A Modulation Strategy for Active – Power Decoupled Wide Battery Voltage Range 1-phase 1-stage EV Charger

Ph.D. Registration Seminar

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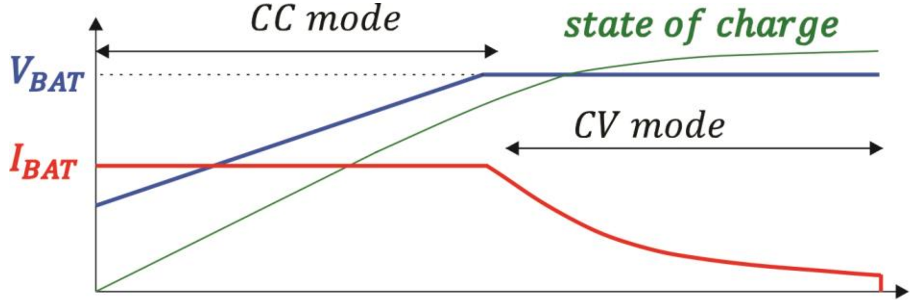
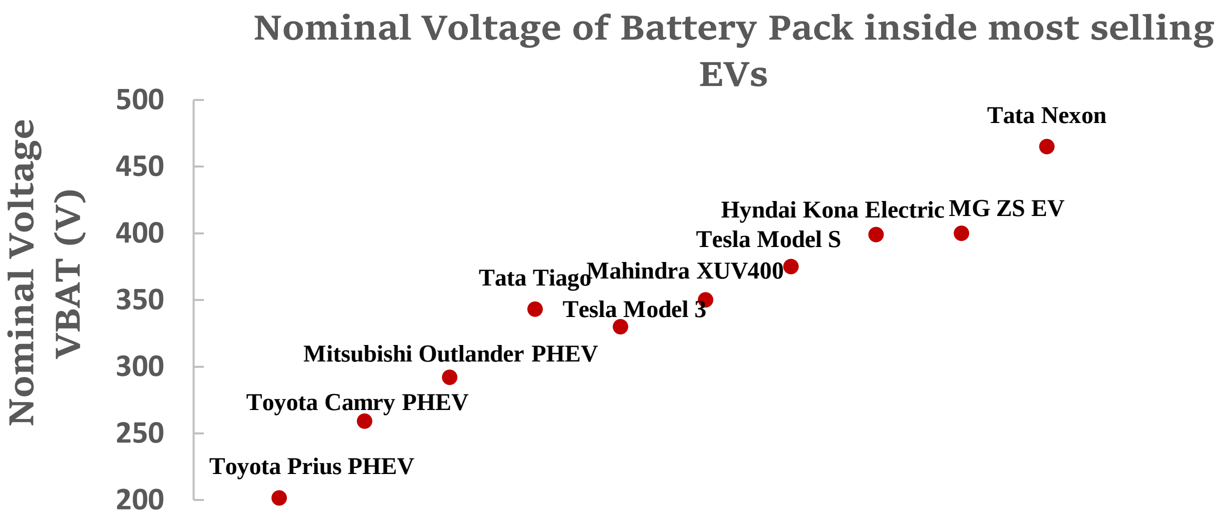
CONTENT

Introduction & Prior Art
Research Objectives

Introduction

Li-ion battery pack charging profile



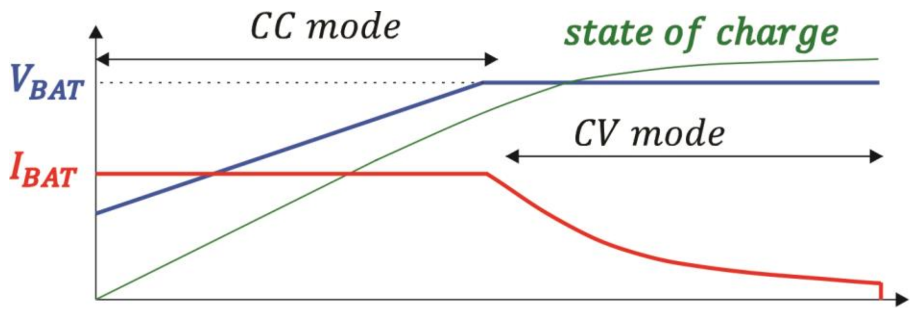


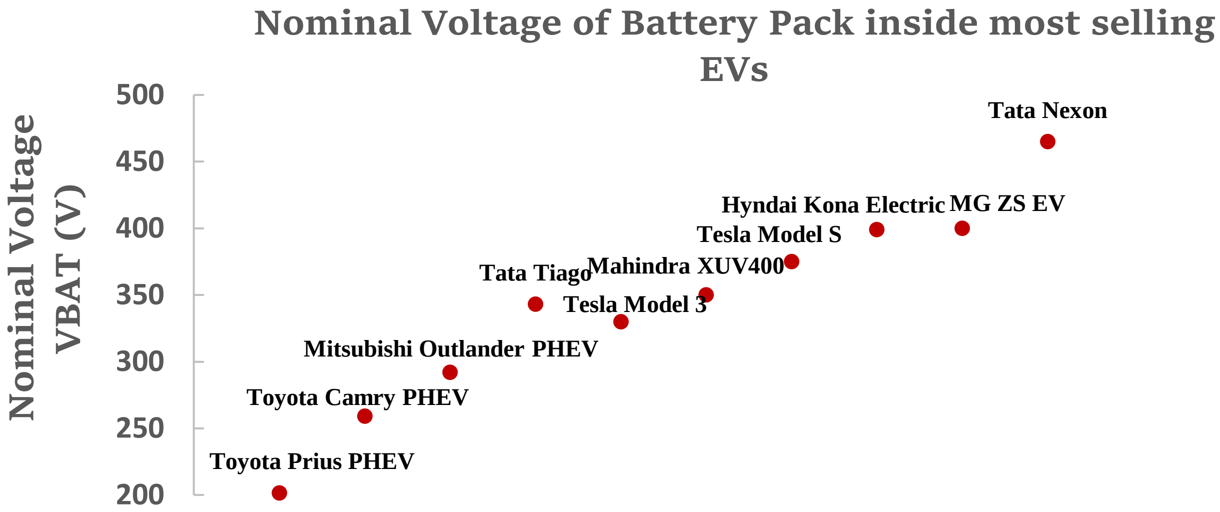
Requirements of modern On-board EV charger

- Bidirectional power flow capability for V2G application.
- Unity power factor operation with line current THD < 8% [IEEE 519-2022].
- High-frequency isolation instead of line-frequency transformer isolation.
- Converter efficiency > 95%

Introduction

Li-ion battery pack charging profile





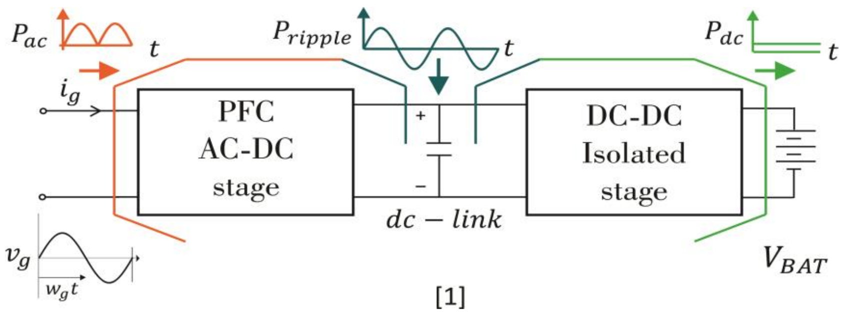
Requirements of modern On-board EV charger

