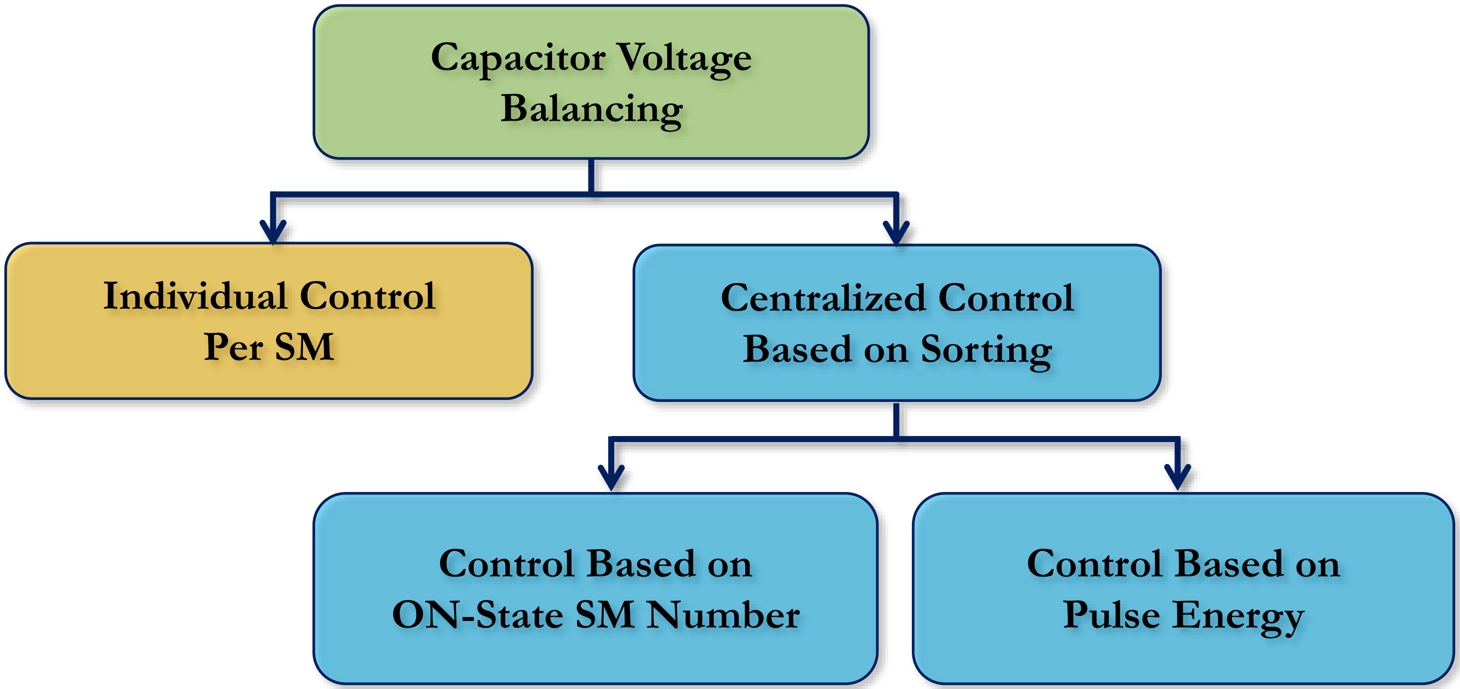
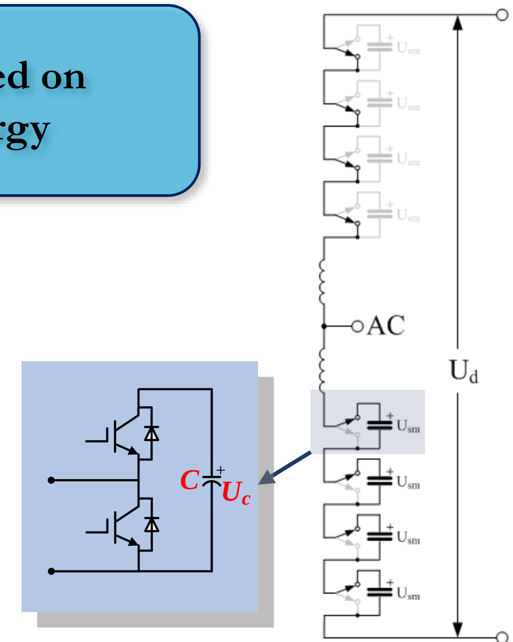
- **Capacitor Voltage Balancing Control**

Capacitor Voltage Balancing Methods



- Voltage unbalance is unavoidable, due to:
  - Component parameter difference and aging
  - Unequal power distribution
  - Inconsistent transmission delay of the driving signals
  - ...

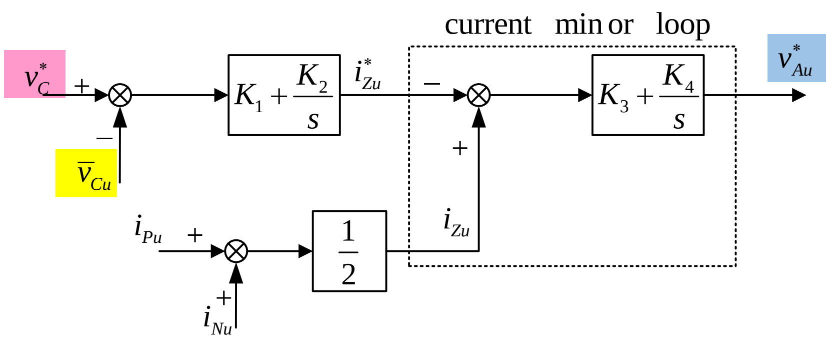


Capacitor voltage balancing is the prerequisite for stable operation of MMC

Method-1: Individual Control Per SM

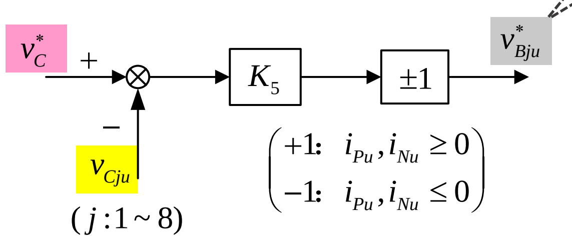
- Averaging Control

Force arm SMs' average voltage $\overline{v_{cu}} = \sum_{j=1}^{n} v_{cju} \Big/ n$ to follow its command v_c^*

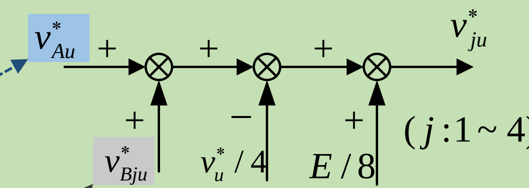


- Balancing Control

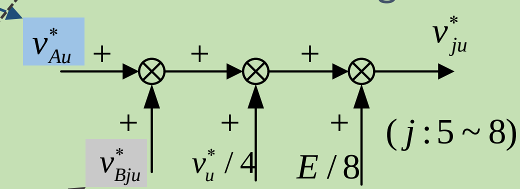
Force individual SM voltage v_{cju} to follow its command v_c^*

