A Highly Efficient Wide Battery Voltage Range Dual Active Bridge-based Single-stage Bidirectional EV Onboard Charger Without Low-Frequency Harmonics in the Charging Current

INTELEC 2024 | Bengaluru, India

Paper ID: 72

Presenter: Soumya Ghorai

Coauthor: Souvik Chattopadhyay

IIT Kharagpur, India

Power Electronics Project Laboratory

05/08/2024

Outline

- Introduction
- Converter Topology
- Modulation & Control
- Conduction Loss Profile
- Switching Loss Profile
- Components
- Measured Waveforms
- Conclusions

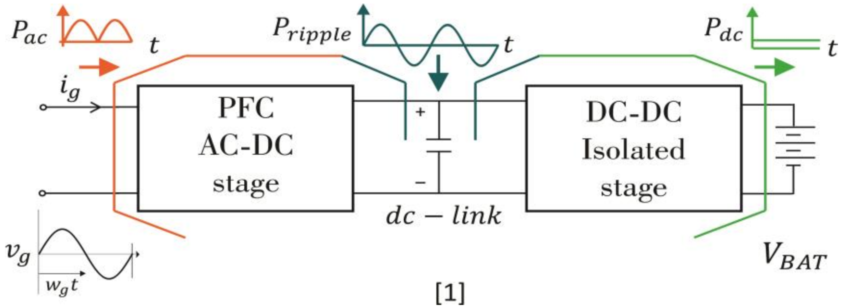
Introduction

Introduction: The objective of the Work

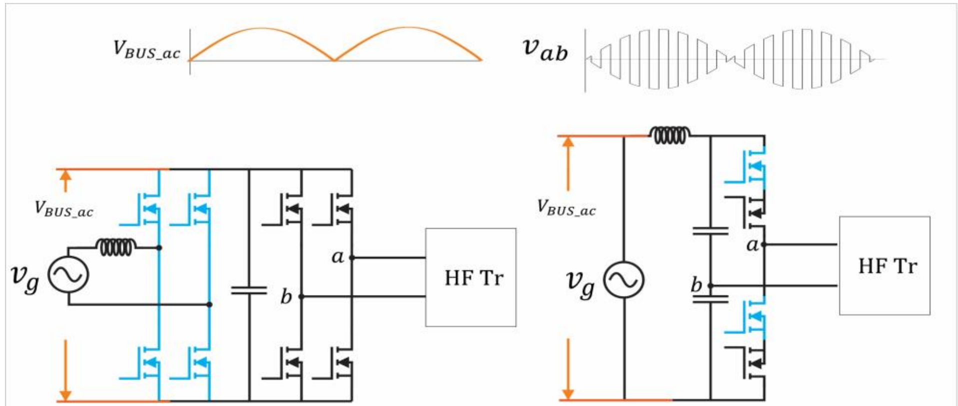
1-phase 1-stage Topologies (Existing)

Advantages

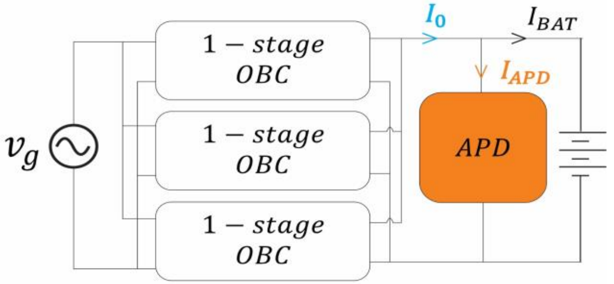
- Reduction in device counts and thermal footprint.
- Rectified sine AC bus: Charge storage less design. No side effect?



[1]



[2] [3]



[4][5][6]

Disadvantages

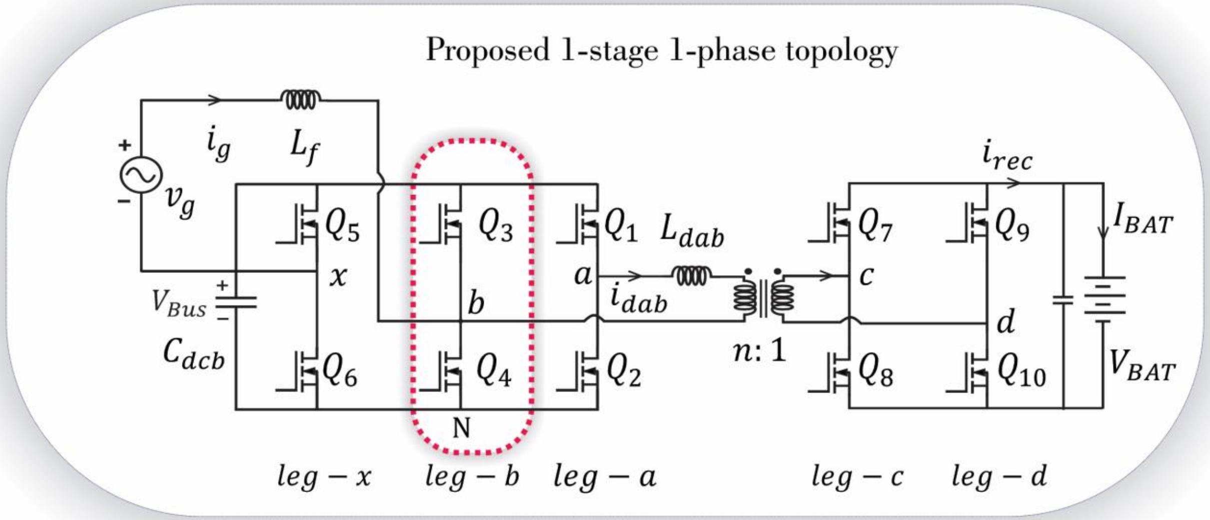
- Sinusoidal charging. → APD cell. Extra Circuitry!
- Efficiency dropping when V_{BAT} varies. → Wide variation of switching frequency!