- Bidirectional power flow capability for V2G application.
- Unity power factor operation with line current THD < 8% [IEEE 519-2022].
- High-frequency isolation instead of line-frequency transformer isolation.
- Converter efficiency > 95%
- Wide range battery voltage operation.
- Low-frequency ripple-free charging current. [1]

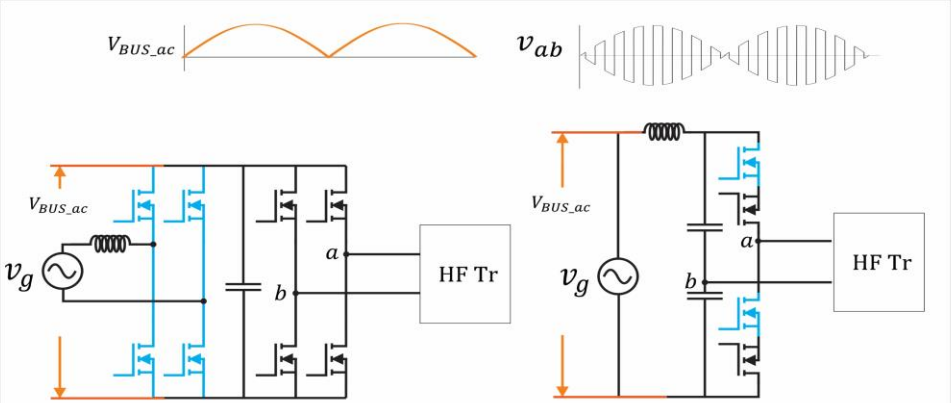
1-phase 1-stage Topologies (Prior Arts)

Advantages

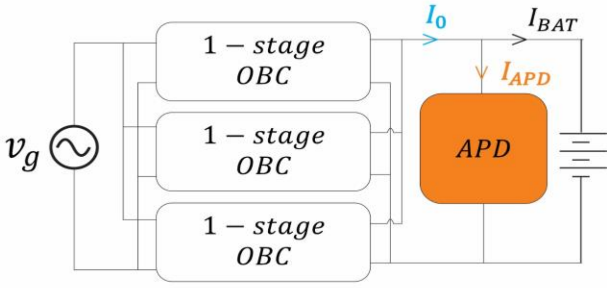
- Reduction in device counts and thermal footprint.
- Rectified sine AC bus: Charge storage less design.



[1]



[2] [3]



[4][5][6]

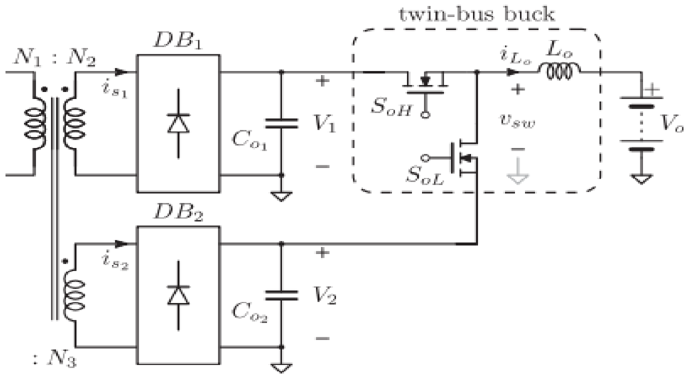
Disadvantages

- Sinusoidal charging. → APD cell. Extra Circuitry!
- Efficiency dropping when V_{BAT} varies. → Wide variation of switching frequency!

280-480 V variation. 20-120kHz @ 3.3kW

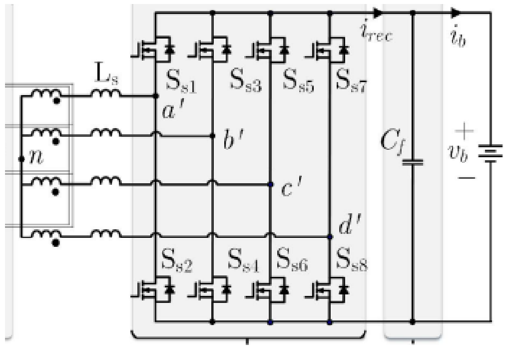
F. Jauch and J. Biela, "Combined Phase-Shift and Frequency Modulation of a Dual-Active-Bridge AC–DC Converter With PFC," in IEEE Transactions on Power Electronics, vol. 31, no. 12, pp. 8387-8397, Dec. 2016

Wide Voltage Variation (Prior Arts)



250-500 V variation. DC-DC LLC topology.
Full load efficiency: 96.5-98.5% @6kW

N. Zanatta, T. Caldognetto, D. Biadene, G. Spiazzi and P. Mattavelli, "A Two-Stage DC-DC Isolated Converter for Battery-Charging Applications," in IEEE Open Journal of Power Electronics, vol. 4, pp. 343-356, 2023

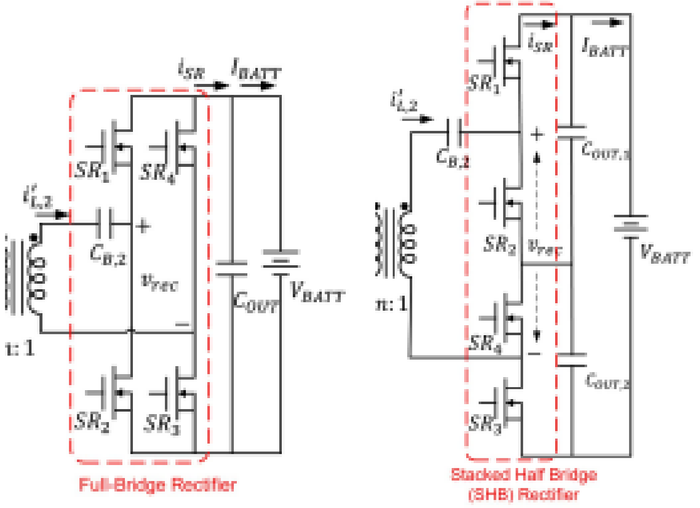


150-750 V variation. 1-stage AC-DC DAB topology.
Full load efficiency: 91-94.5% @ 2kW

T. -T. LE, R. M. Hakim and S. Choi, "A High-Efficiency Bidirectional Single-Stage AC-DC Converter Under Wide Voltage Range for Fast Chargers," in IEEE Transactions on Power Electronics, vol. 38, no. 4, pp. 4945-4956

150-950 V variation. CLLC DC-DC topology.
Full load efficiency: 97-98.5% @ 6.6 kW

S. Mukherjee, J. M. Ruiz and P. Barbosa, "A High Power Density Wide Range DC–DC Converter for Universal Electric Vehicle Charging," in IEEE Transactions on Power Electronics, vol. 38, no. 2, pp. 1998-2012, Feb. 2023