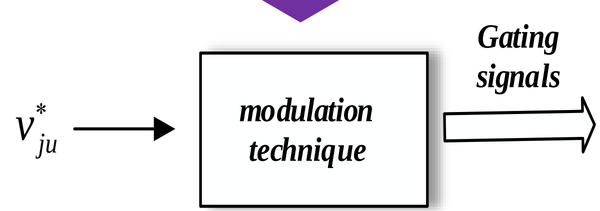


✓ Upper arm SM voltage command



✓ Lower arm SM voltage command

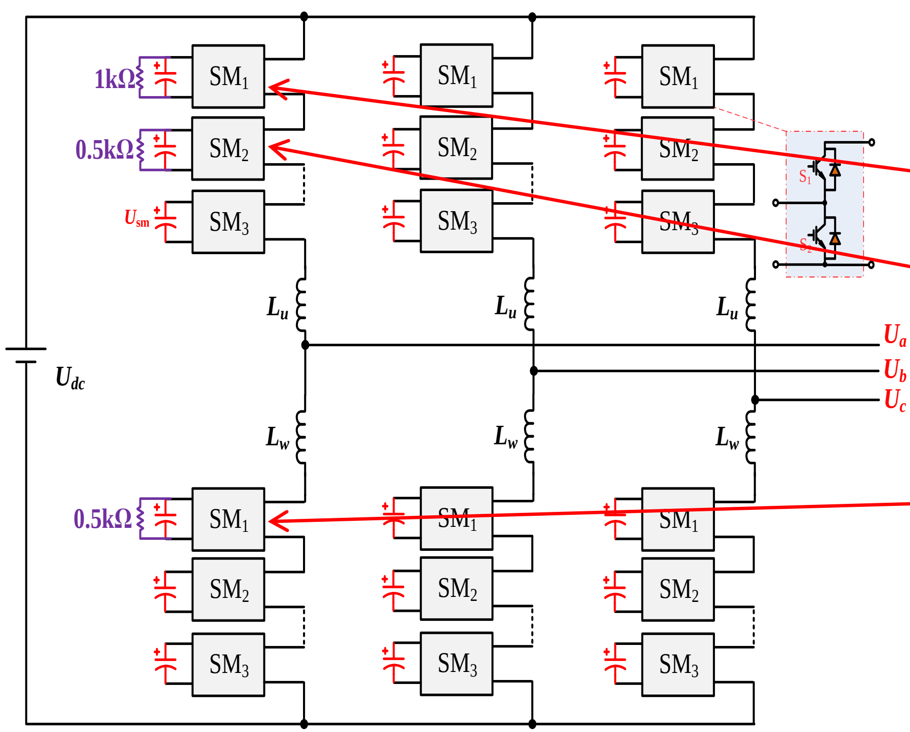




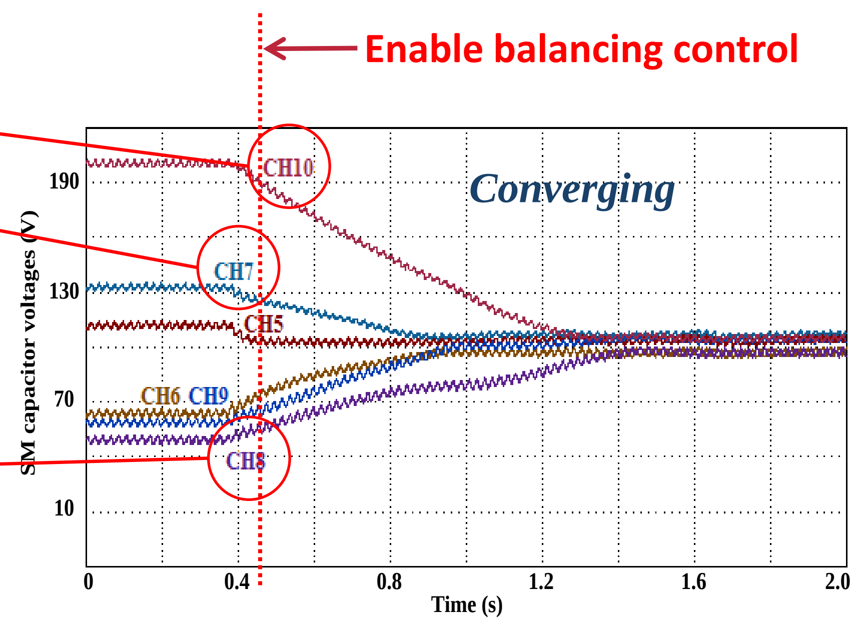
Each SM has a closed loop control

❑ Experimental Verification

- Experiment with 3 SMs per arm
- Nominal capacitor voltage is 100V
- Voltage unbalance is intentionally introduced by paralleling resistors to some of the SMs