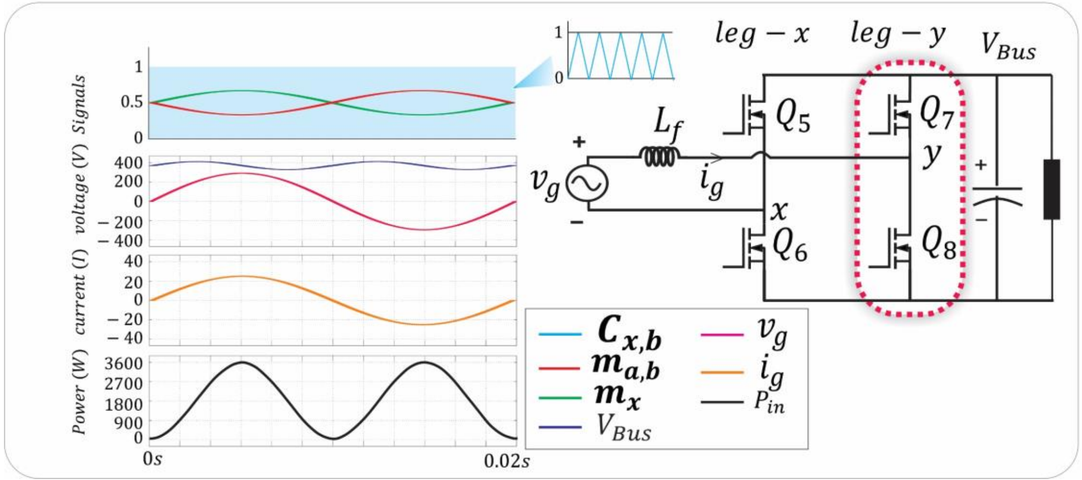
Converter Topology

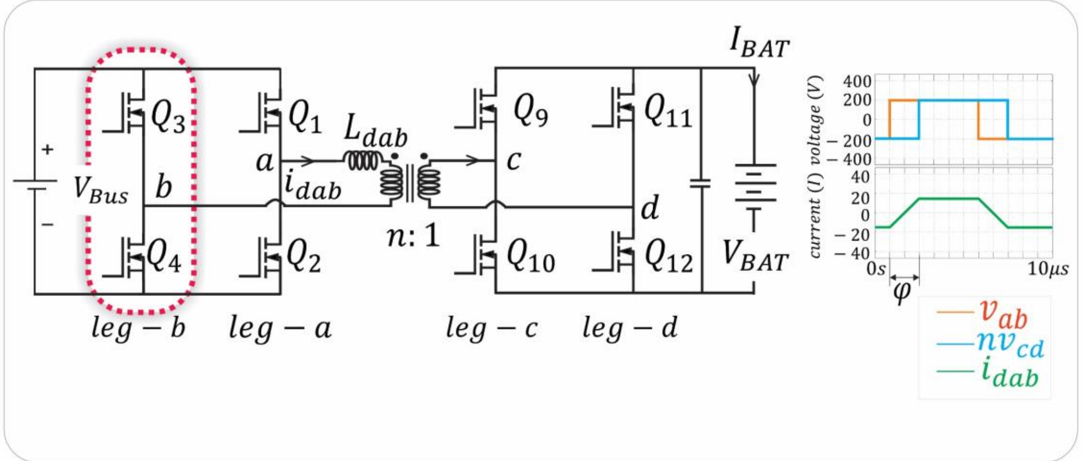
Converter Topology

The proposed topology: Core advantages

- DC charging – APD without extra circuitry.
- Peak Efficiency >98% @ 3.6kW power, 220V AC supply
  - Reactive power less HF operation.
  - ZVS turn-on and partial ZCS turn-off.
- Flat efficiency curve for $300-500V\ V_{BAT}$ variation.