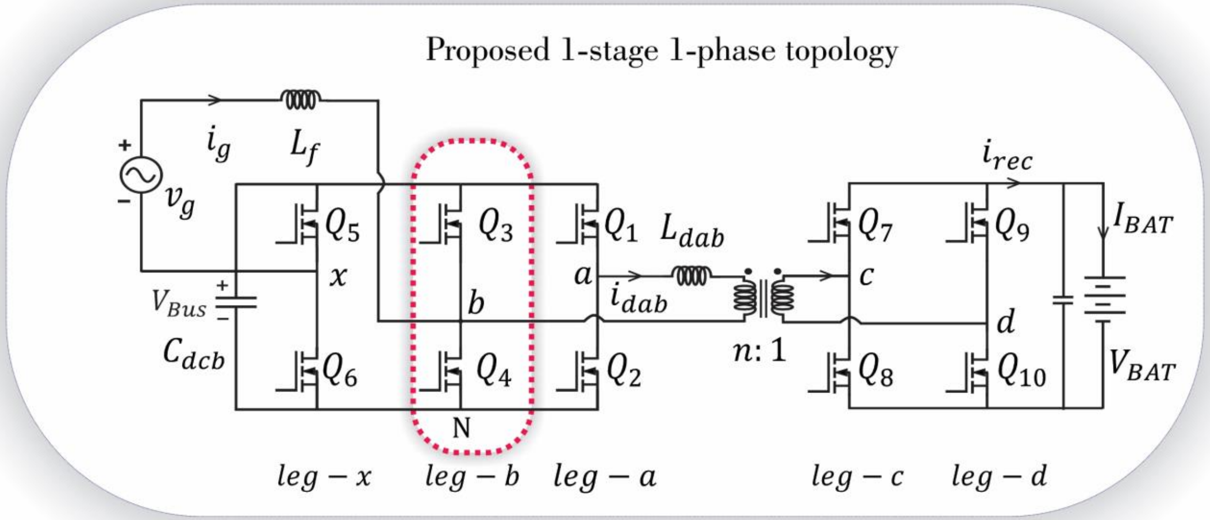
Research Objectives

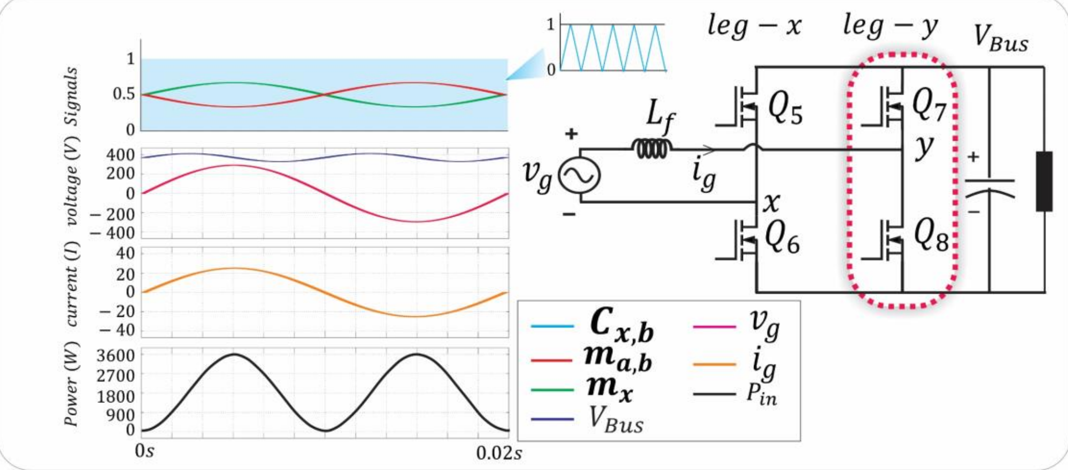
Sl. No.	Objective	Status
1	**A 1-phase 1-stage DAB isolated bidirectional On-board charger topology with flat-efficiency curve under a 110 V -230 V AC (RMS), 200V - 500V battery voltage operation.**	Ongoing
2	**To achieve ripple-free DC charging current in the 1-phase 1-stage DAB isolated topology output by decoupling the active power without any extra APD circuitry.**	Ongoing
3	**To design and implement a 3-phase to DC high power phase modular 1-stage DAB isolated converter for fast charging. Desired efficiency > 95% for 250-400V battery voltage.**	Starting
4	**Multi-loop control operation of series connected AC-DC 1-stage modules for transformerless medium voltage fast charger (MVAC-LVDC) applications.**	Not Yet Started

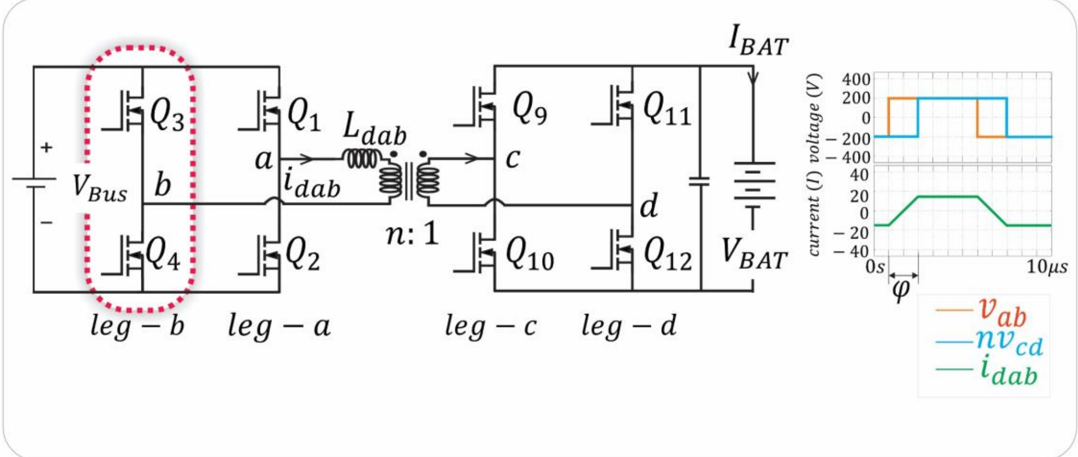
Proposed Topology & Modulation for Wide Range Operation

The proposed topology

- Three-leg structure at the AC side
  - Leg-x : PFC
  - Leg-b : PFC+ DAB
  - Leg-a : DAB

