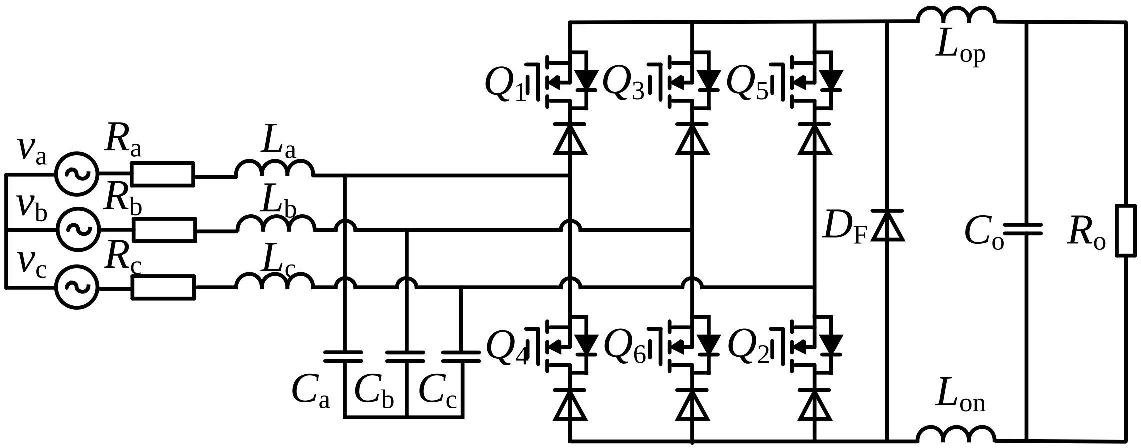
Analysis of Input Current Distortion in Three-phase Current Source PWM Rectifier

Binghui Li, Sichuan University

Background



Six-switch Current source rectifier

hybrid vehicle charging

new energy

telecom application

Background

Modulation strategy

- Selective Harmonics Elimination (SHE)
  - ✓ reduction of low-order harmonics in the AC current
  - ✗ not suitable for dynamic performance and requires pre-computation leading to more computational complexity
- Sinusoidal Pulse Width Modulation (SPWM)
  - ✓ Low harmonic content in the output current and suitable for various PWM rectifier topologies
  - ✗ Difficult to implement in digital control and may result in higher switching losses
- The Space Vector Pulse Width Modulation (SVPWM)
  - ✓ More efficient utilization of DC bus voltage
  - ✓ Easy to implement and control

Background

Modulation strategy

- Selective Harmonics Elimination (SHE)
  ✓ reduction of low-order harmonics in the AC current
  ✗ not suitable for dynamic performance and requires pre-computation leading to more computational complexity

- Sinusoidal Pulse Width Modulation (SPWM)
  ✓ Low harmonic content in the output current and suitable for various PWM rectifier topologies
  ✗ Difficult to implement in digital control and may result in higher switching losses

- The Space Vector Pulse Width Modulation (SVPWM)
  ✓ More efficient utilization of DC bus voltage
  ✓ Easy to implement and control

Background

Modulation strategy

- Selective Harmonics Elimination (SHE)
  ✓ reduction of low-order harmonics in the AC current
  ✗ not suitable for dynamic performance and requires pre-computation leading to more computational complexity

- Sinusoidal Pulse Width Modulation (SPWM)
  ✓ Low harmonic content in the output current and suitable for various PWM rectifier topologies
  ✗ Difficult to implement in digital control and may result in higher switching losses