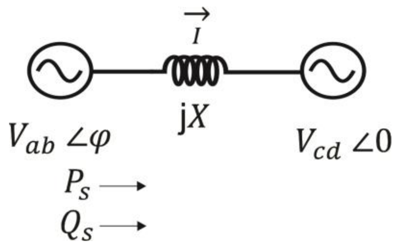


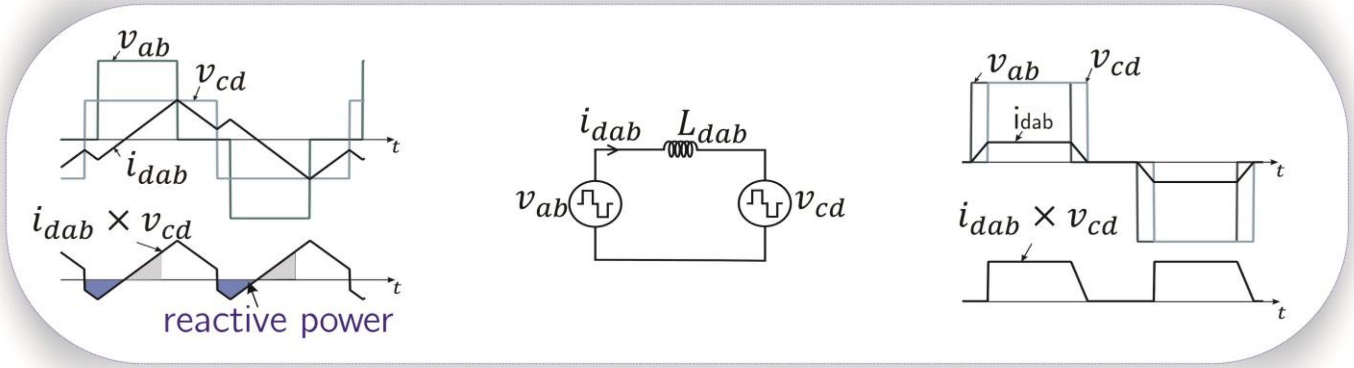


Modulation & Control

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

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





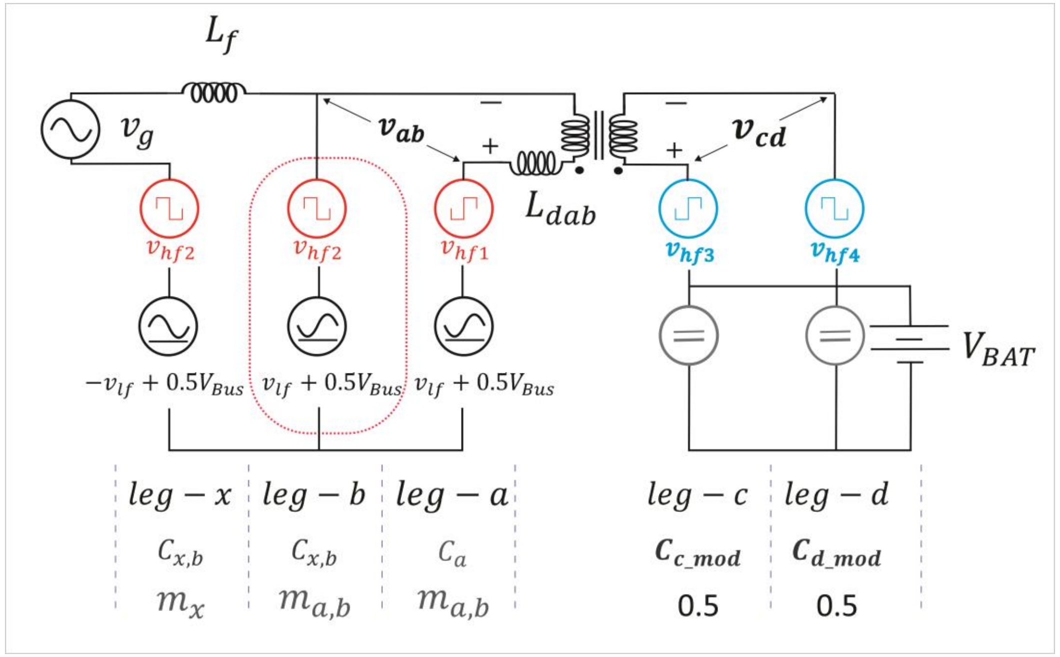
$$P_S = \frac{|V_{ab}||V_{cd}|}{X}\sin\varphi \qquad Q_S = |V_{ab}| \cdot \frac{(|V_{ab}| - |V_{cd}|\cos\varphi)}{X}$$

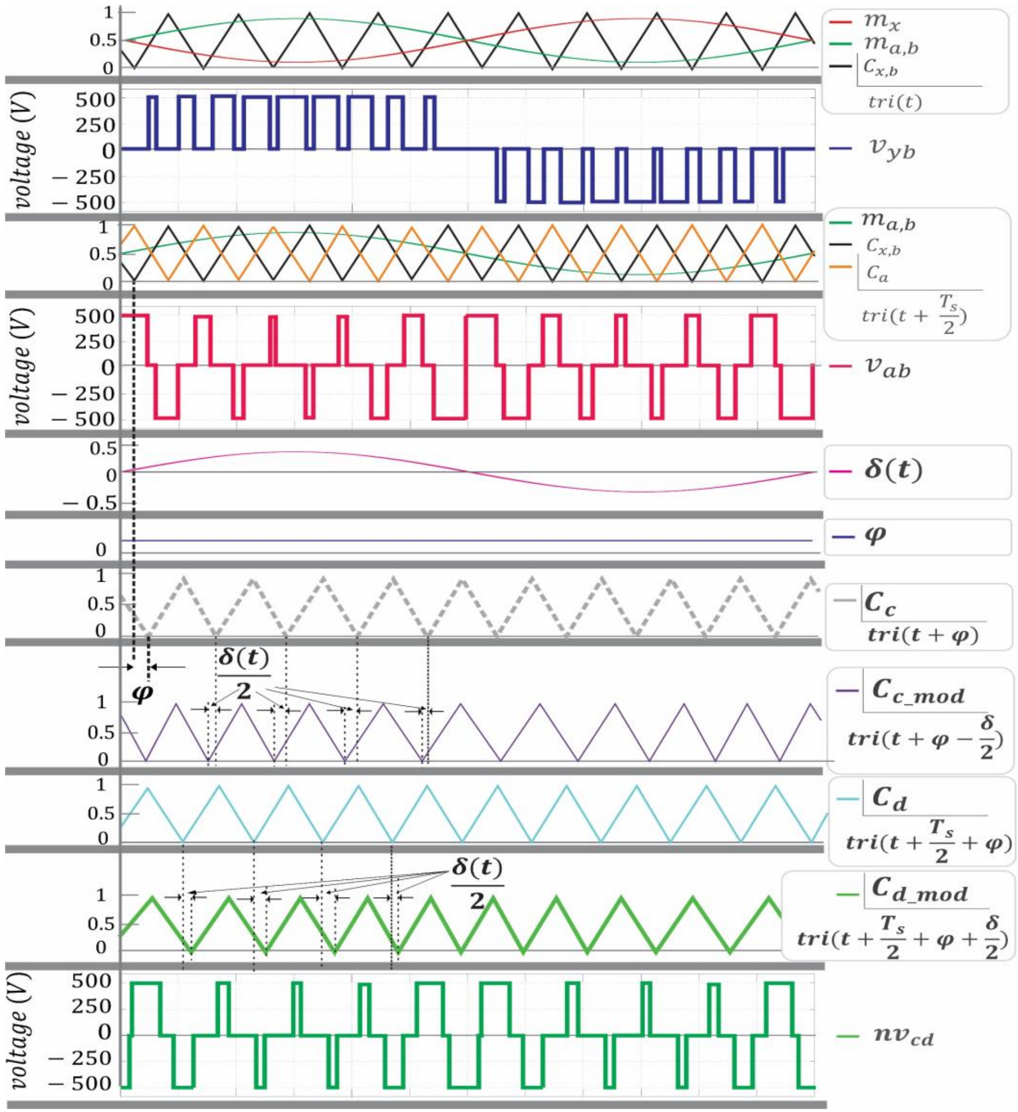
$$\vec{I} = \frac{|V_{ab}|\sin\varphi}{X} - j\frac{(|V_{ab}| - |V_{cd}|\cos\varphi)}{X}$$

Modulation & Control: Wide Battery Voltage operation

Sinusoidal carrier shift at the DC bridge

A carrier shifting function is introduced DC side bridge to effectively emulate the sinusoidal duty variation of the AC side bridge.

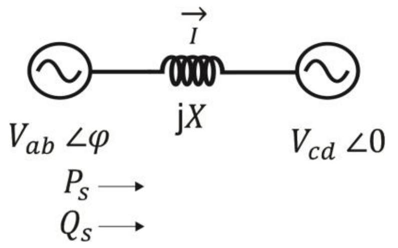




- DC bus regulations maintaining $V_{BUS} = nV_{BAT}$

A Highly Efficient Wide Battery Voltage Range Dual Active Bridge-based Single-stage Bidirectional EV Onboard Charger Without Low-Frequency Harmonics in the Charging Current. Soumya Ghorai, Souvik Chattopadhyay.