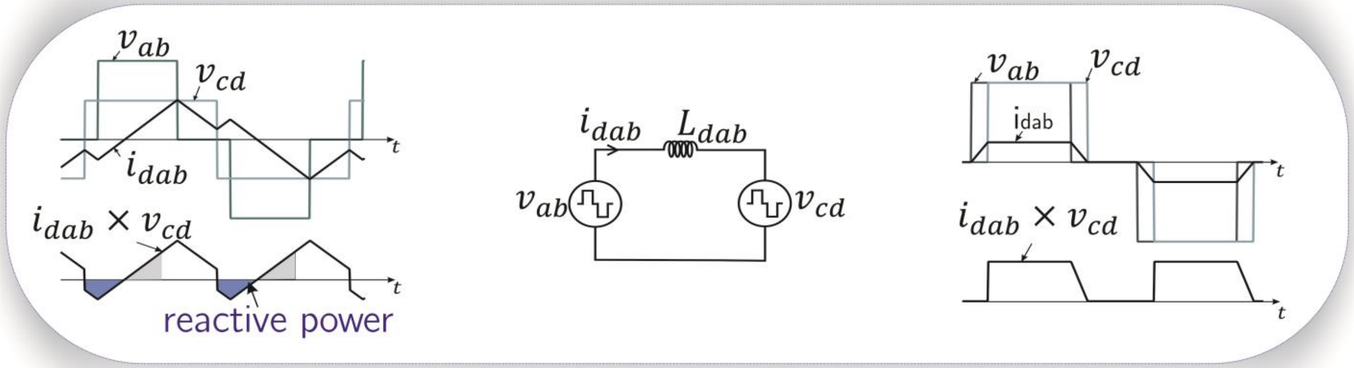


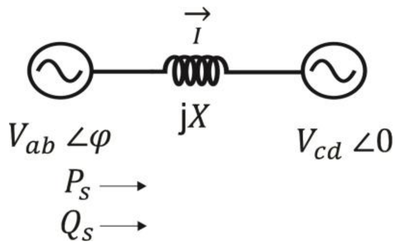




In every switching cycle, $v_{ab_{RMS}} = n v_{cd_{RMS}}$

- Equal pulse width by carrier-shift technique
- Equal Magnitude by selecting proper n



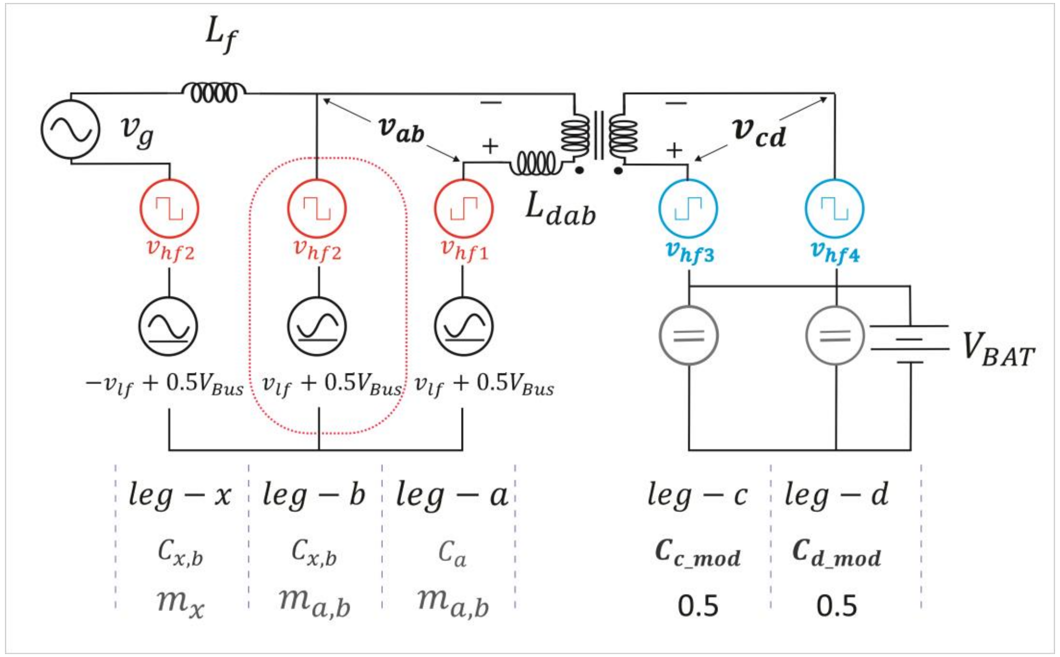


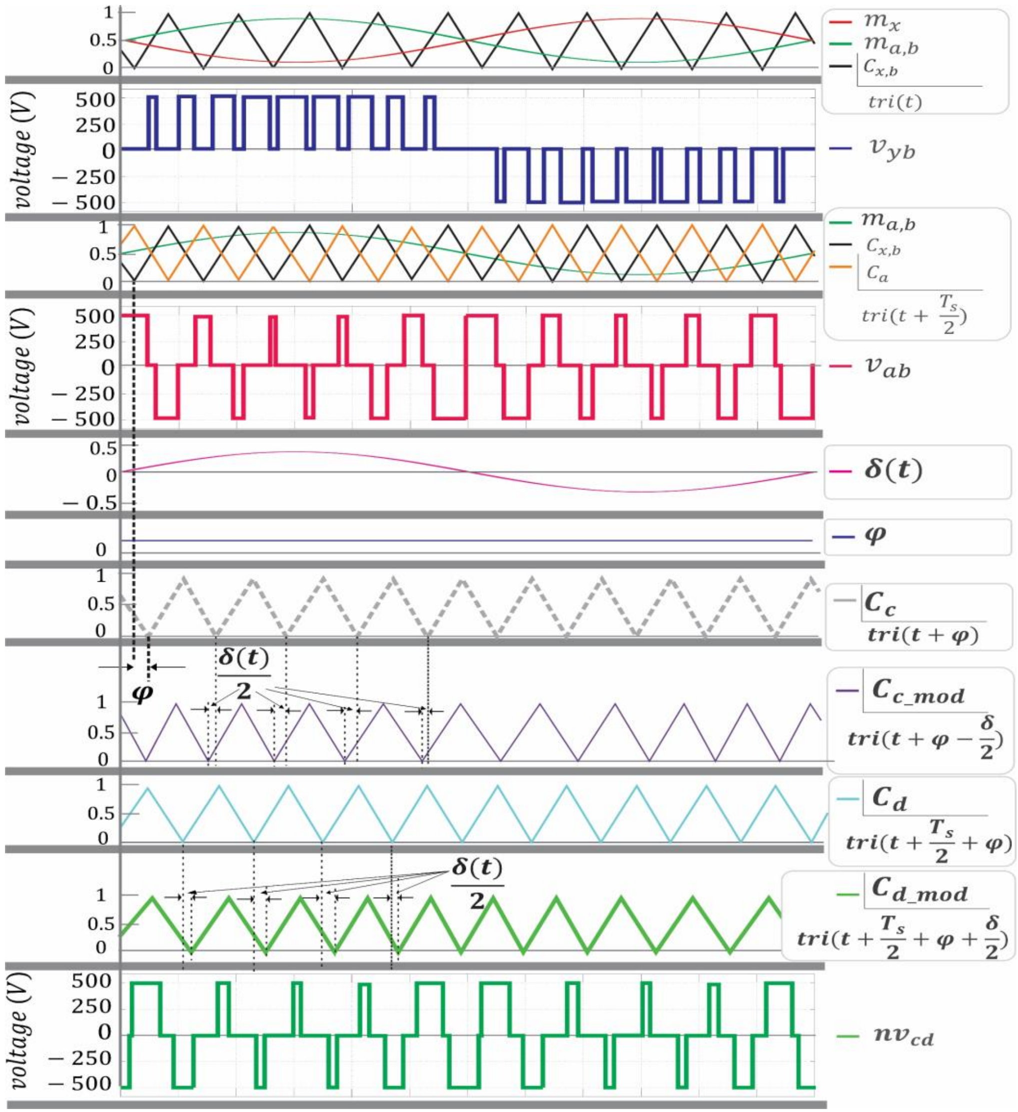
$$P_S = \frac{|V_{ab}||V_{cd}|}{X} \sin\varphi \qquad Q_S = |V_{ab}| \cdot \frac{(|V_{ab}| - |V_{cd}|\cos\varphi)}{X}$$

$$\vec{I} = \frac{|V_{ab}|\sin\varphi}{X} - j\frac{(|V_{ab}| - |V_{cd}|\cos\varphi)}{X}$$