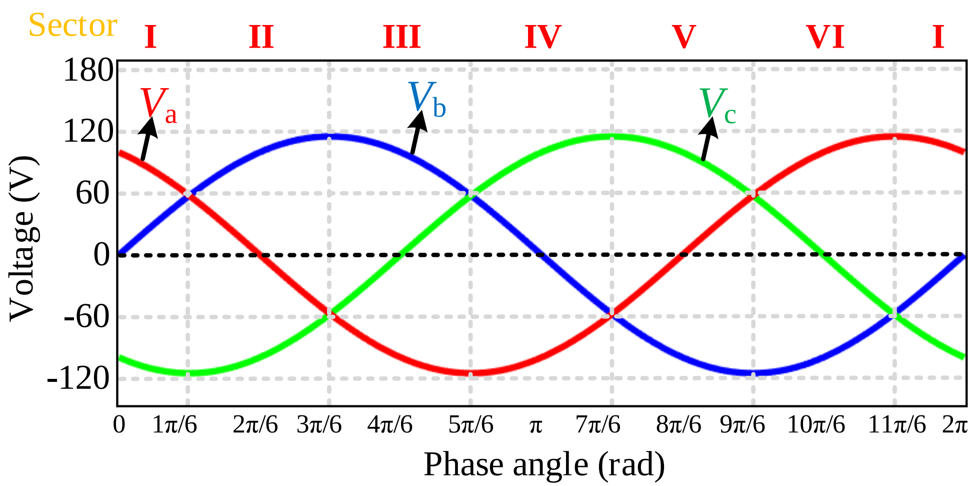
- The Space Vector Pulse Width Modulation (SVPWM)
  ✓ More efficient utilization of DC bus voltage
  ✓ Easy to implement and control

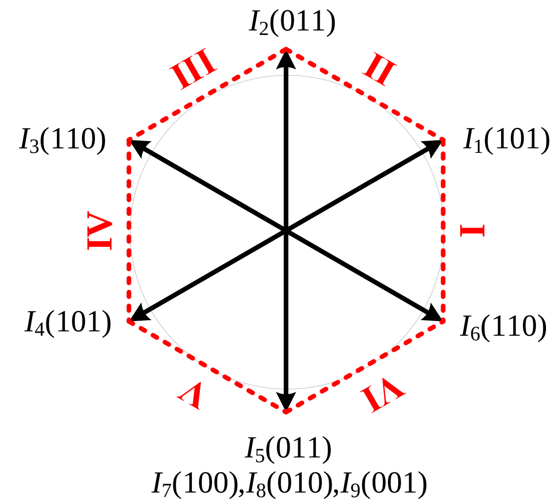
SVPWM enjoys widespread applications

SVPWM in CSR

The Space Vector Pulse Width modulation (Traditional 6-sector)

- ✓ More efficient utilization of DC bus voltage
- ✓ Easy to implement and control



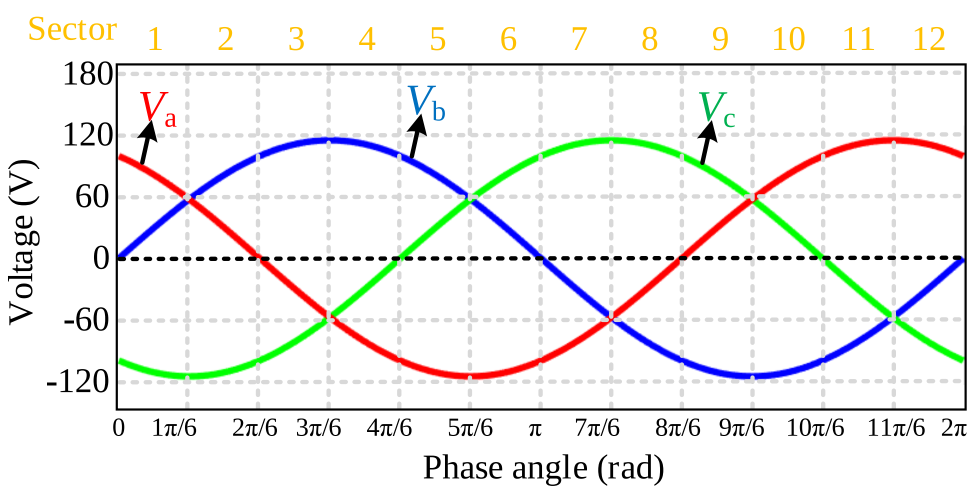


Sector division for 6-sector SVPWM in input voltage

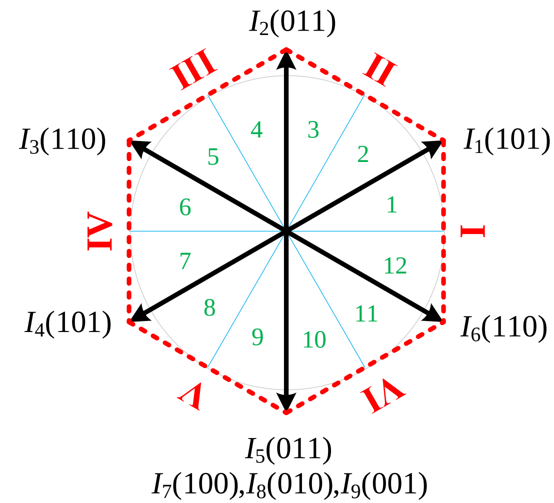
Sector division in space vector plane

SVPWM in CSR

- The Space Vector Pulse Width Modulation (12-sector)
  - ✓ Lower switching losses
  - ✓ Reduce inductance current ripple



