Integrated Onboard Chargers (OBCs) for Electric Vehicles (EVs)

The future of Transportation Electrification

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Background Story

01. Fossil fuel from internal combustion engine vehicles causes greenhouse gas emissions

02. EVs produce no carbon emissions, have efficient motors and better performance

03. Availability of reliable power sources to charge EVs

04. Unavailability of efficient and reliable chargers hinders the adoption of EVs at a faster rate

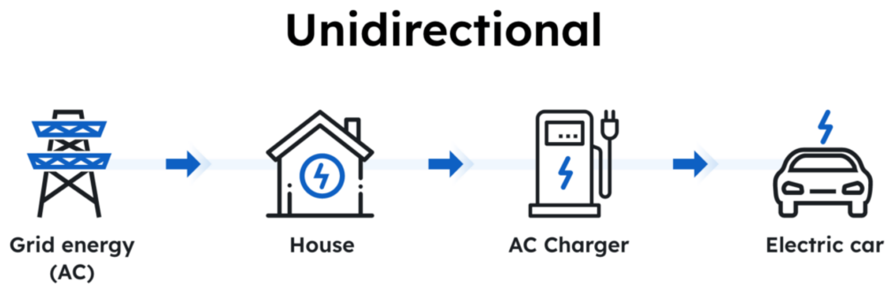
Power Flow Functionalities of EV Chargers

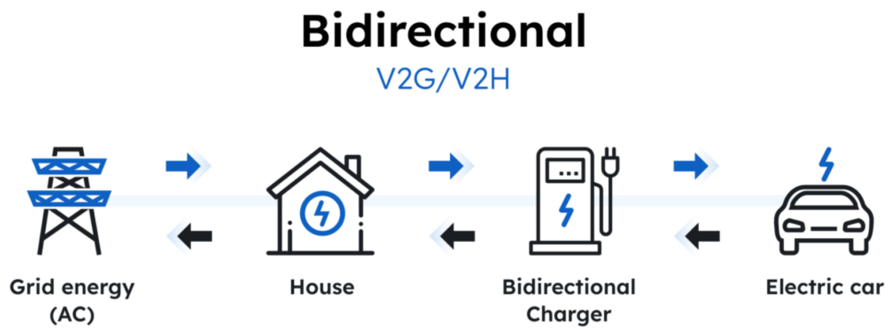
01. Power flow can be unidirectional or bidirectional