Sinusoidal carrier shift at the DC bridge

- The sinusoidal carrier shifting function is coming from the modulation signal.
- DC bus is regulated @ $V_{BUS} = nV_{BAT}$





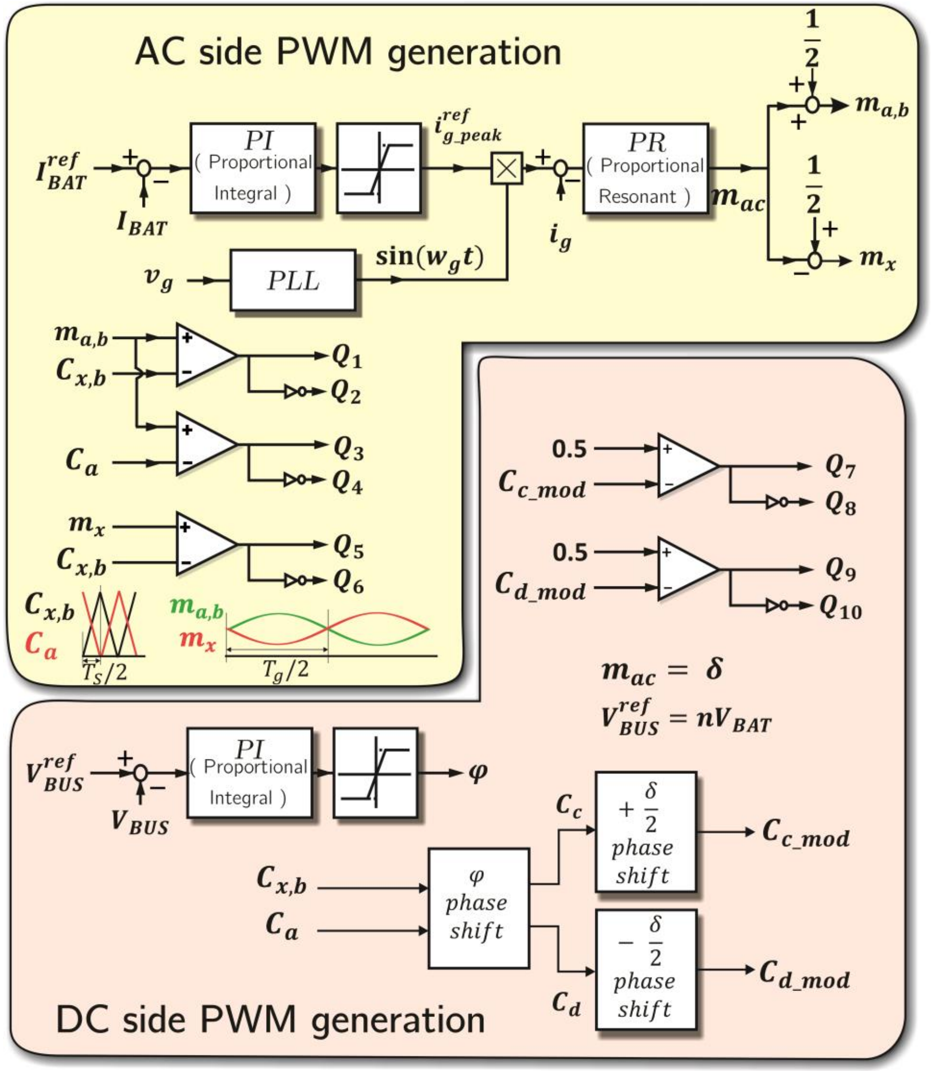
Control Architecture and Operating Modes