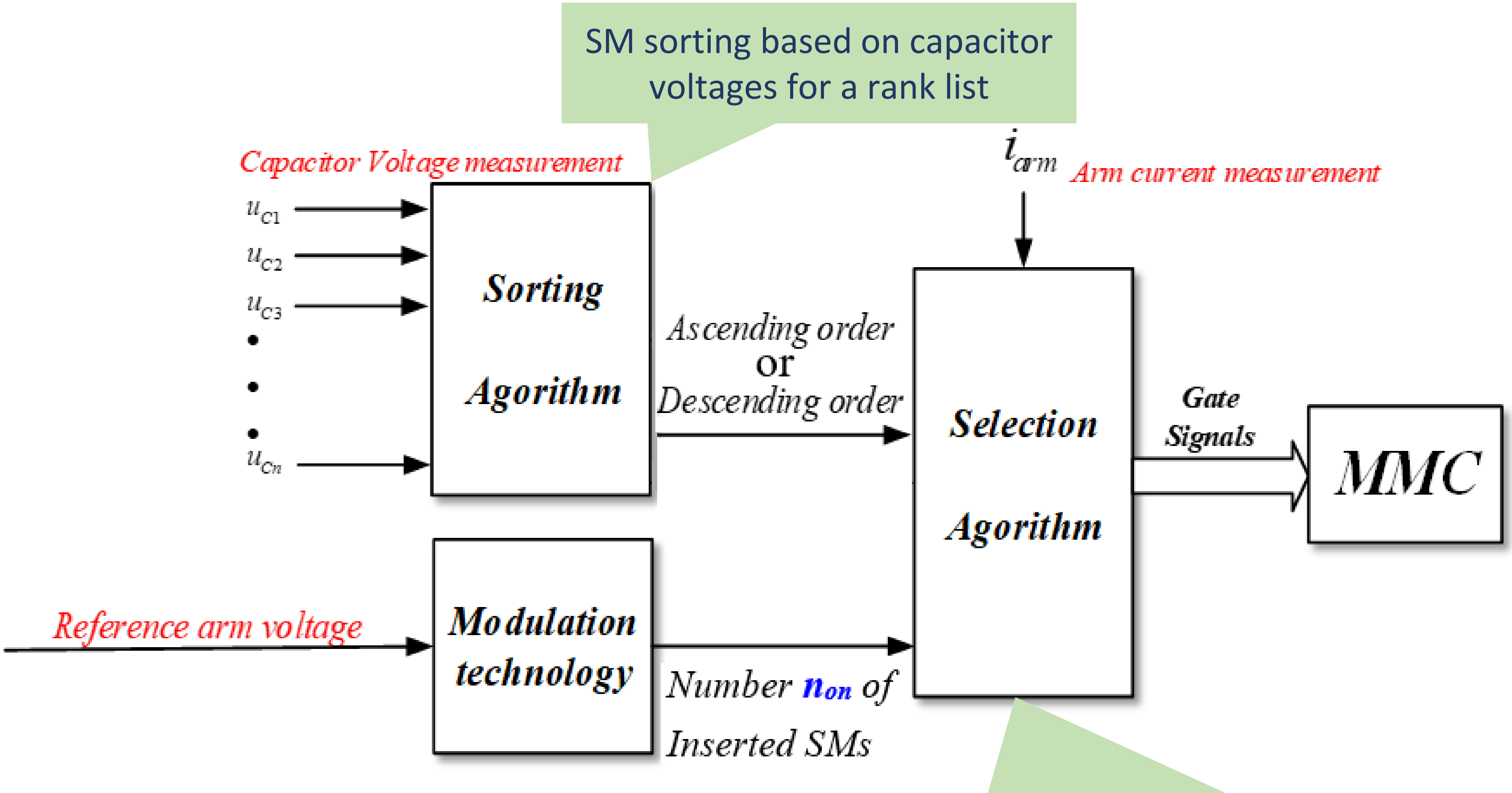


Experimental circuit configuration



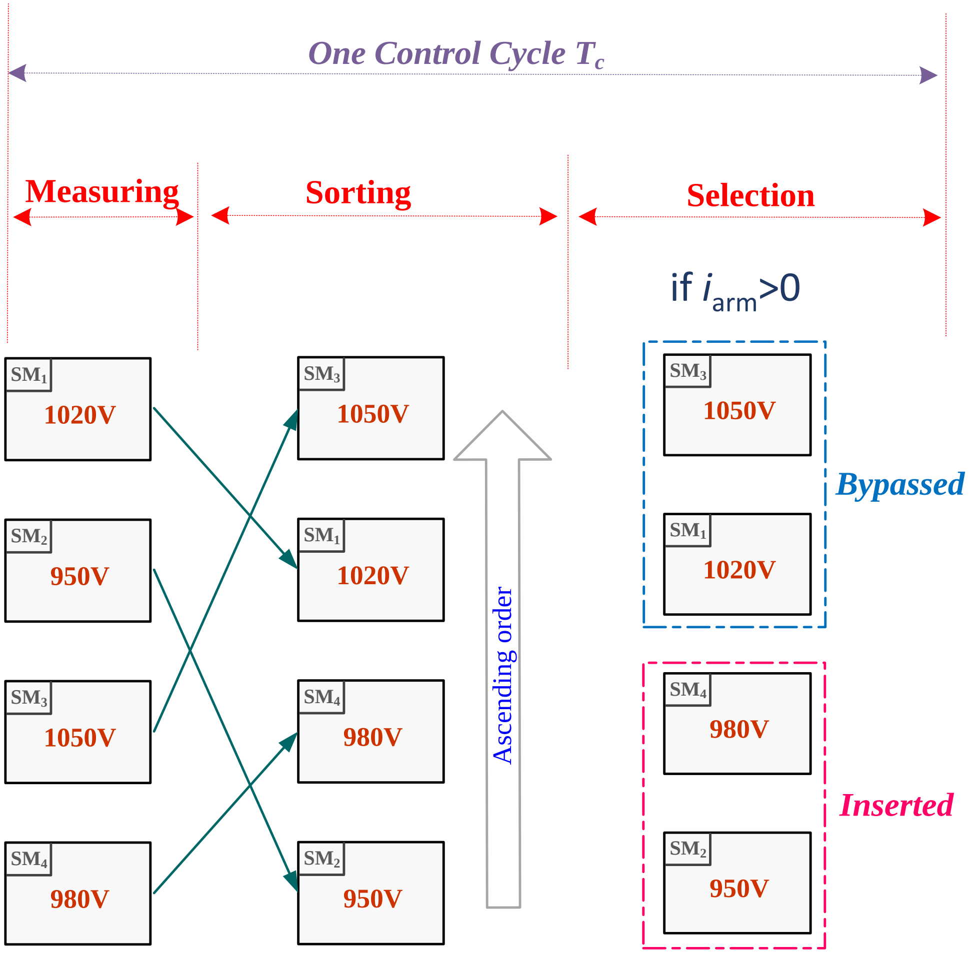
Capacitor voltages of 6 SMs in the same phase

Method-2: Based on Voltage Sorting & ON-State SMs Number



- ✓ $i_{arm} > 0$: n_{on} number of SMs with the lowest voltage are switched on.
- ✓ $i_{arm} < 0$: n_{on} number of SMs with the highest voltage are switched on.

❑ Example



- *Example with 4 SMs per arm*
- *2 of 4 SMs need to be inserted*
- *Nominal capacitor voltage is 1000V*

✓ Implemented with the PSC-PWM, LSC-PWM, NLM, SHE, SAM, and SVM schemes

✓ Proper compromise between switching frequency and capacitor voltage deviation [1], [2]

	Inserted (S_1 is on)	Bypassed (S_2 is on)
i_{arm}>0	charged	unchanged
i_{arm}<0	discharged	unchanged

[1] Z. Li, "Power Module Capacitor Voltage Balancing Method for a ±350-kV/1000-MW Modular Multilevel Converter," IEEE Trans. Power Electron., vol. 31 no. 6, pp. 3977–3984, Jun. 2016.
[2] Q. Tu, "Reduced Switching-Frequency Modulation and Circulating Current Suppression for Modular Multilevel Converters," IEEE Trans. Power Del., vol. 26, no. 3, pp. 2009–2017, July. 2011.

Method-3: Control Based on Pulse Energy

- Improved PS-PWM

$$0 < \Delta\theta < 2\pi/N$$

- High-frequency arm current:

$$i_{fS\_sum}(t) = \frac{2V_c}{\pi\omega_s L_s}\frac{\sin\frac{n\Delta\theta}{2}}{\sin\frac{\Delta\theta}{2}}\cos\left(\frac{\Delta\theta_u - \Delta\theta_l}{4}\right)\cos\left(\omega_s t - \frac{n-1}{2}\Delta\theta - \frac{\pi}{2}\right)$$