Sector division for 6-sector SVPWM in input voltage

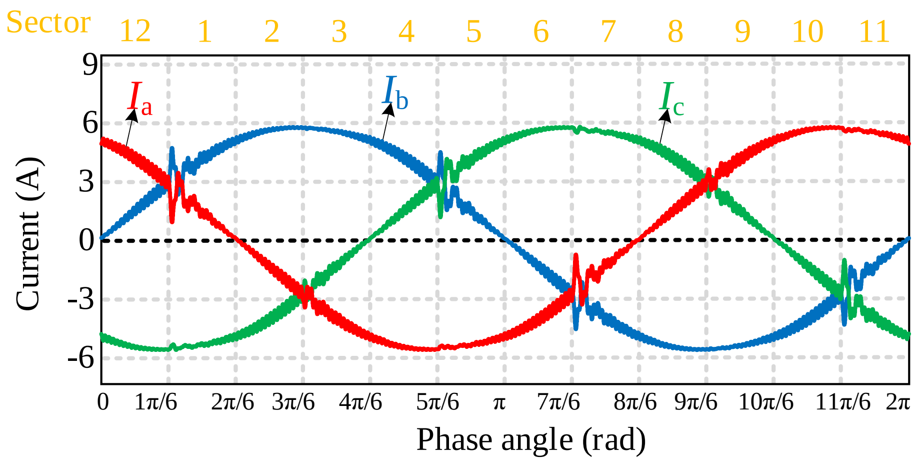


Sector division in space vector plane

12-sector modulation exhibits superior performance

Input Current Distortion

Hardware factors
Modulation factors



Input current waveforms

- Affect the input current harmonics [1]
- Reduce the efficiency of the rectifier [1]
- Exerts influence on the stability of the system [2]

[1] T. Nussbaumer and J. W. Kolar, "Improving mains current quality forthree-phase three-switch buck-type pwm rectifiers," IEEE Transactionson Power Electronics, vol. 21, DOI 10.1109/TPEL.2006.876856, no. 4, pp. 967–973, 2006.

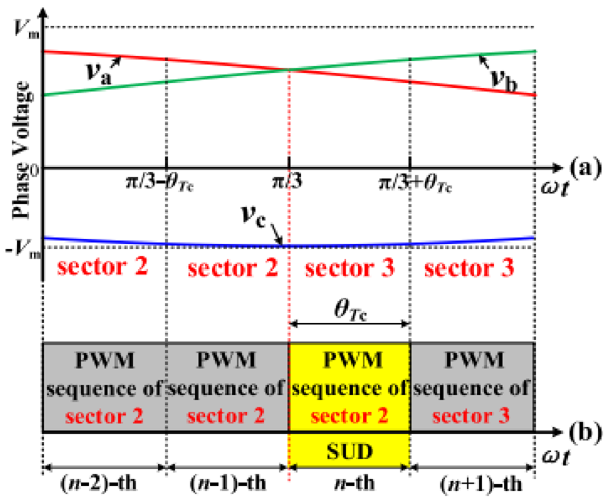
[2] L. Schrittwieser, J. W. Kolar, and T. B. Soeiro, "Novel swiss recti fier modulation scheme preventing input current distortions at sector boundaries," IEEE Transactions on Power Electronics, vol. 32, DOI 10.1109/TPEL.2016.2609935, no. 7, pp. 5771–5785, 2017.