The Control Architecture

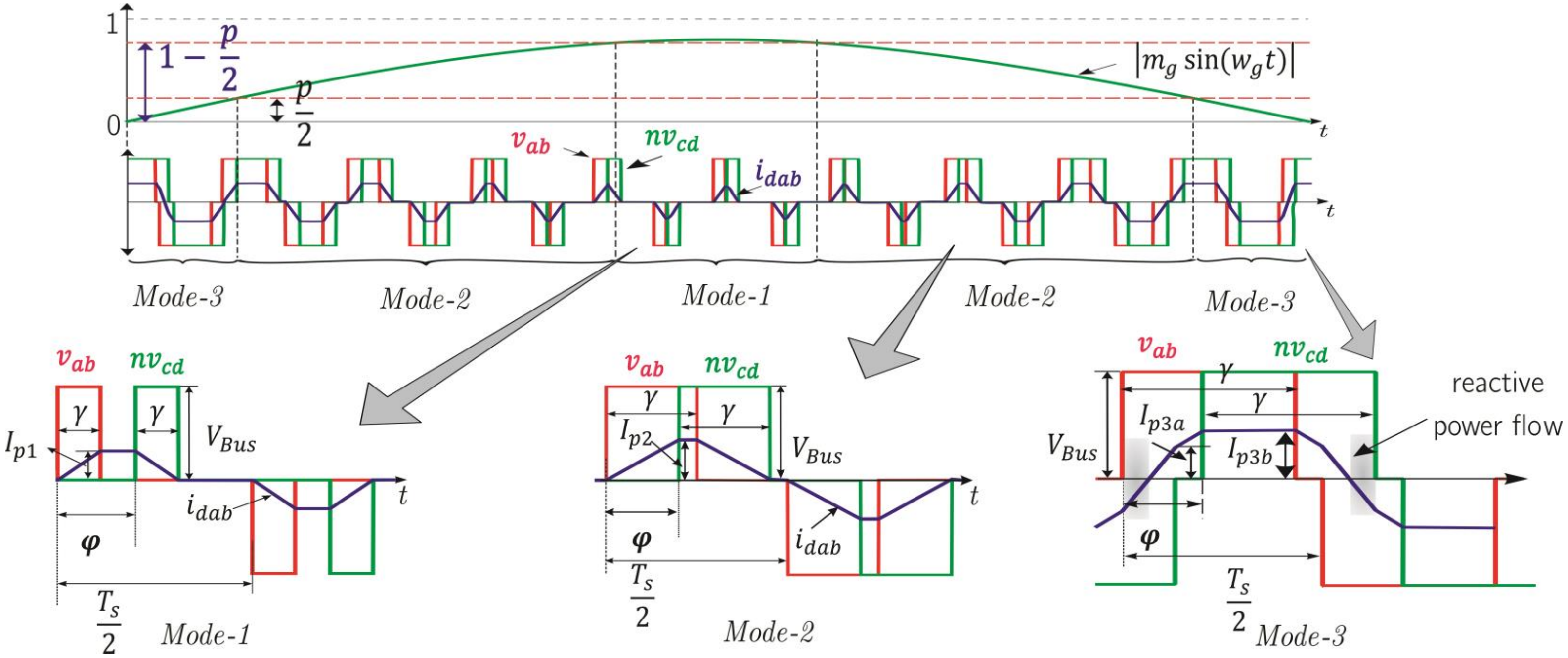
$$m_{ac} = m_g \sin(w_g t)$$

$$\delta(t) = m_{ac} = m_g \sin(\omega_g t)$$

$$V_{BUS} = nV_{BAT}$$



Different Modes of Operation



$$m_{ac} = m_g \sin(w_g t)$$

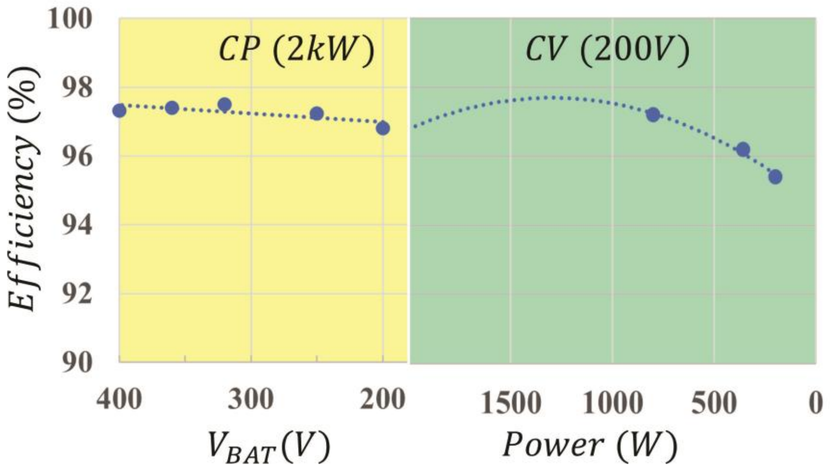
$$v_{ab_{RMS}}|_{T_s} = V_{Bus}\sqrt{1-(m_{ac})^2}$$

- Switching cycle average power transfer Mode-2: $P_{dab}|_{T_s} = \frac{V_{BUS}^2 T_s}{4L_{dab}}\left(1-|m_{ac}|-\frac{p}{2}\right)$ where, $p = \frac{\phi}{T_s/4}$

Converter Specs and Measured Waveforms

Prototype Specs and Measured Efficiency

Image of the Hardware prototype

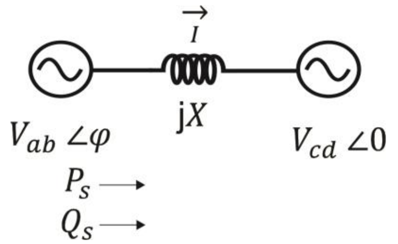


Specifications	
Power Rating	2kW
AC input voltage	220V (rms), 50Hz
Battery voltage	200-500 V
Switches	NTHLO40N120SC1, 1.2kV, 40mΩ
Switching frequency	100kHz
Transformer turns ratio	1.8 : 1 (AC side: DC side)
Dab inductance	40μH
DC bus capacitance	260 μF, 4 qty of C4AQCBW5750A3NJ
Filter Inductor	1mH
Controller	XE6SLX9 FPGA

The measured efficiency for constant power(2kW) battery voltage 200V-400V (yellow area) and 200V constant voltage charging down to 200W (10% of rated power) (green area)

Proposed Active-power Decoupling (APD) Control

Active power control via phase-shift modulation



$$|V_{ab}| - |V_{cd}|\cos\varphi = 0$$

$$P_S = Const.\ if \quad \sin\varphi \propto \frac{1}{|V_{ab}||V_{cd}|}$$

$$i_{DAB} = \frac{|V_{ab}|\sin\varphi}{\omega\, L_{dab}}$$

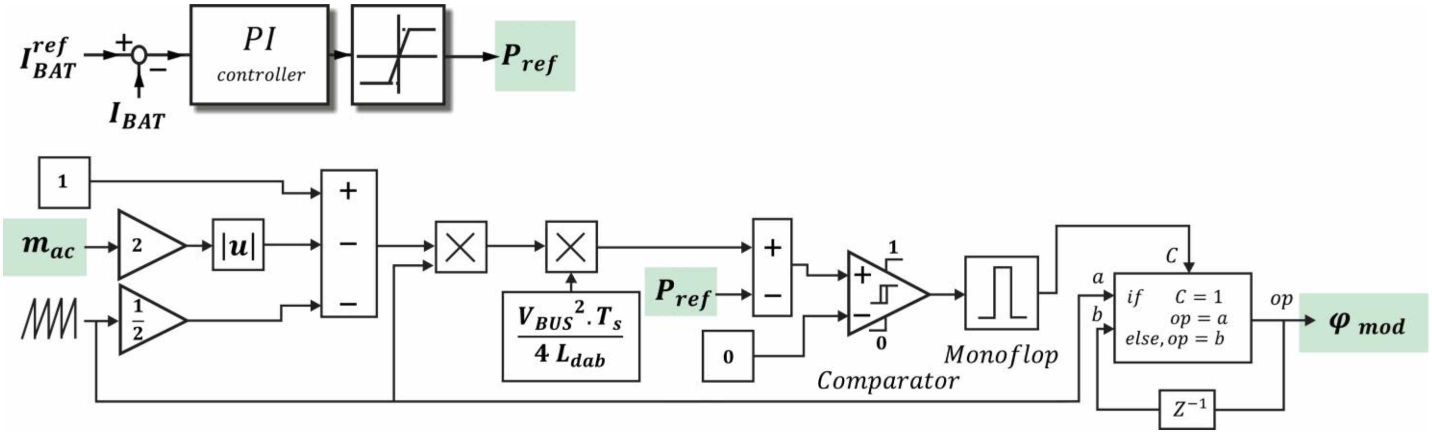
$$P_S = \frac{|V_{ab}||V_{cd}|}{X}\sin\varphi \qquad Q_S = |V_{ab}| \cdot \frac{(|V_{ab}| - |V_{cd}|\cos\varphi)}{X}$$