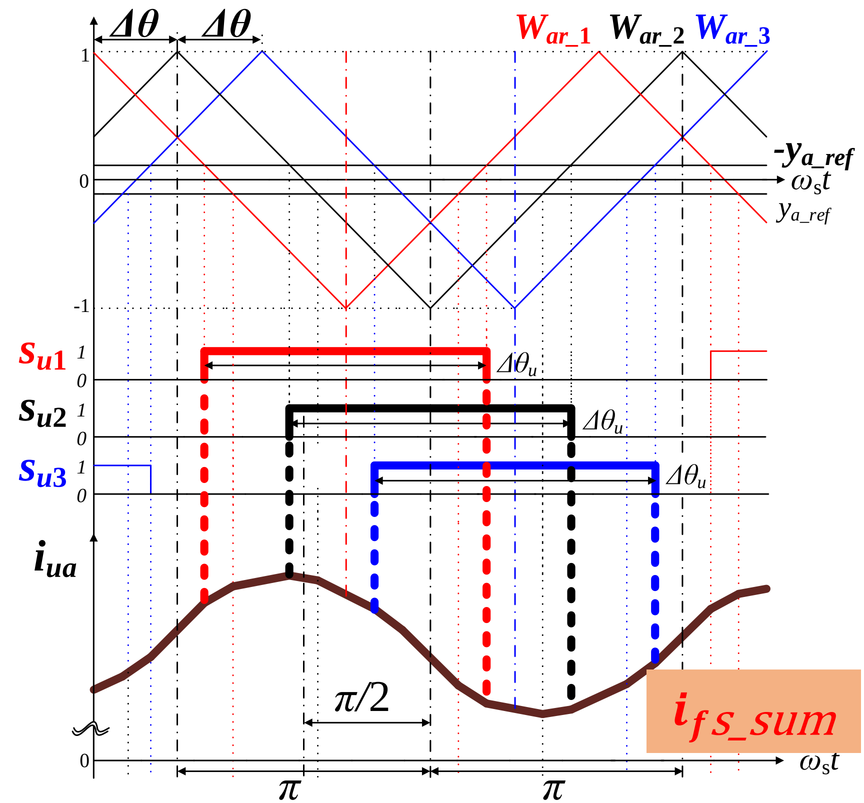
- Energy of pulses (S_{u1}, S_{u2} , S_{u3}):

$$\begin{cases} Q_{u1} = \int_0^{2\pi} S_{u1} \cdot i_{ua} d(\omega_s t) \\ Q_{u2} = \int_0^{2\pi} S_{u2} \cdot i_{ua} d(\omega_s t) \\ Q_{u3} = \int_0^{2\pi} S_{u3} \cdot i_{ua} d(\omega_s t) \end{cases}$$

S_{u1} close to peak value of i_{fS_sum} (π/2)

$$Q_{u1} > Q_{u2} > Q_{u3}$$

S_{u3} far from peak value of i_{fS_sum} (π/2)

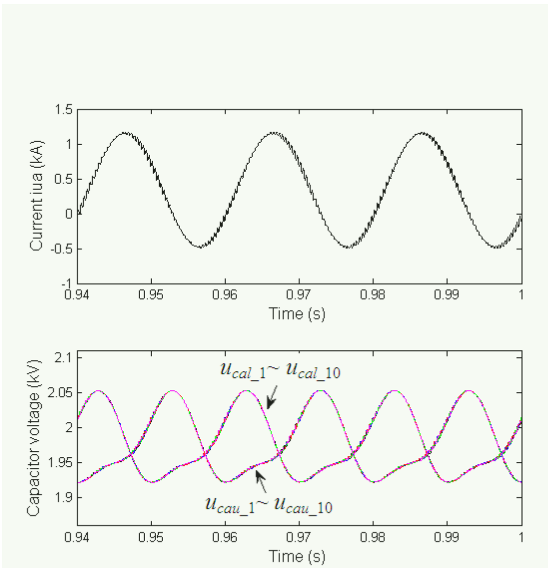


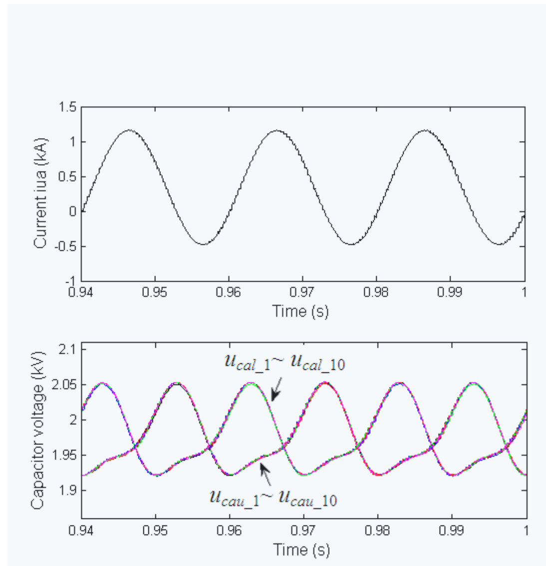
- Capacitor Voltage-Balancing Control

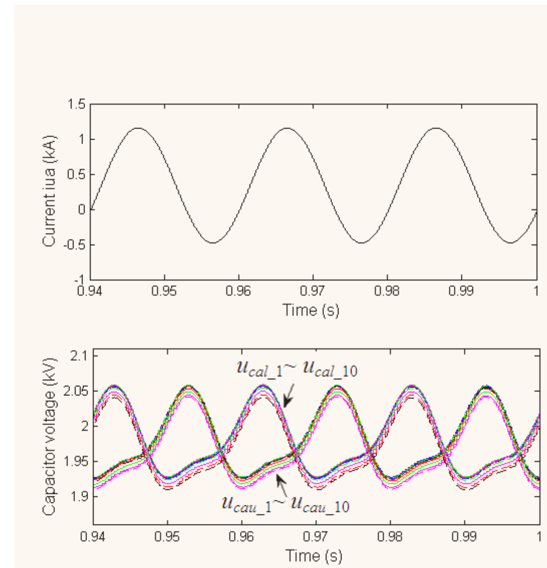
✓ Pulse close to peak value of i_{fS_sum} → SM (high capacitor voltage)

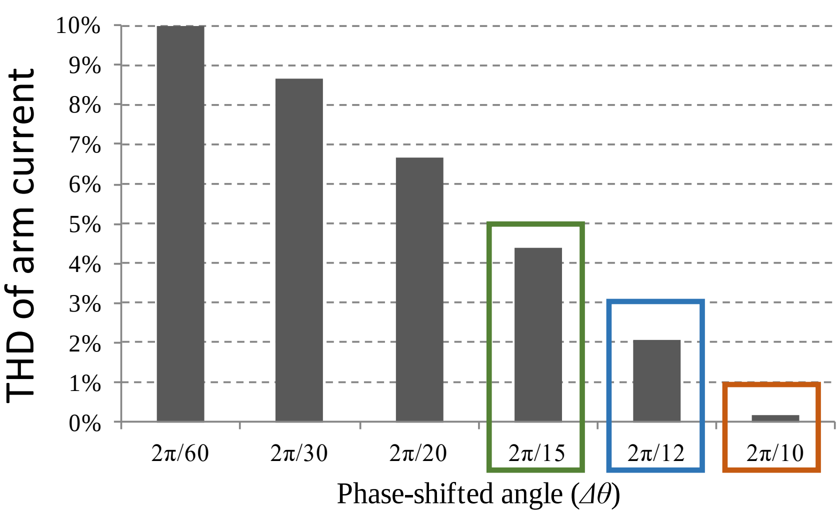
✓ Pulse far from peak value of i_{fS_sum} → SM (low capacitor voltage)