Active power control via phase-shift modulation



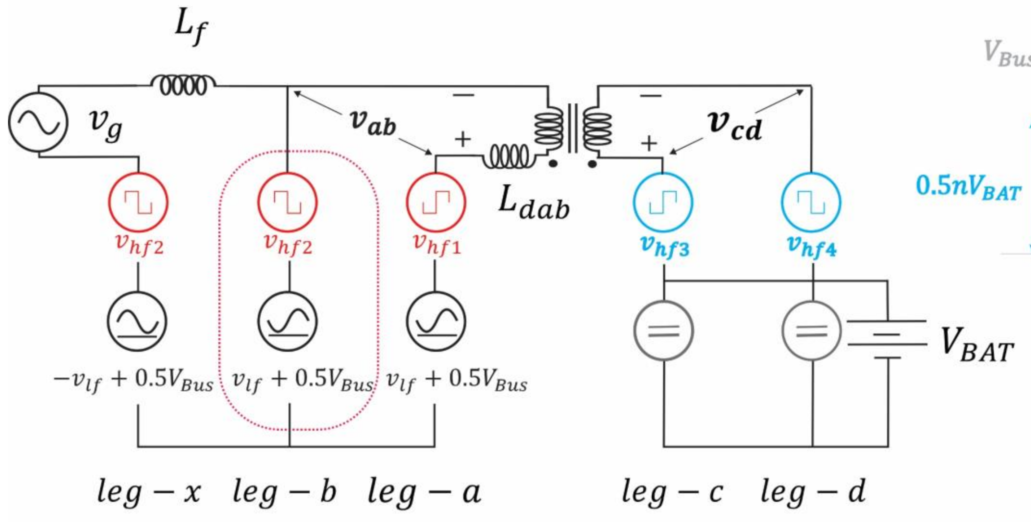
$$|V_{ab}| - |V_{cd}|\cos\varphi = 0$$

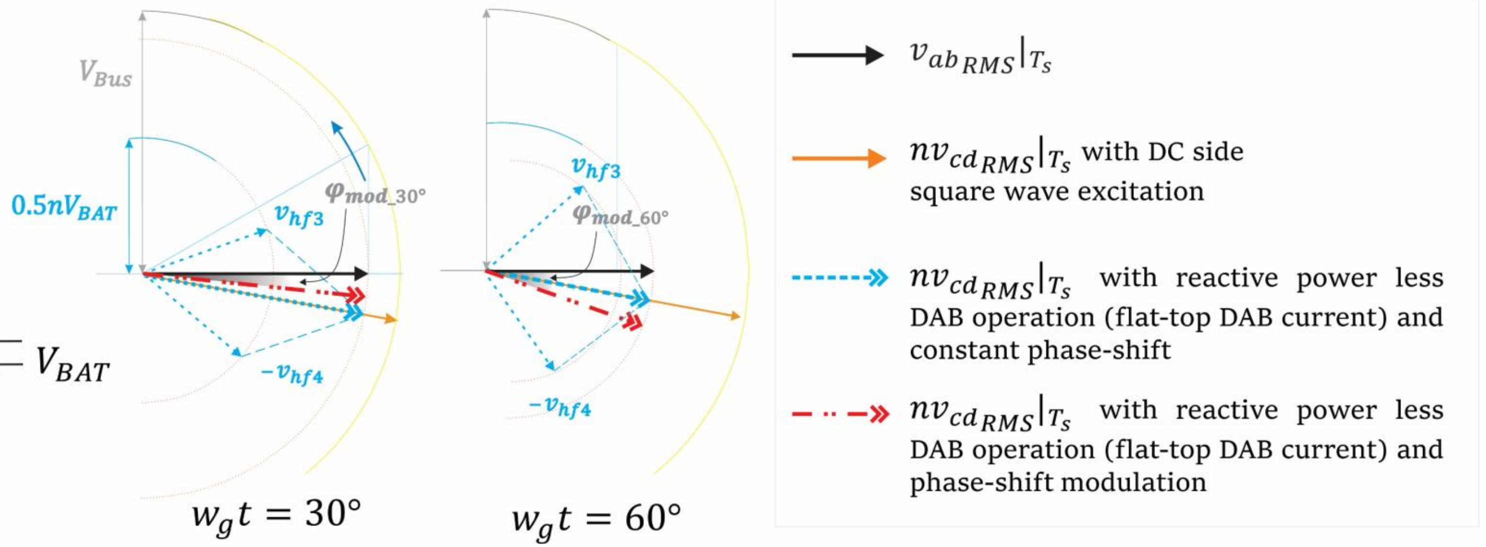
$$P_S = Const.\ if\ \ \sin\varphi \propto \frac{1}{|V_{ab}||V_{cd}|}$$