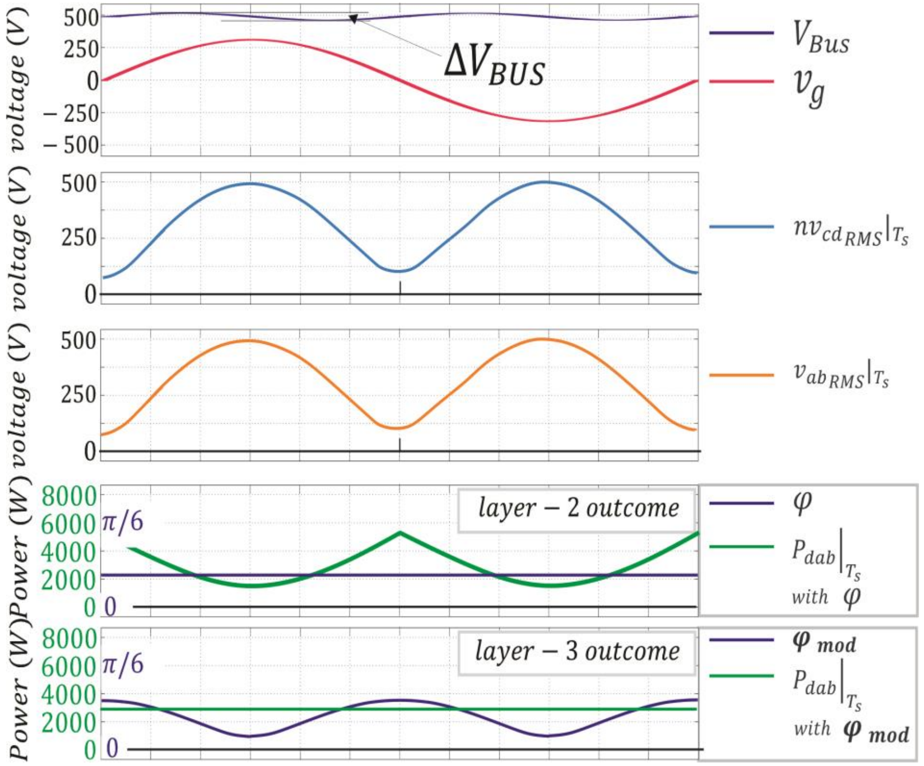
$$\vec{I} = \frac{|V_{ab}|\sin\varphi}{X} - j\,\frac{(|V_{ab}| - |V_{cd}|\cos\varphi)}{X}$$

Digital control by sensing only inputs and outputs

- Switching cycle average power transfer Mode-2:

$$P_{dab}|_{T_s} = \frac{V_{BUS}^2 T_s}{4L_{dab}}(1 - |m_{ac}| - \frac{p}{2}) \quad \text{where,} \quad p = \frac{\phi}{T_s/4}$$

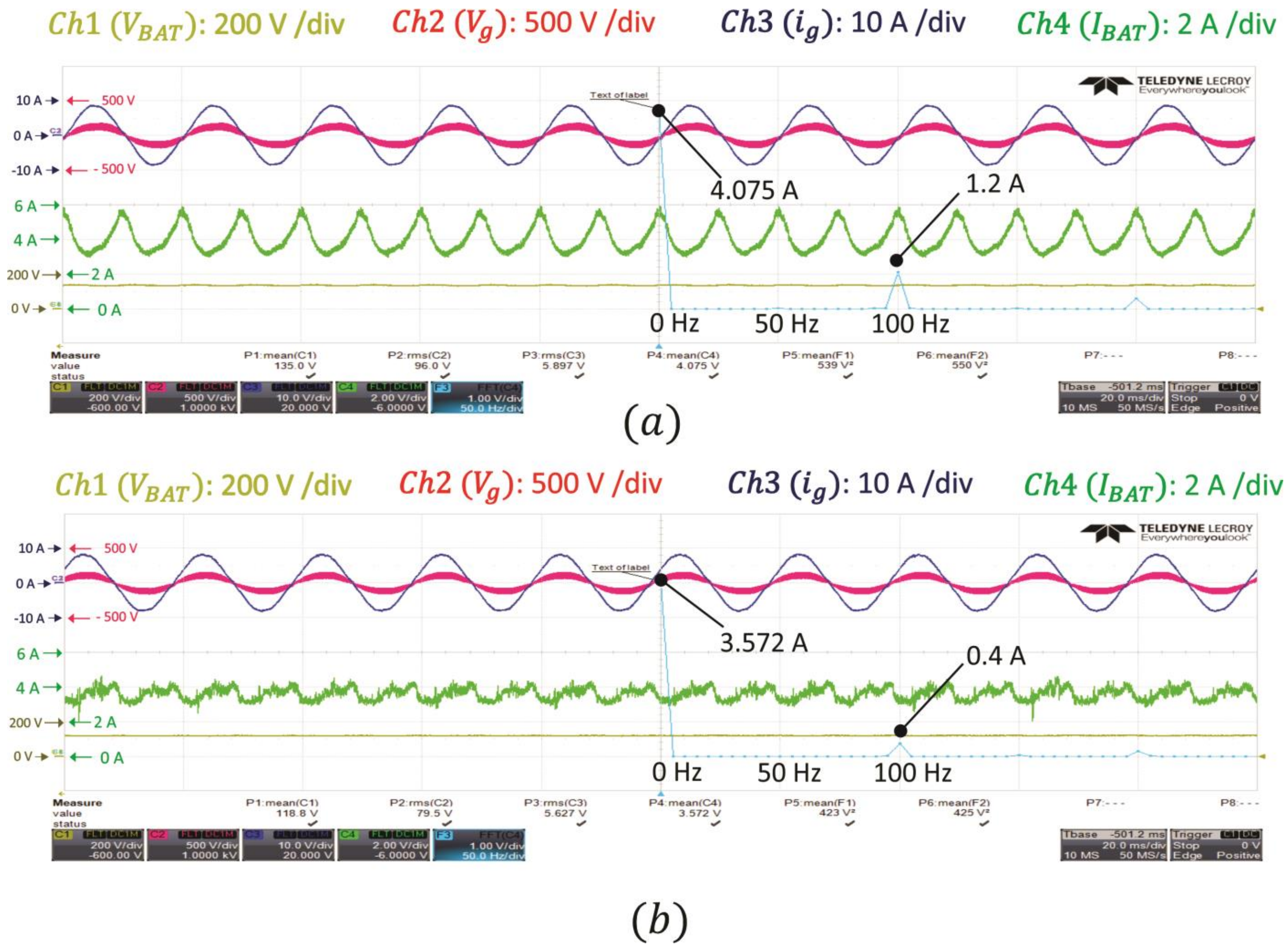




No high-frequency current sensing. Overall sampling frequency @ 100 kHz.
Phase shift is modulated for each switching cycle using a ramp function of the switching frequency @100kHz and adjustable delay block.