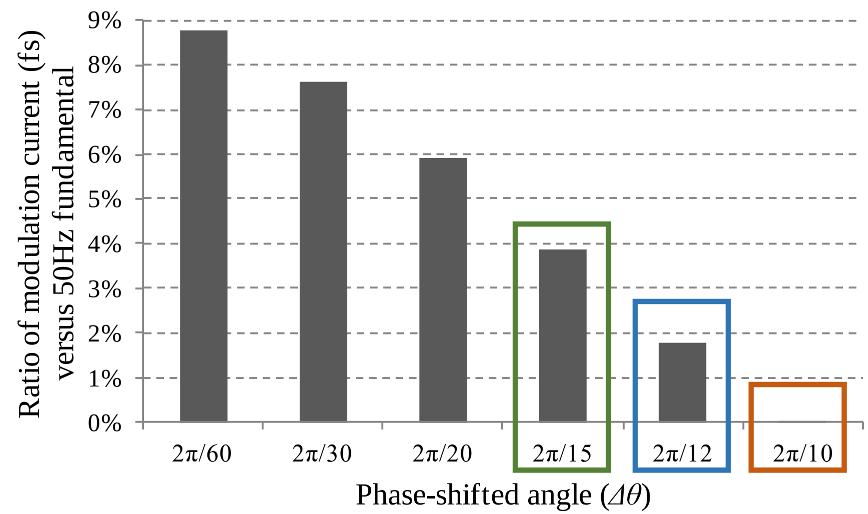
❑ Simulation （MMC with N=10 SMs/Arm）



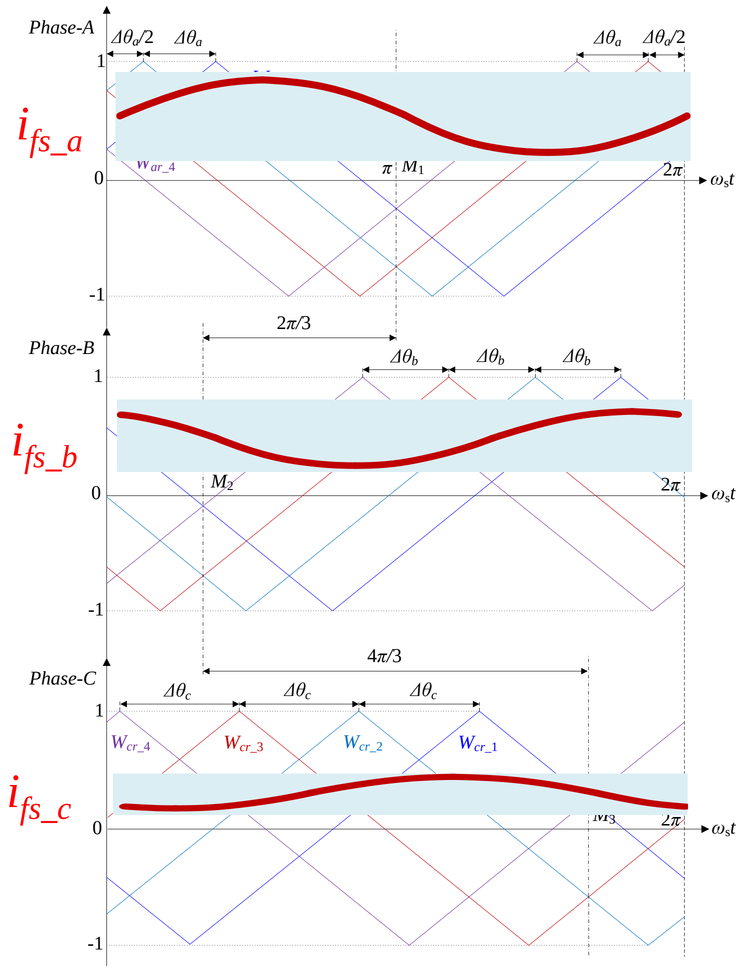




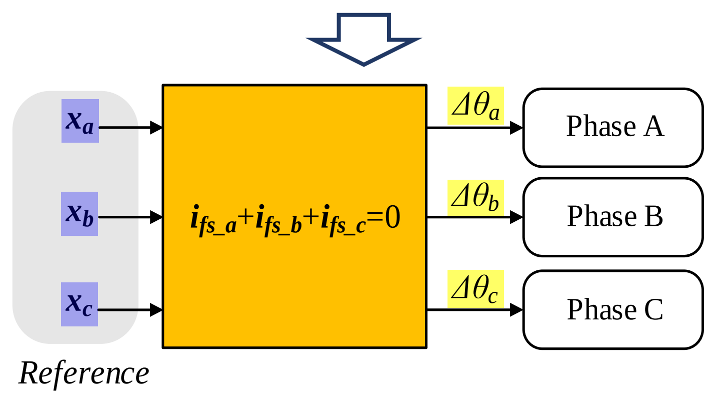




Control for Eliminating DC-Link Current Ripple



$$
\begin{cases}
i_{fs\_a}(t) = \dfrac{2V_c}{\omega_s L_s \pi} \cdot \cos\left(\dfrac{\pi}{2} x_a\right) \cdot \dfrac{\sin \dfrac{n\Delta\theta_a}{2}}{\sin \dfrac{\Delta\theta_a}{2}} \cdot \sin(\omega_s t) \\
i_{fs\_b}(t) = \dfrac{2V_c}{\omega_s L_s \pi} \cdot \cos\left(\dfrac{\pi}{2} x_b\right) \cdot \dfrac{\sin \dfrac{n\Delta\theta_b}{2}}{\sin \dfrac{\Delta\theta_b}{2}} \cdot \sin\left(\omega_s t + \dfrac{2\pi}{3}\right) \\
i_{fs\_c}(t) = \dfrac{2V_c}{\omega_s L_s \pi} \cdot \cos\left(\dfrac{\pi}{2} x_c\right) \cdot \dfrac{\sin \dfrac{n\Delta\theta_c}{2}}{\sin \dfrac{\Delta\theta_c}{2}} \cdot \sin\left(\omega_s t - \dfrac{2\pi}{3}\right)
\end{cases}
$$

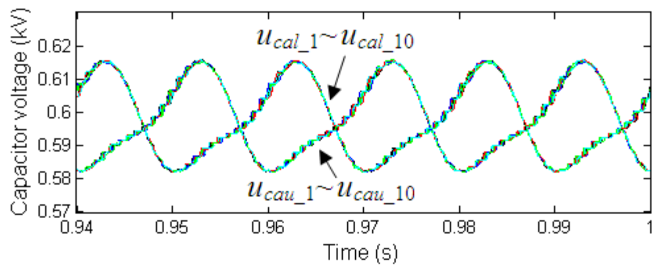


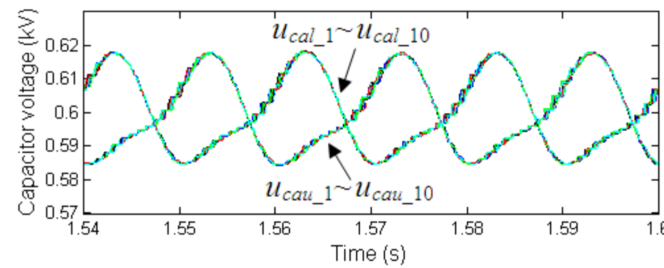
i_{fs_a}, i_{fs_b}, i_{fs_c} flow in three-phase of MMC, but not on the dc link of MMC.