02. Unidirectional performs only G2V operation

03. Bidirectional performs G2V, V2H, V2G, V2X

04. Bidirectional injects power back for frequency control, load levelling and peak shaving





Primary Types of Electric Vehicle Charging

01. The two main types are off-board and on-board

02. The off-board chargers are DC fast chargers

03. They are installed in the charging stations outside the vehicle

04. Off-board chargers have a high infrastructure cost

Primary Types of Electric Vehicle Charging

01. Onboard chargers get their AC supply mainly from the grid

02. Onboard chargers are bulky, slow and low power density chargers

03. Installation done inside the vehicle

04. Renewable energy companies see potential in wave energy integration.

Levels of EV Chargers

01. Main levels of EV Charging: Levels I, II and III

02. Determined based on its location, charging time, and power ratings

03. Level I charges with 120 Vrms supply

04. Charging time, power and current ratings of 4-11 hours, 1.4kW and 12A, respectively

Levels of EV Chargers

01. Level II could have a single-phase or three-phase supply of 240 Vrms

02. Charging time, power and current ratings of 1-4 hours, 4kW and 17A, respectively

03. Level III charger is a DC fast charger

04. Power rating above 50kW

05. Takes approximately 0.2 – 0.5 hours to fully charge

The Categories of Integrated OBCs

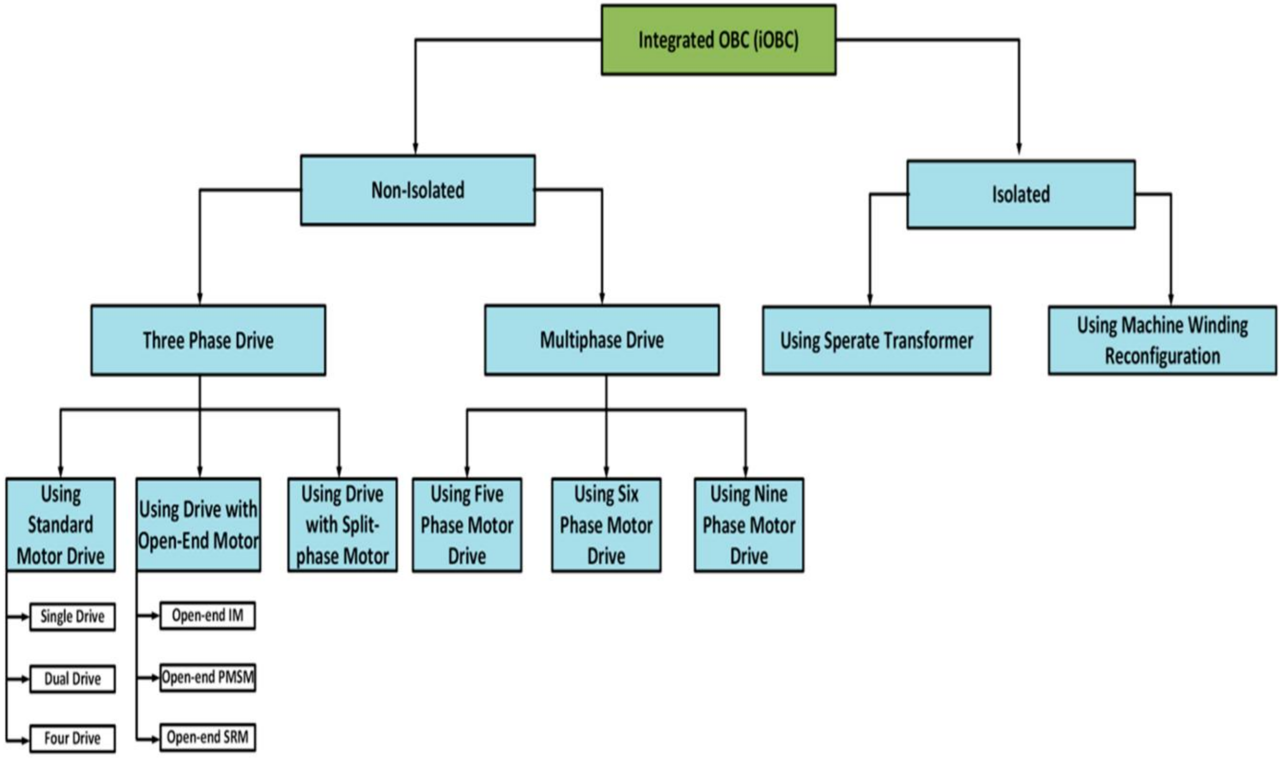
01. Determined based on their design criteria: Isolated and Non-Isolated