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

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

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

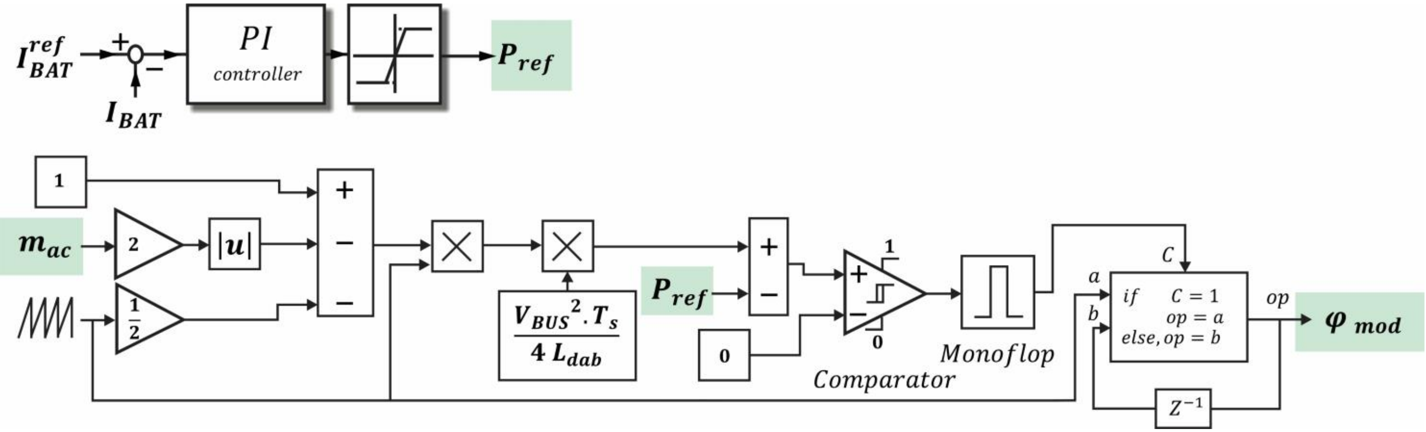


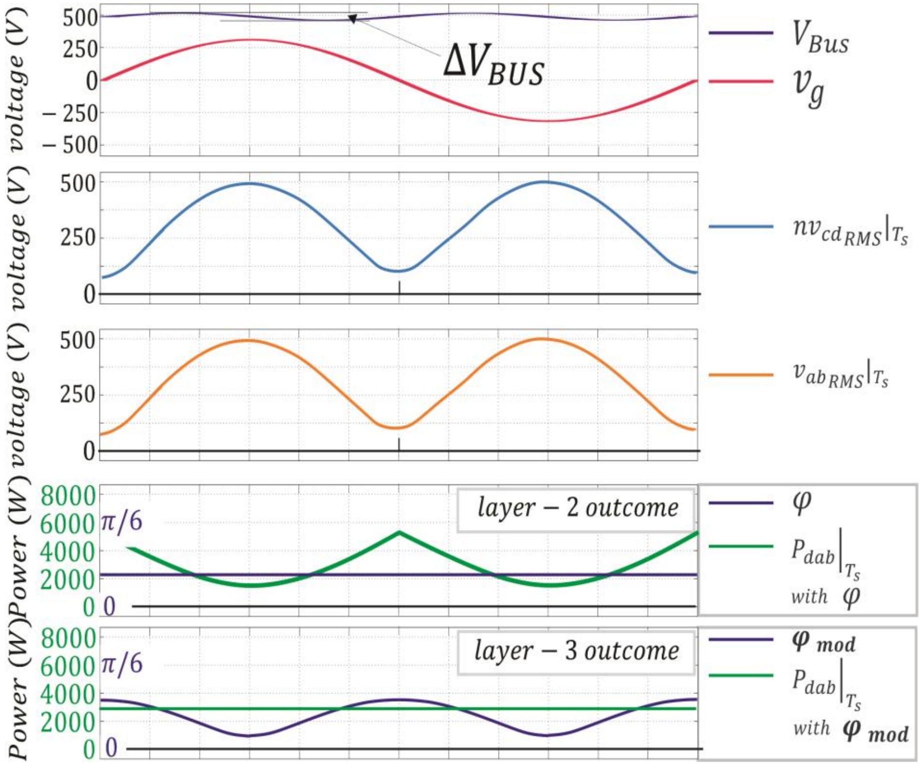


Modulation & Control: Implementation in Digital domain

Digital control by sensing only inputs and outputs

- The switching cycle active power transfer through DAB is calculated for fixed phase-shift flat-top modulation.
- Using that formula, phase shift is modulated to send constant active power over the line cycle.





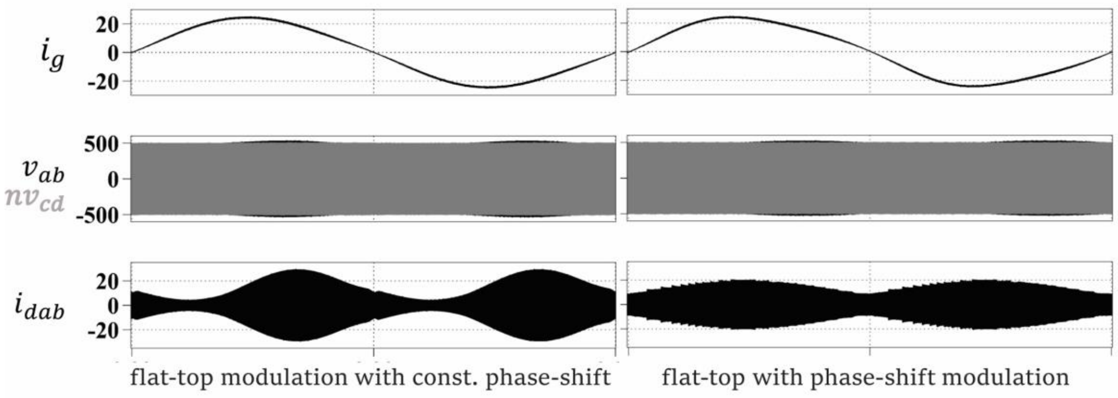
- **No high-frequency current shaping. Overall sampling frequency @ 50 kHz.**
- **Phase shift is adjusted for each switching cycle using a ramp function of the switching frequency @100kHz.**