Simulation Verification

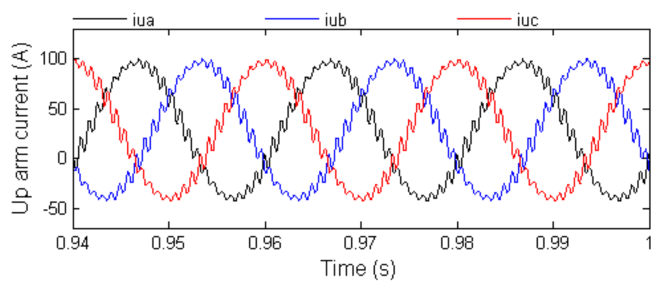
Without proposed control | With proposed control

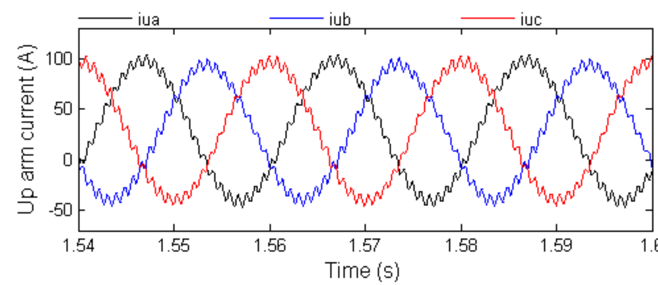
- Capacitor voltage



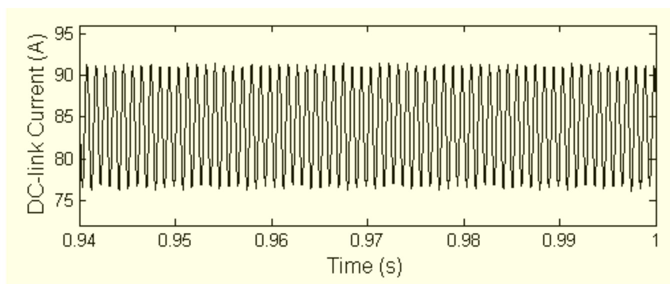


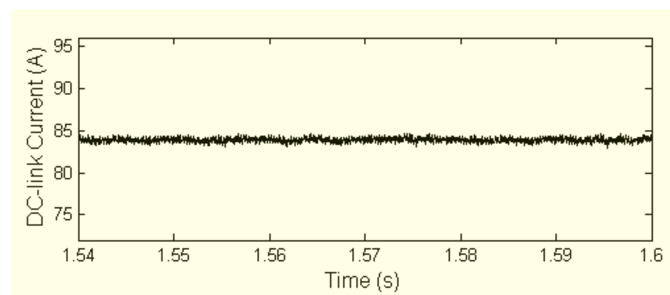
- Upper arm current





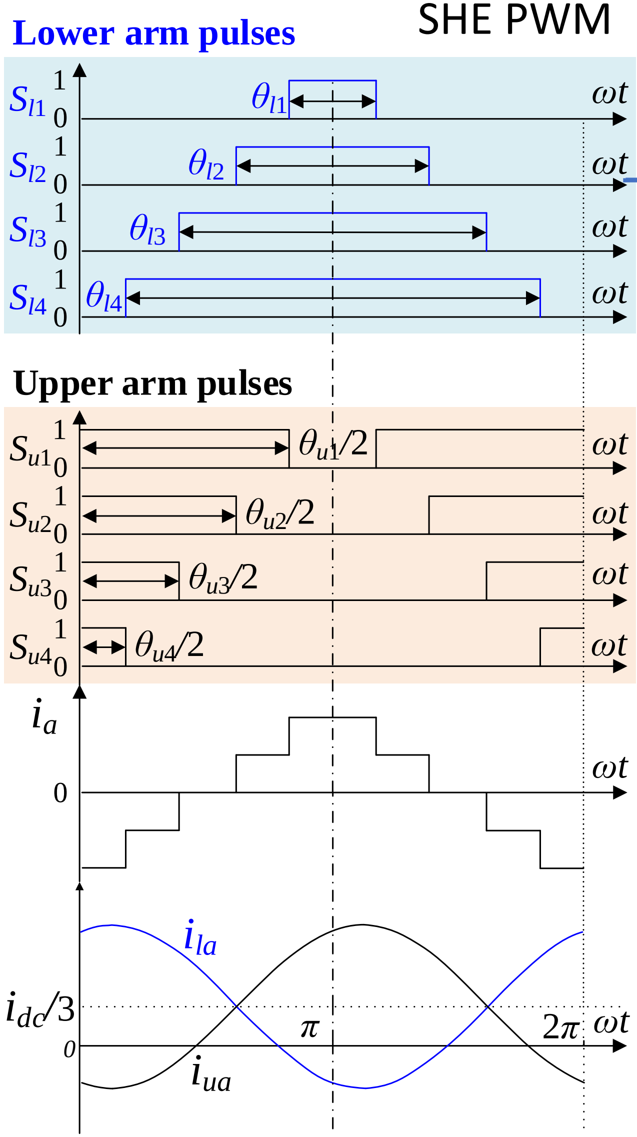
- DC-link current



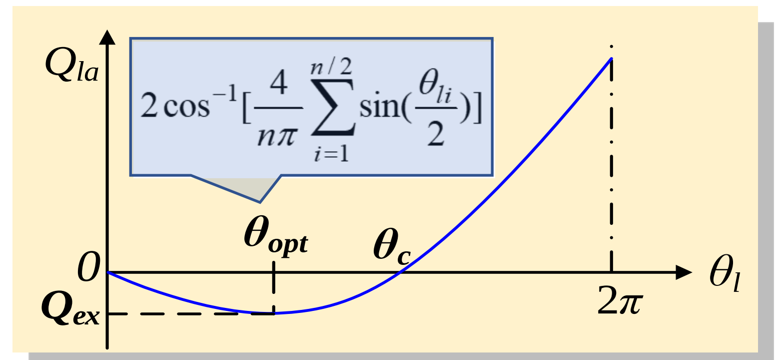


Method-4: Control Based on Pulse Energy

SHE PWM



- Energy of pulse is

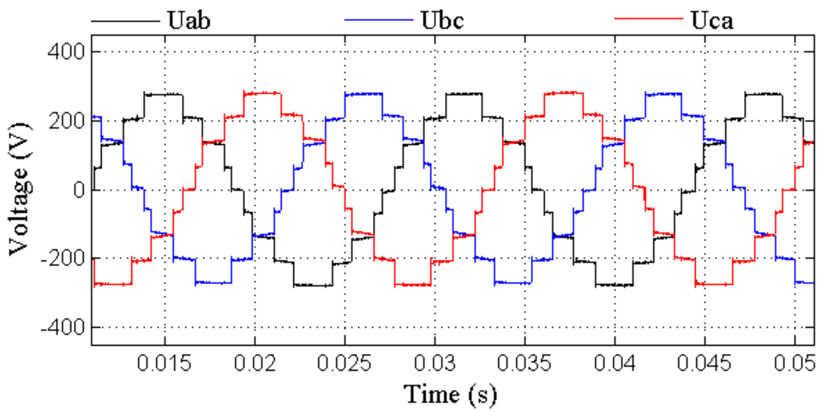


θ_l	Q_{la}
$0 \rightarrow \theta_{opt}$	Reduce
θ_{opt}	Minimum
$\theta_{opt} \rightarrow 2\pi$	Increase