Input Current Distortion

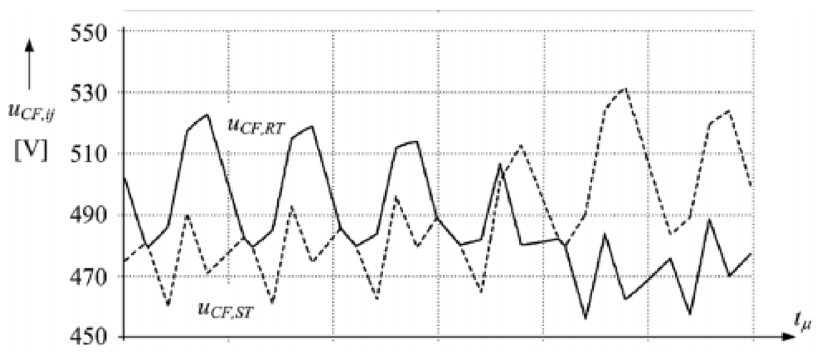
Hardware factors

Modulation factors

- Time delays of digital control [3]



- Sliding intersections of the input filter capacitor voltages [4]



Hardware-induced distortions effectively suppressed

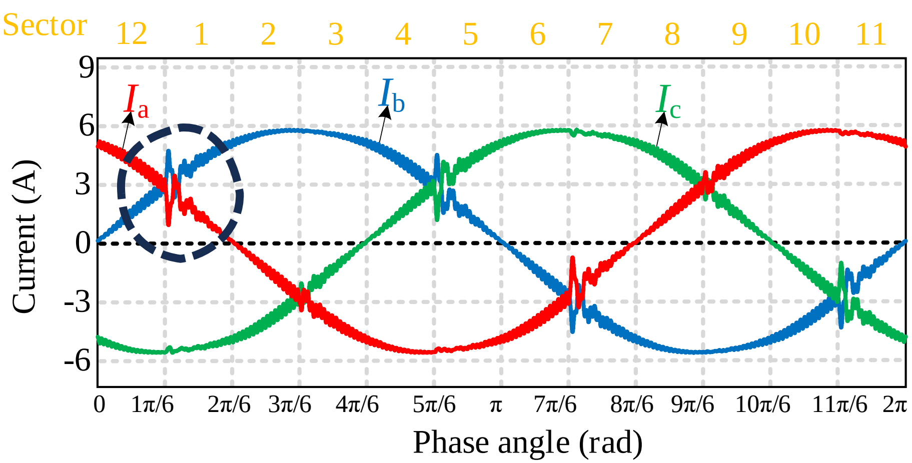
[3] Q. Chen, J. Xu, Z. Tao, H. Ma and C. Chen, "Analysis of Sector Update Delay and Its Effect on Digital Control Three-Phase Six-Switch Buck PFC Converters With Wide AC Input Frequency," in IEEE Transactions on Power Electronics, vol. 36, no. 1, pp. 931-946, Jan. 2021, doi: 10.1109/TPEL.2020.2999360.

[4] T. Nussbaumer and J. W. Kolar, "Improving mains current quality forthree-phase three-switch buck-type pwm rectifiers," IEEE Transactionson Power Electronics, vol. 21, DOI 10.1109/TPEL.2006.876856, no. 4, pp. 967–973, 2006.