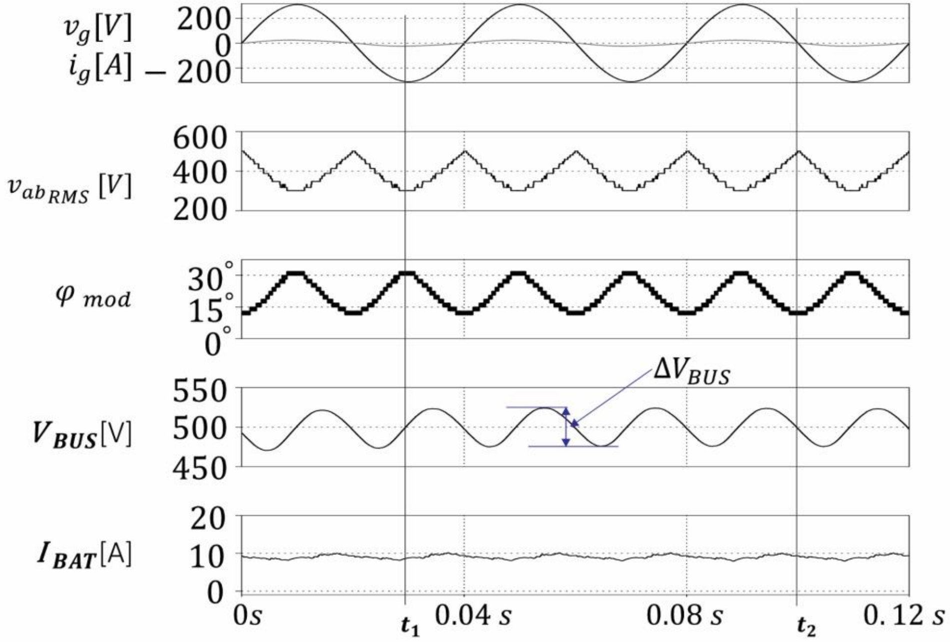
Conduction Loss Profile

Conduction Loss Profile

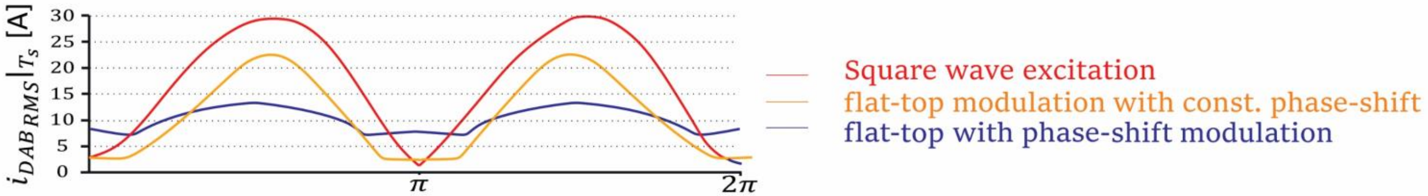
The biggest save!

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





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



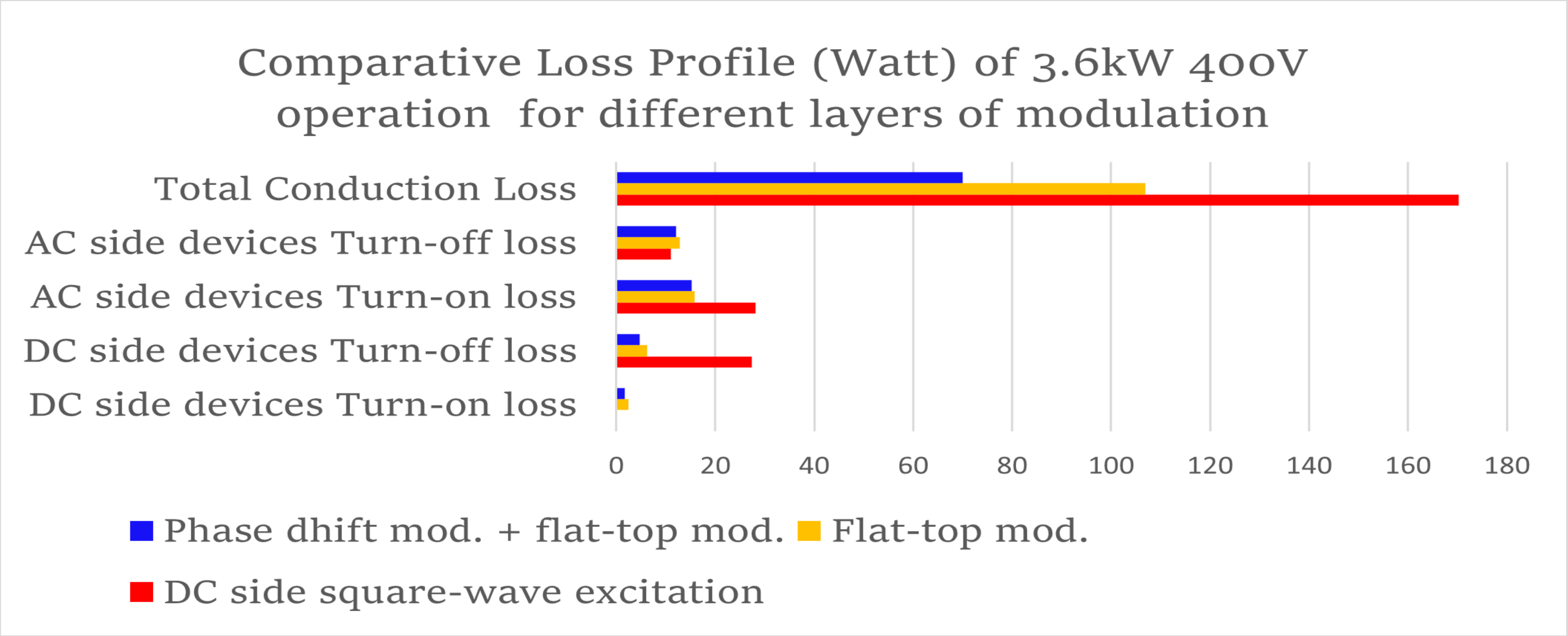
Switching Loss Profile

Switching Loss Profile

Cutting down the turn-off loss!

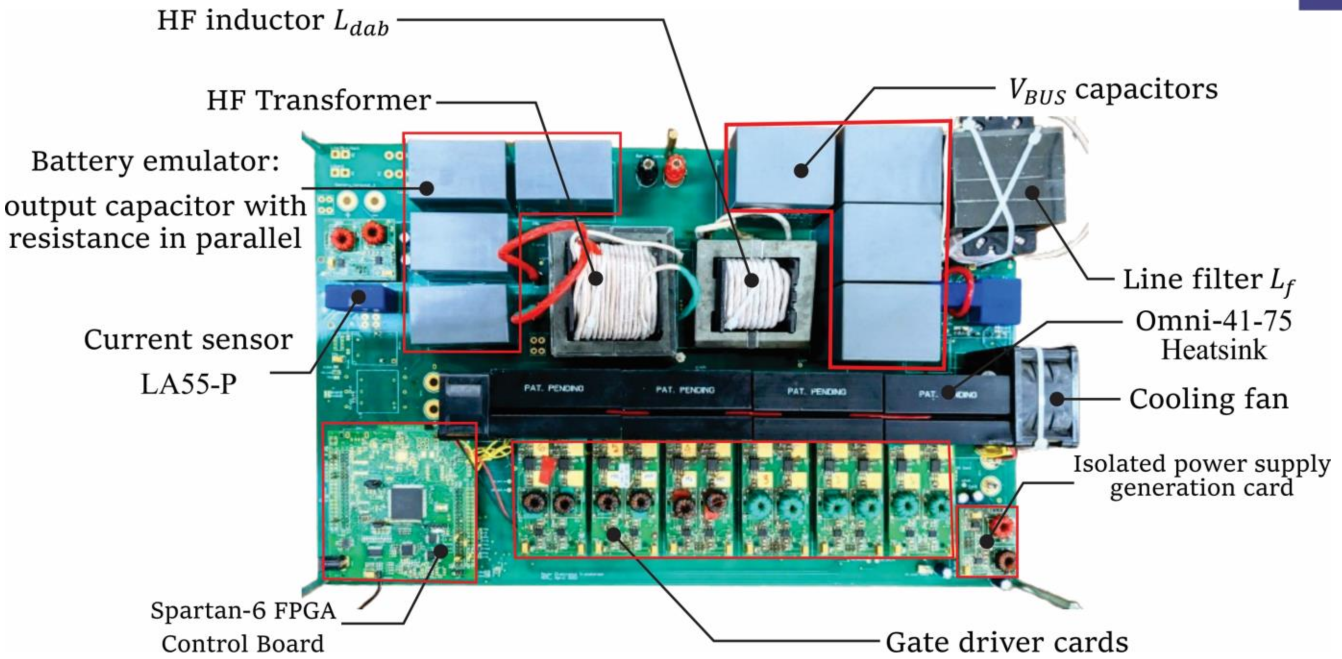
- **60% reduction in turn-off loss due to the trapezoidal shape of HF current.**
- **Always ZVS turn-on for $Q_7 - Q_{10}$.**
- **Enhanced ZVS for *PFC switch*: Q_3 & Q_4 : 65%.**