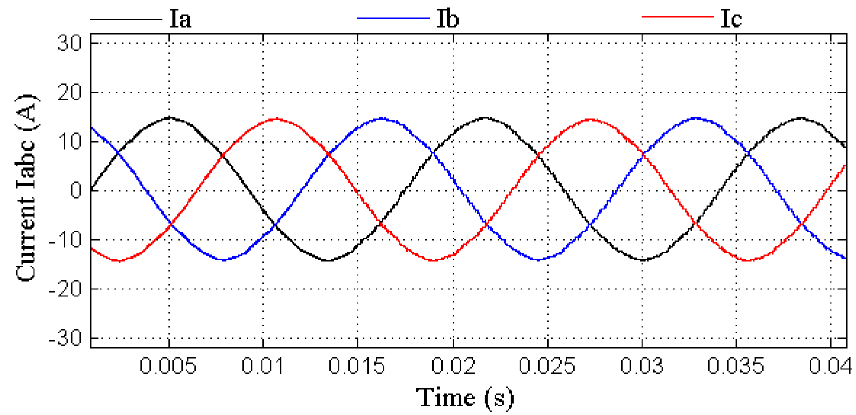
Voltage-Balancing Control

SM	Pulse Distribution
High voltage	Pulse with θ_l close to $\boldsymbol{\theta_{opt\_l}}$
Low voltage	Pulse with θ_l far from $\boldsymbol{\theta_{opt\_l}}$

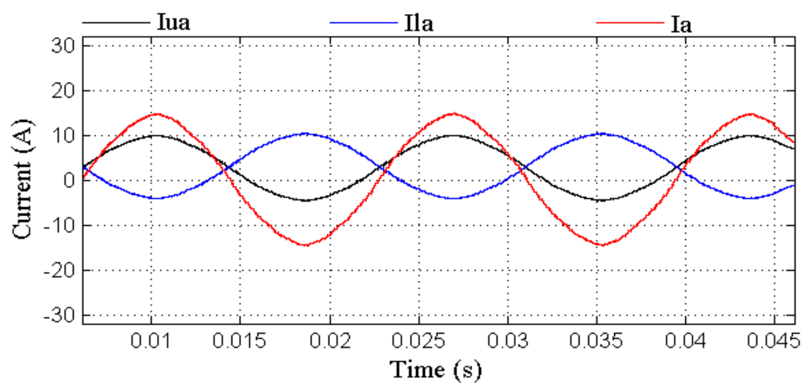
Experiment Verification



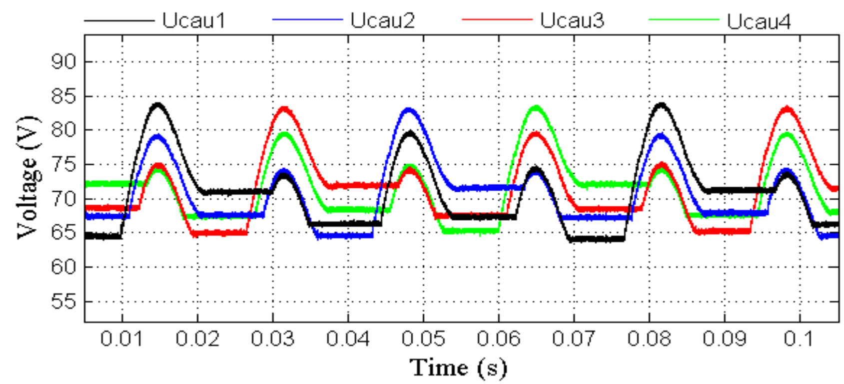
Output Voltage



Output Current



Arm Current



Capacitor Voltage

Method-5: Control Based on Pulse Energy

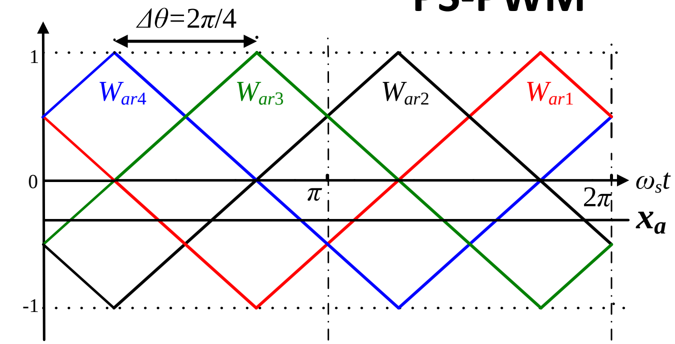
Energy of Pulses $S_{la1} \sim S_{lan}$:

$$Q_{lai} = \pi(1 + x_\alpha)i_0 + \frac{\pi^2}{2} k\,\lambda_i (i = 1, 2, \ldots, n)$$

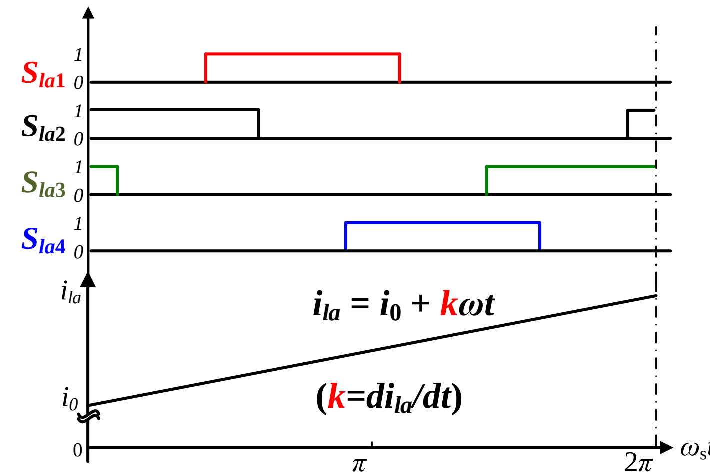
with

$$\lambda_i = \begin{cases} 4x_a + (1 - x_a)\dfrac{2i-1}{\pi}\Delta\theta, (i = 1, 2, \ldots, n), \textit{Mode I} \\ (1 + x_a)\left(2 - \dfrac{2i-1}{\pi}\Delta\theta\right), (i = 1, 2, \ldots, n/2), \textit{Mode II} \\ (1 + x_a)\left(6 - \dfrac{2i-1}{\pi}\Delta\theta\right), (i = n/2 + 1, \ldots, n), \textit{Mode II} \end{cases}$$