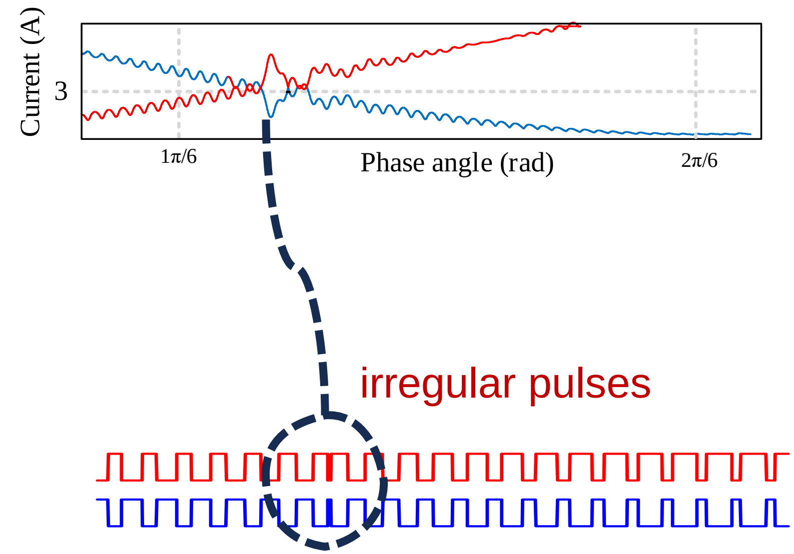
Input Current Distortion

Hardware factors

Modulation factors



Input current waveforms

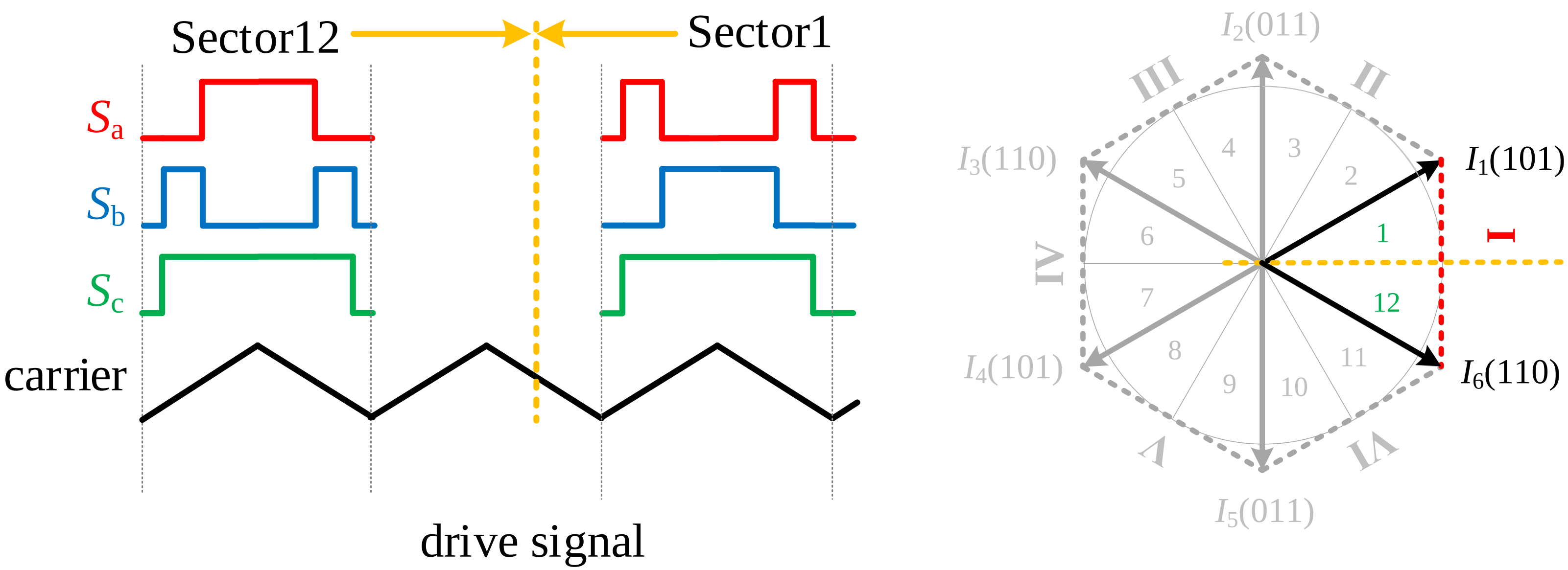


Driver signals

The origin of irregular pulses remains undetermined

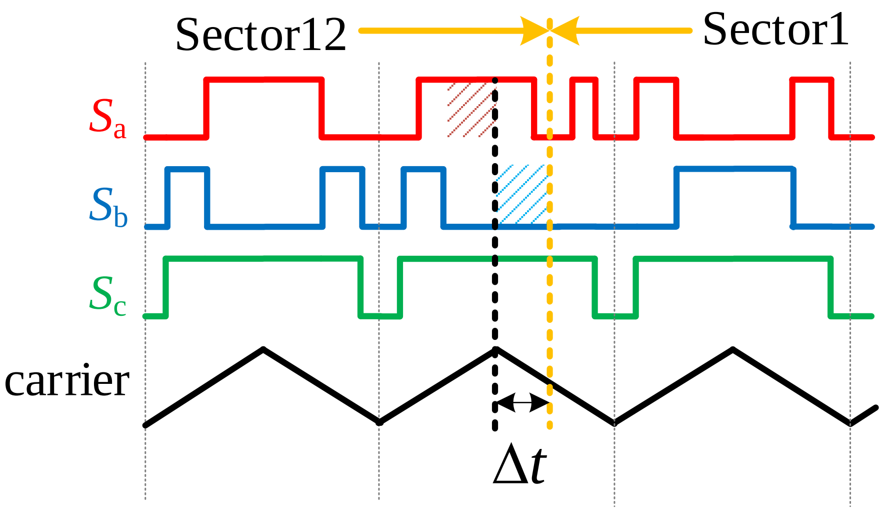
[5] M. I. Haq, A. H. Hanan, A. Qadeer, B. Salimov, M. I. Younas, and I. M. Talha, "Design and implementation of an efficient single stage three phase ac-dc buck converter for hybrid vehicle charging," in 2020 IEEE 4th Conference on Energy Internet and Energy System Integration (EI2), DOI 10.1109/EI250167.2020.9346944, pp. 2930–2935, 2020.