Measured Waveforms for APD

Measured Waveforms

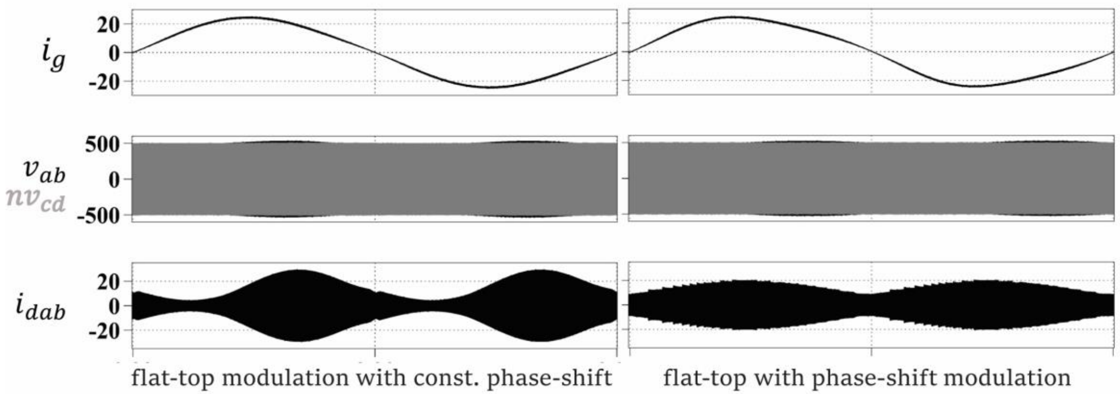


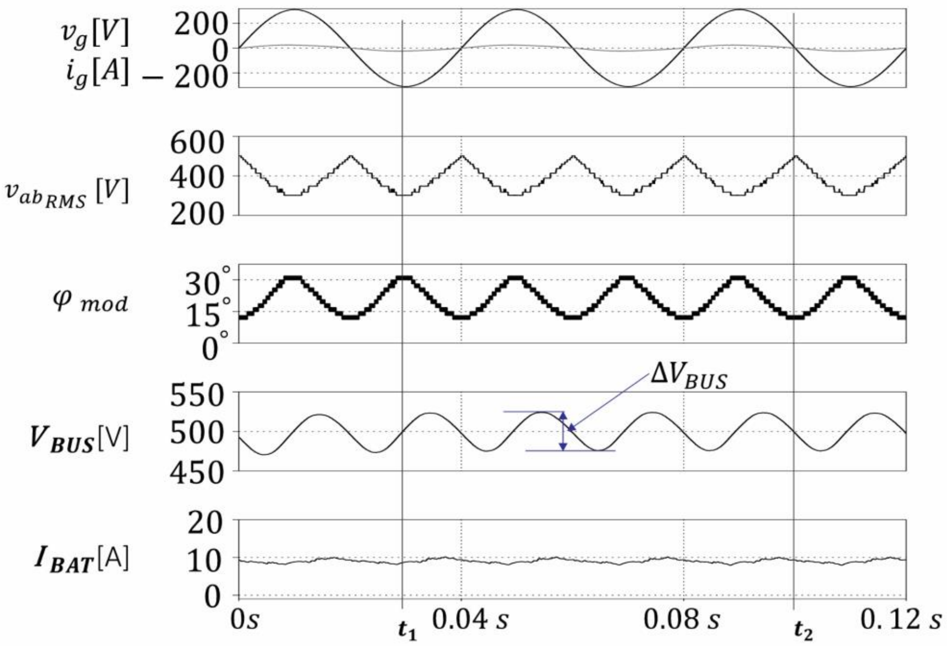
(a) 600 W result for scheme-1 with FFT of charging current
(b) 600 W result for scheme-2 with FFT of charging current

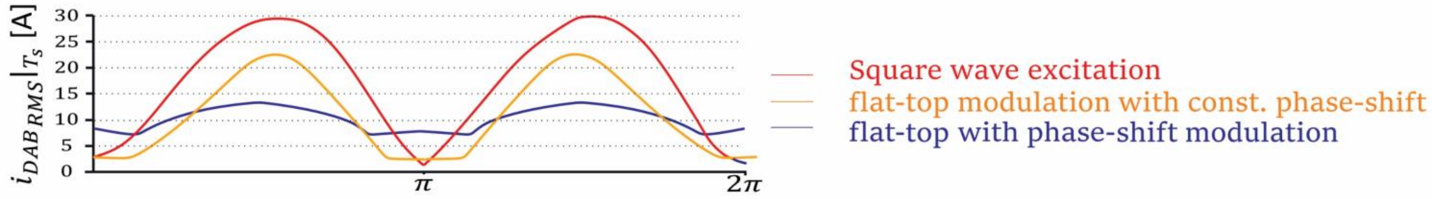
Effect on the Loss Profile

Conduction Loss Reduction

- 60% reduction in conduction loss compared to square-wave excitation.





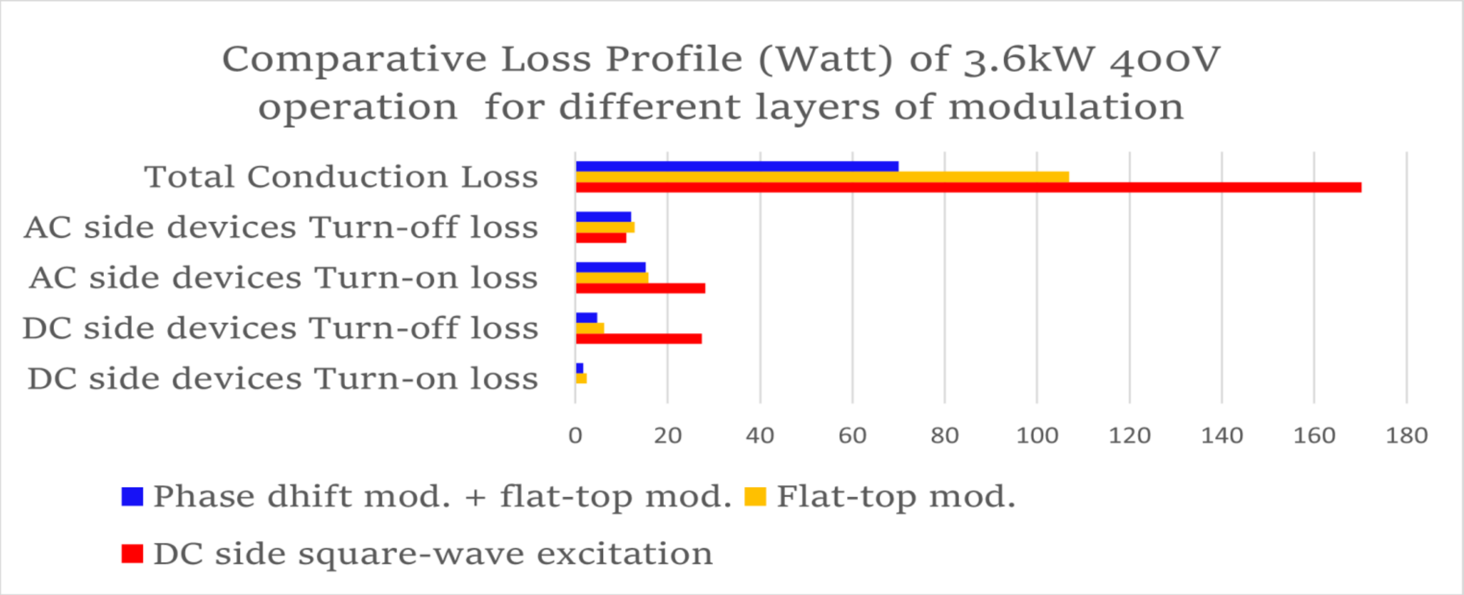


DAB current follows the least RMS path resulting in the minimum conduction loss.

Turn-off Loss Reduction

- 60% reduction in turn-off loss
- Always ZVS turn-on for $Q_7 - Q_{10}$
- Enhanced ZVS for $PFC\ switch$: Q_3 & Q_4 : 65%

Overall Loss Profile Comparision



Conclusions

- A 1-phase 1-stage on-board charger topology is shown with wide range operation and active power decoupling.

- The proposed combined pulse-width and phase-shift modulation strategy achieves active power decoupling without extra circuitry, eliminating the double line-frequency AC ripple in the battery charging current.

- The proposed modulation achieves the least RMS DAB current trajectory throughout the line cycle while facilitating Zero Voltage Switching (ZVS) for enhanced efficiency.

- Efficiency is predicted to exceed 98% and preliminary testing results support the prediction.

- More analytical details and results with rated power will be provided in the subsequent publications.

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Thank You.
Any Questions?