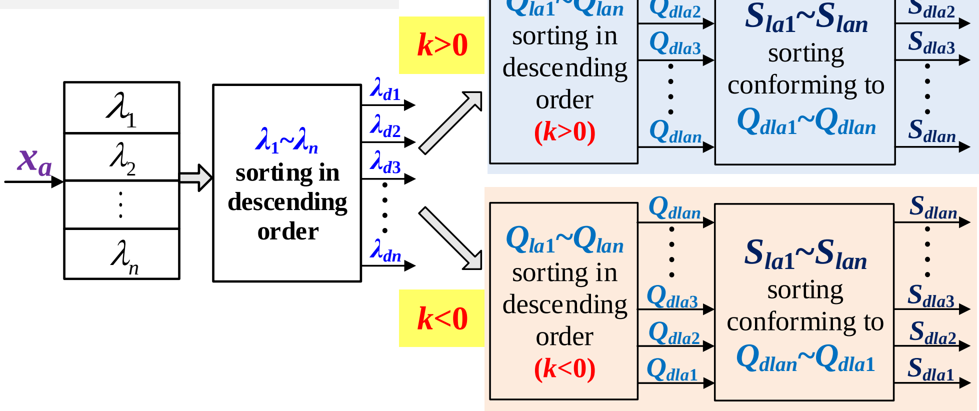
PS-PWM



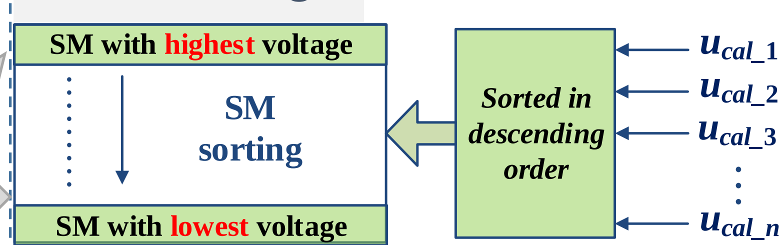
Lower arm pulses



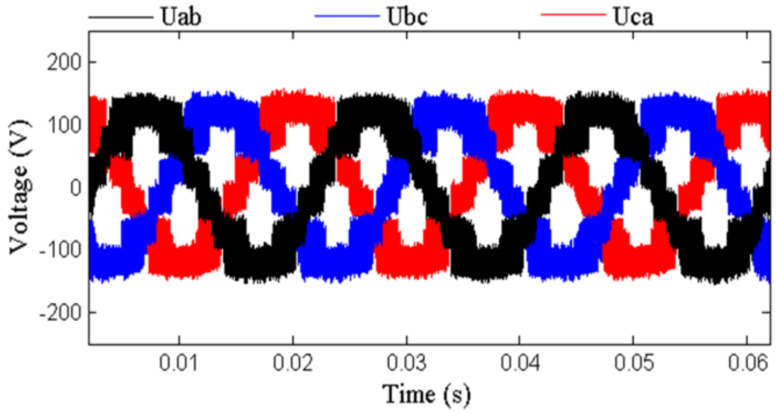
Pulse Sorting



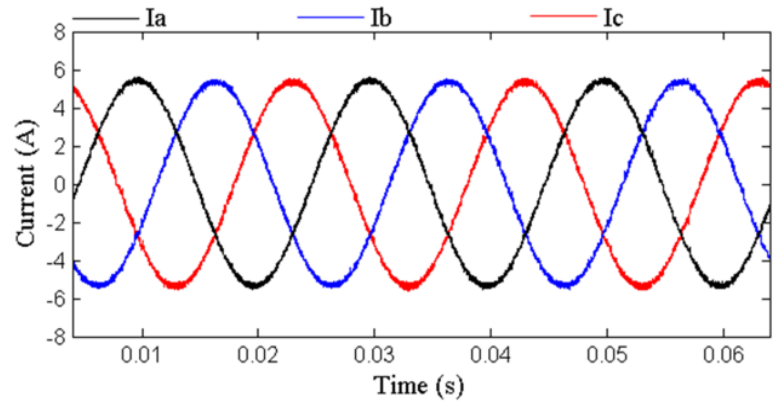
SM Sorting



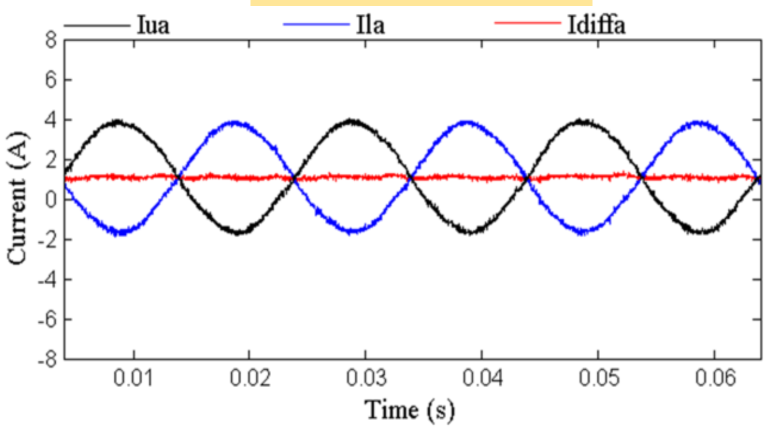
❑ Experiment Verification



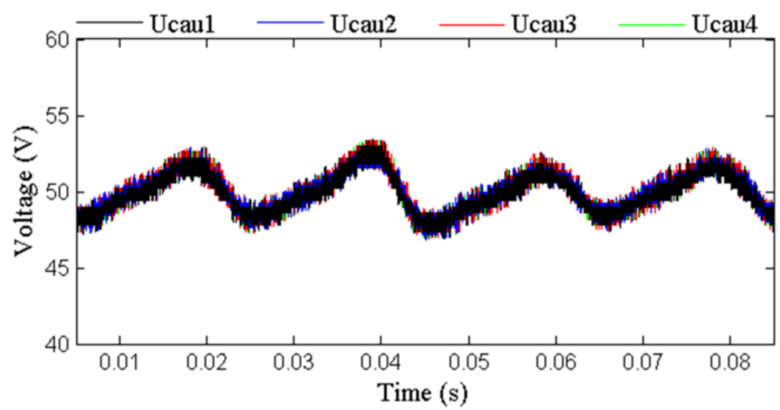
Output Voltage



Output Current



Arm Current



Capacitor Voltage

[1] Deng F, Chen Z. Voltage-Balancing Method for Modular Multilevel Converters Under Phase-Shifted Carrier-Based Pulse width Modulation[J]. IEEE Transactions on Industrial Electronics, 2015, 62(7):4158-4169.

Thanks!

Evaluation for This Course

- The course performance will be evaluated by submitting a paper report.
- The subject of this report must be related to the contents presented in this course. Otherwise, the report is unacceptable. Any topic introduced in this course can be used for the report.
- The report must include the abstract, necessary background, detailed principles and methods, and simulation results. Therefore, the simulation work should be completed before preparing the report.
- The left four classes are left for you to complete the simulation work and the paper report. The deadline for submission of the report is June 30, 2021.