Irregular pulses



Duty cycles uniform near sector boundary

Irregular pulses

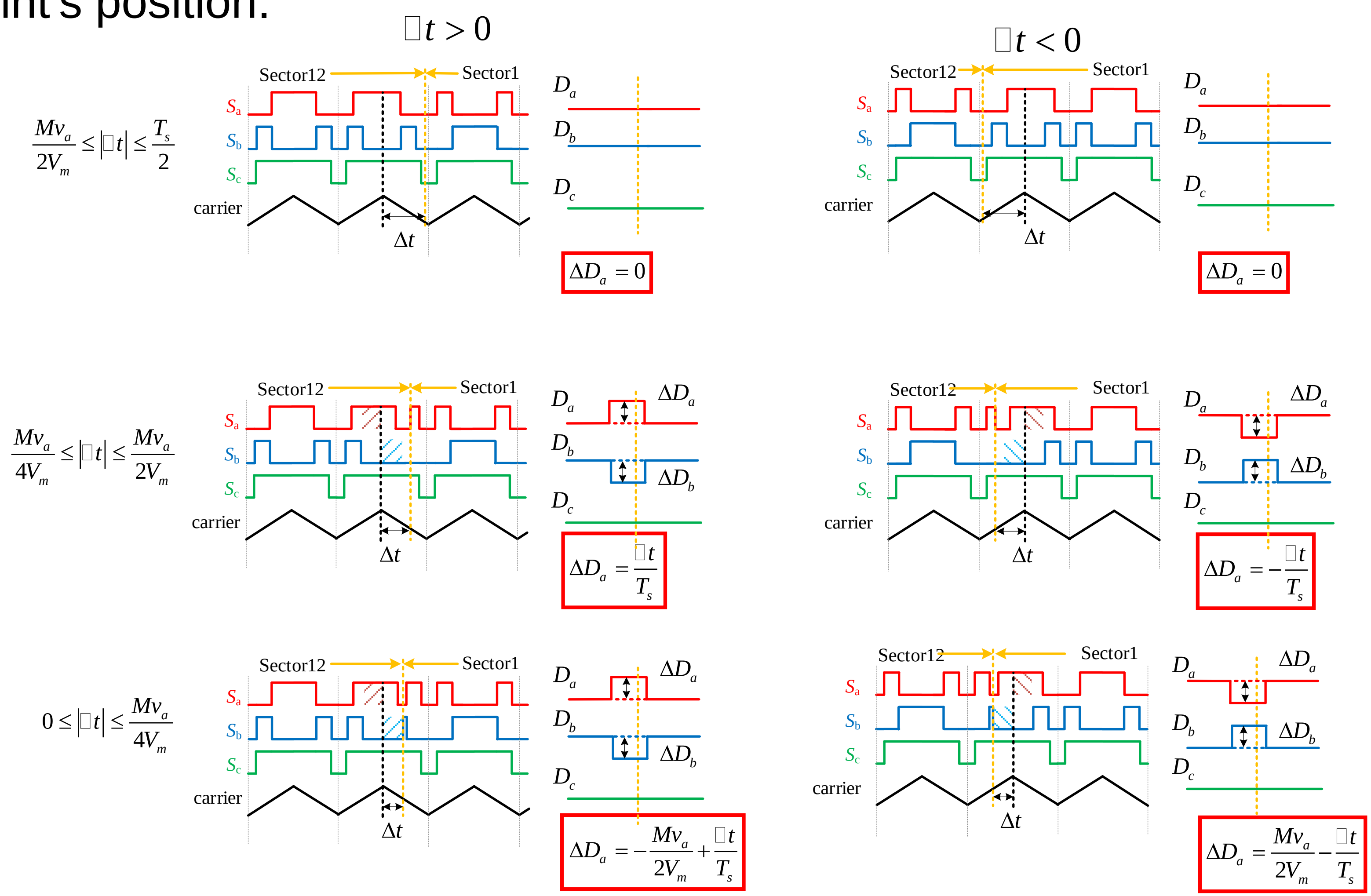


$$\Delta D_a = \frac{\Delta t}{T_s}$$

Duty cycles change abruptly at sector boundary

Duty cycle abrupt variation

The variation in duty cycle is depending on the sector switching point's position.



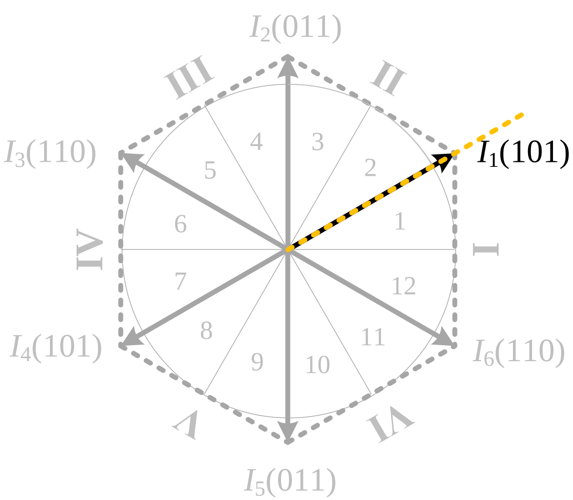
Duty cycle abrupt variation

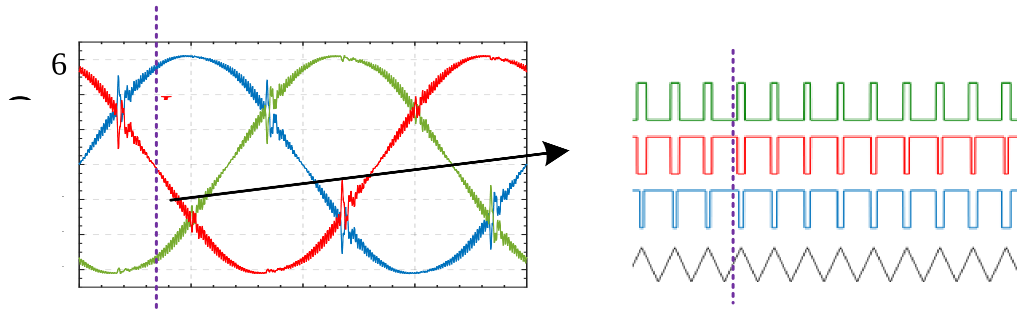
$$\Delta D_a = \begin{cases} 0 & -\dfrac{T_s}{2} \le \square t \le -\dfrac{Mv_a}{2V_m} \\ -\dfrac{Mv_a}{2V_m} + \dfrac{\square t}{T_s} & -\dfrac{Mv_a}{2V_m} \le \square t \le -\dfrac{Mv_a}{4V_m} \\ -\dfrac{\square t}{T_s} & -\dfrac{Mv_a}{4V_m} \le \square t \le 0 \\ \dfrac{\square t}{T_s} & 0 \le \square t \le \dfrac{Mv_a}{4V_m} \\ \dfrac{Mv_a}{2V_m} - \dfrac{\square t}{T_s} & \dfrac{Mv_a}{4V_m} \le \square t \le \dfrac{Mv_a}{2V_m} \\ 0 & \dfrac{Mv_a}{2V_m} \le \square t \le \dfrac{T_s}{2} \end{cases}$$

- Applying compensation to irregular pulses can mitigate current distortion
- Increasing the switching frequency can mitigate current distortion [6]

[6] M. I. Haq, A. H. Hanan, A. Qadeer, B. Salimov, M. I. Younas, and I. M. Talha, "Design and implementation of an efficient single stage three phase ac-dc buck converter for hybrid vehicle charging," in 2020 IEEE 4th Conference on Energy Internet and Energy System Integration (EI2), DOI 10.1109/EI250167.2020.9346944, pp. 2930–2935, 2020.