Loss Profile Comparison



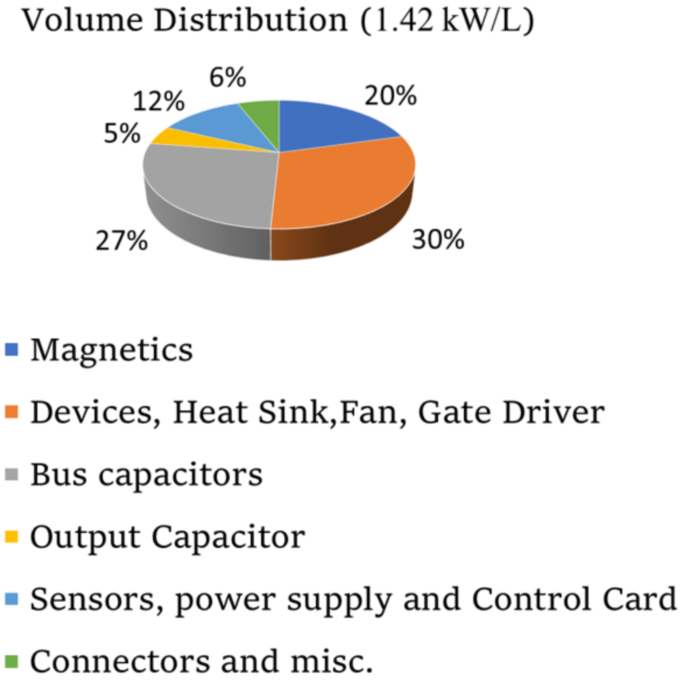
Components

Components



Conventional design

- $1.2kV, 40m\Omega$ SiC devices (NTHL040N120SC1)
- $500\mu F$, 650V film capacitors at DC bus



- Magnetics:
  - HF Transformer: 500:400, EE80/38/20, one pair, Litz wire, 36AWG,200 strands
  - HF DAB Inductance: 13μH, EE30/15/7, 200 strands, Litz. Wire. , 36AWG
  - Line filter: 500μH, EE70/33/32 , 2 pairs, 36AWG Litz. Wire,100 strands

Measured Waveforms

Measured Waveforms: Wide Battery Voltage Operation

$V_{BAT} = 200V\ @2kW\ Line\ current\ ZC$

$V_{BAT} = 200V\ @2kW\ Line\ current\ peak$

Measured Efficiency @ flat-top mod.
Varying the Bus voltage accordingly

Line current quality

- $\boldsymbol{THD = 0.5\%, PF = 0.999\ @2kW}$
- $\boldsymbol{THD = 10.10\ \%, PF = 0.995\ @200\ W}$

$V_{BAT} = 300V\ @2kW\ Line\ current\ ZC$

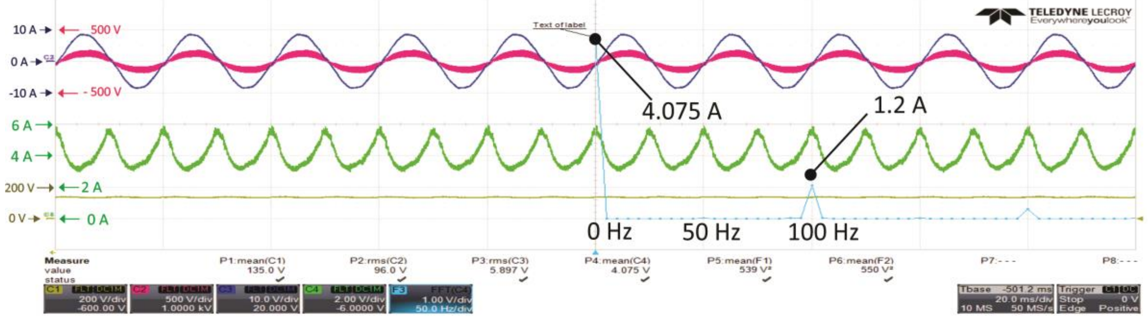
$V_{BAT} = 300V\ @2kW\ Line\ current\ peak$

Measured Waveforms: Low-Frequency Ripple Free Charing Current

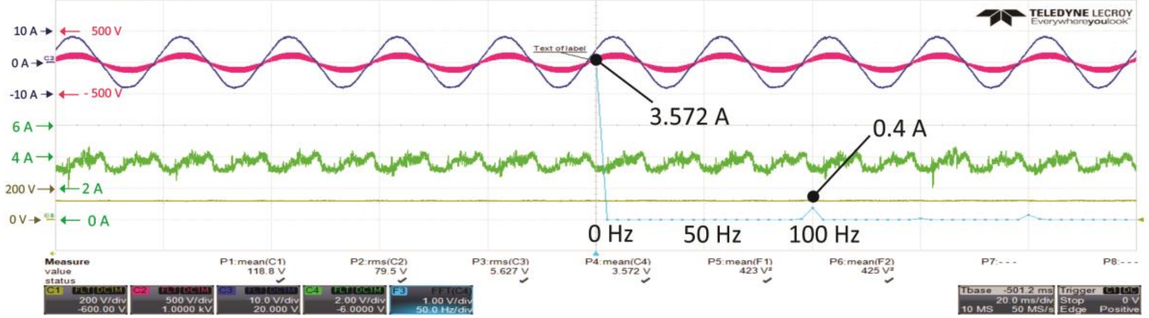
Charging current quality

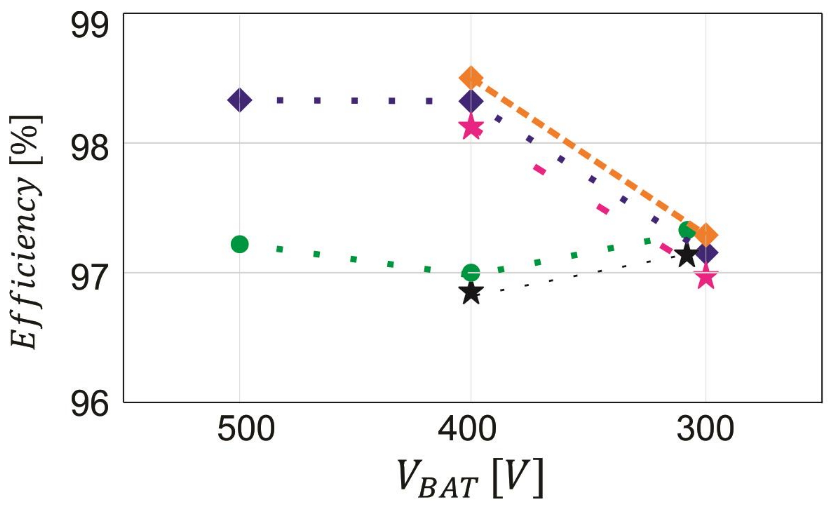
- 2^{nd} harmonic ripple in I_{BAT} 35% to 8% . Better tuning required !
- Efficiency increase by 1%

$Ch1\ (V_{BAT})$: 200 V /div $Ch2\ (V_g)$: 500 V /div $Ch3\ (i_g)$: 10 A /div $Ch4\ (I_{BAT})$: 2 A /div



$Ch1\ (V_{BAT})$: 200 V /div $Ch2\ (V_g)$: 500 V /div $Ch3\ (i_g)$: 10 A /div $Ch4\ (I_{BAT})$: 2 A /div





- ● Predicted outcome with flat-top operation, phase-shift not modulated @ 2kW
- ★ Measured outcome with flat-top operation, phase-shift not modulated @ 2kW
- ◆ Predicted outcome with flat-top operation and phase-shift modulation @ 3.6kW
- ◆ Predicted outcome with flat-top operation and phase-shift modulation @ 720W
- ★ Measured outcome with flat-top operation and phase-shift modulation @ 720W

Conclusions

Conclusions

- A 1-phase 1-stage on-board charger topology is shown with 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.

References

1. M. J. Brand, M. H. Hofmann, S. S. Schuster, P. Keil and A. Jossen, "The Influence of Current Ripples on the Lifetime of Lithium-Ion Batteries," in *IEEE Transactions on Vehicular Technology*, vol. 67, no. 11, pp. 10438-10445, Nov. 2018, doi: 10.1109/TVT.2018.2869982
2. B. Whitaker *et al*., "A High-Density, High-Efficiency, Isolated On-Board Vehicle Battery Charger Utilizing Silicon Carbide Power Devices," in *IEEE Transactions on Power Electronics*, vol. 29, no. 5, pp. 2606-2617, May 2014, doi: 10.1109/TPEL.2013.2279950
3. L. Xue, Z. Shen, D. Boroyevich, P. Mattavelli and D. Diaz, "Dual Active Bridge-Based Battery Charger for Plug-in Hybrid Electric Vehicle With Charging Current Containing Low Frequency Ripple," in *IEEE Transactions on Power Electronics*, vol. 30, no. 12, pp. 7299-7307, Dec. 2015, doi: 10.1109/TPEL.2015.2413815.
4. B. Li, Q. Li, F. C. Lee, Z. Liu and Y. Yang, “A High-Efficiency High-Density Wide-Bandgap Device-Based Bidirectional On-Board Charger,” in IEEE Journal of Emerging and Selected Topics in Power Electronics, vol. 6, no. 3, pp. 1627-1636, Sept. 2018, doi: 10.1109/JESTPE.2018.2845846.
5. A. K. Bhattacharjee and I. Batarseh, "Sinusoidally Modulated AC-Link Microinverter Based on Dual-Active-Bridge Topology," in *IEEE Transactions on Industry Applications*, vol. 56, no. 1, pp. 422-435, Jan.-Feb. 2020, doi: 10.1109/TIA.2019.2943119.
6. N. D. Weise, G. Castelino, K. Basu and N. Mohan, "A Single-Stage Dual-Active-Bridge-Based Soft Switched AC–DC Converter With Open-Loop Power Factor Correction and Other Advanced Features," in *IEEE Transactions on Power Electronics*, vol. 29, no. 8, pp. 4007-4016, Aug. 2014, doi: 10.1109/TPEL.2013.2293112.
7. J. Everts, F. Krismer, J. Van den Keybus, J. Driesen and J. W. Kolar, "Optimal ZVS Modulation of Single-Phase Single-Stage Bidirectional DAB AC–DC Converters," in *IEEE Transactions on Power Electronics*, vol. 29, no. 8, pp. 3954-3970, Aug. 2014, doi: 10.1109/TPEL.2013.2292026.
8. H. Belkamel, H. Kim and S. Choi, "Interleaved Totem-Pole ZVS Converter Operating in CCM for Single-Stage Bidirectional AC–DC Conversion With High-Frequency Isolation," in *IEEE Transactions on Power Electronics*, vol. 36, no. 3, pp. 3486-3495, March 2021, doi: 10.1109/TPEL.2020.3016684.
9. K. Itoh, M. Ishigaki, N. Kikuchi, T. Harada and T. Sugiyama, "A Single-Stage Rectifier with Interleaved Totem-pole PFC and Dual Active Bridge (DAB) Converter for PHEV/BEV On-board Charger," *2020 IEEE Applied Power Electronics Conference and Exposition (APEC)*, New Orleans, LA, USA, 2020, pp. 1936-1941, doi: 10.1109/APEC39645.2020.9124083.

Control: Generation of PWM signals