Duty cycle abrupt variation



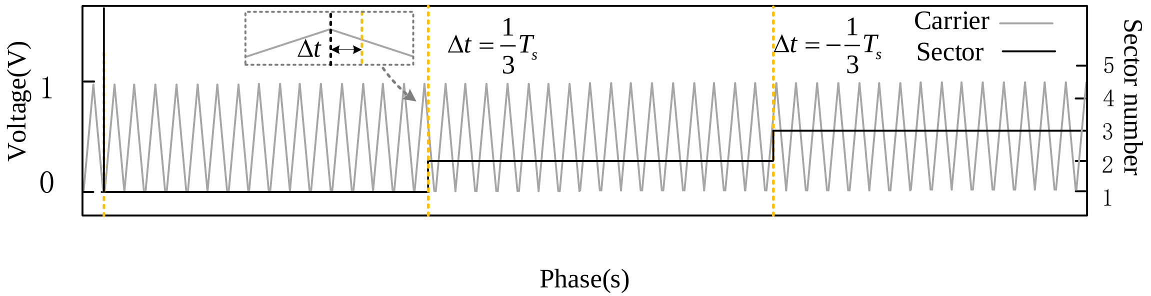


Only one effective vector is applied

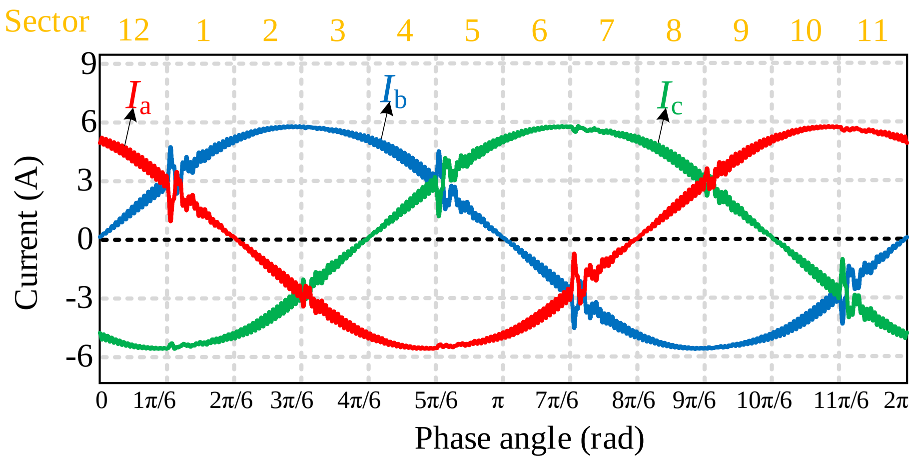
No irregular pulses

Transit smoothly in large sector switches

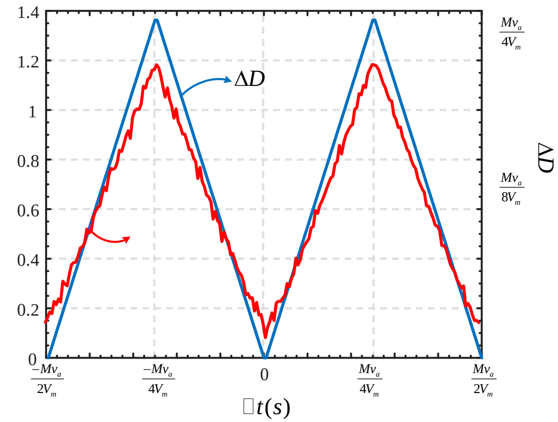
Simulation



When the carrier frequency and position are fixed Δt exhibits periodic variation at each sector boundary



The degree of current distortion demonstrates corresponding periodic variation



Relationship between the degree of current distortion duty cycle variation, and Δt

The simulation results validate the theoretical analysis

Conclusion

- Investigates the cause of current distortion, which arises from irregular pulses (resulting from the difference between carrier and sector switching points' positions)
- Explains the periodic variation in the degree of current distortion
- Provides an explanation for why current distortion occurs only when transitioning from even to odd sectors

pcim ASIA

Thank you

Binghui Li, Sichuan University