02. Isolated integrated OBCs use galvanic isolation

03. Non-isolated use either a multiphase or three-phase

02. Multiphase integrated OBCs share power electronic components

02. Three-phase integrated OBCs grouped single-stage and two-stage



Single-stage and two-stage integrated Three-phase OBCs

01. Single-stage has a simplified topology converting AC-DC in only one stage to charge

02. Reduces the overall weight, but has motor torque generation problems in charging mode

03. Two-stage integrated OBCs have two distinct stages

04. The first stage is the AC-DC rectification stage

05. The second stage is a DC-DC conversion stage to charge the battery

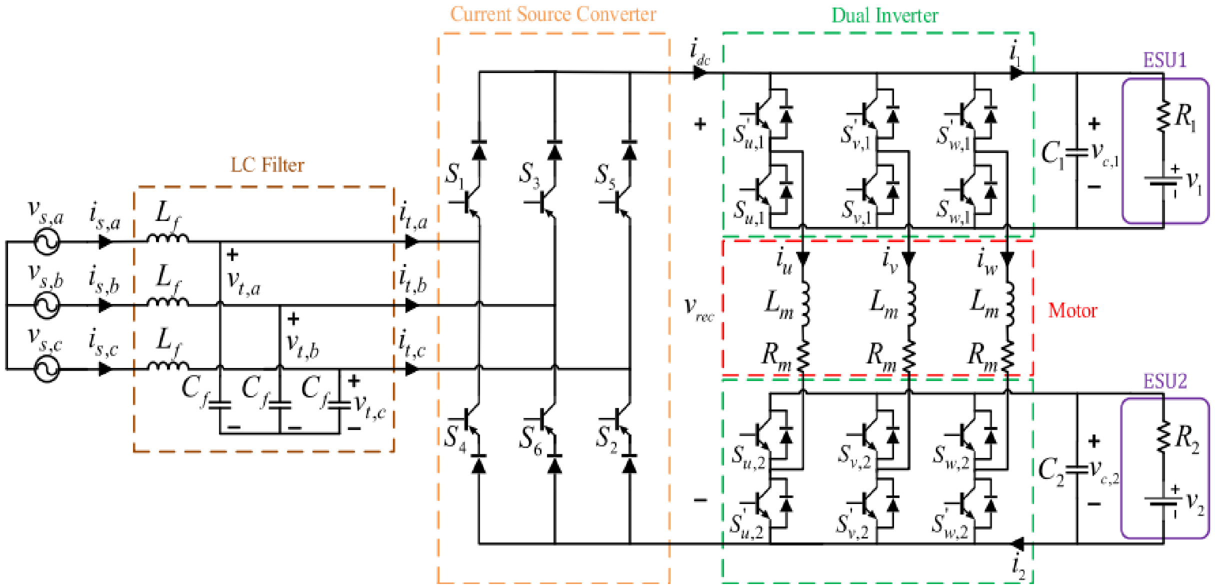
Literature Review

01. A three-phase current source converter-based integrated OBC design [1]

02. Uses an LC filter, PMSM and a current-source converter to charge the battery

03. Implementation of a dual-inverter system to reduce current ripples

04. Major drawback of the design is the unbalanced grid current

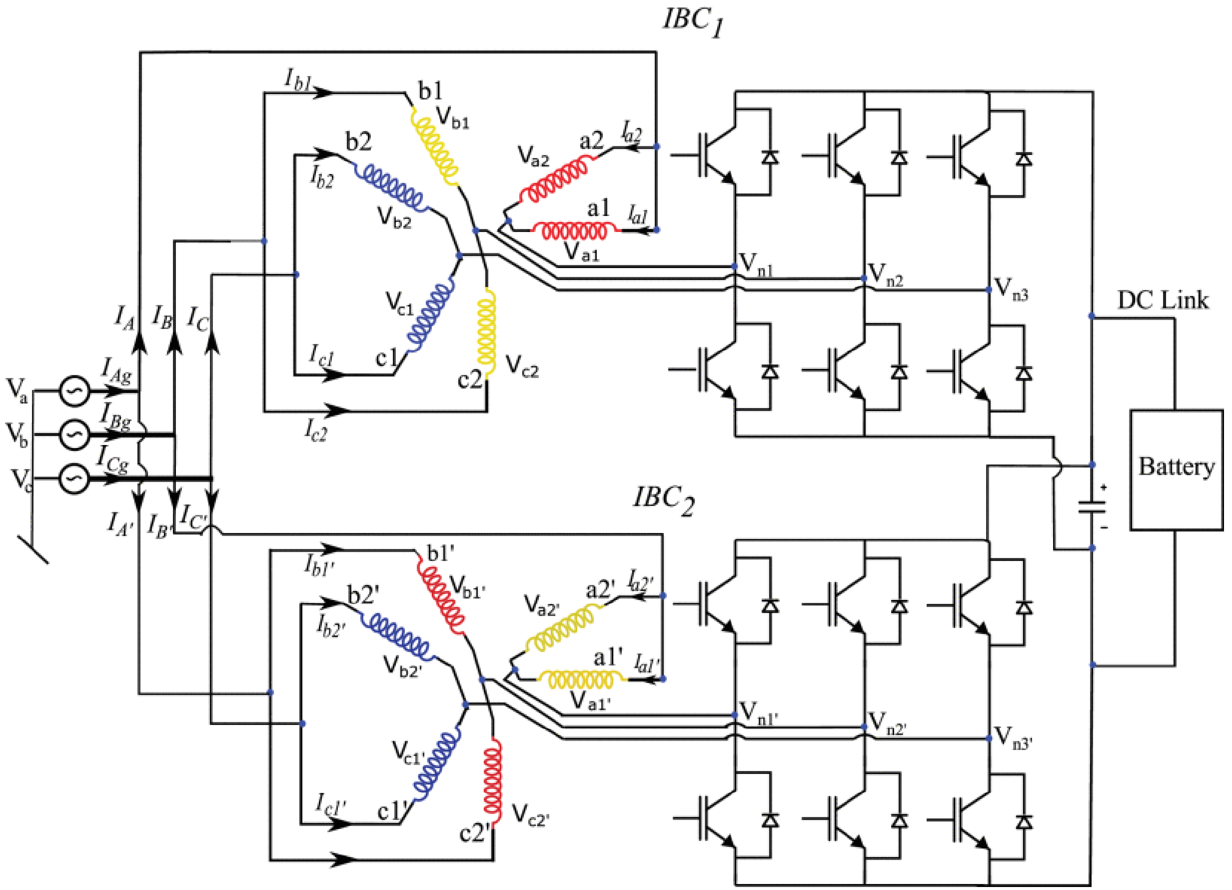


Literature Review

01. A parallel configuration-based integrated OBC is designed to address the current balancing problem [2]

02. Adopts RYB/YRB wiring configuration to get rid of the unbalanced current

03. The design has a major challenge related to its cumbersomeness

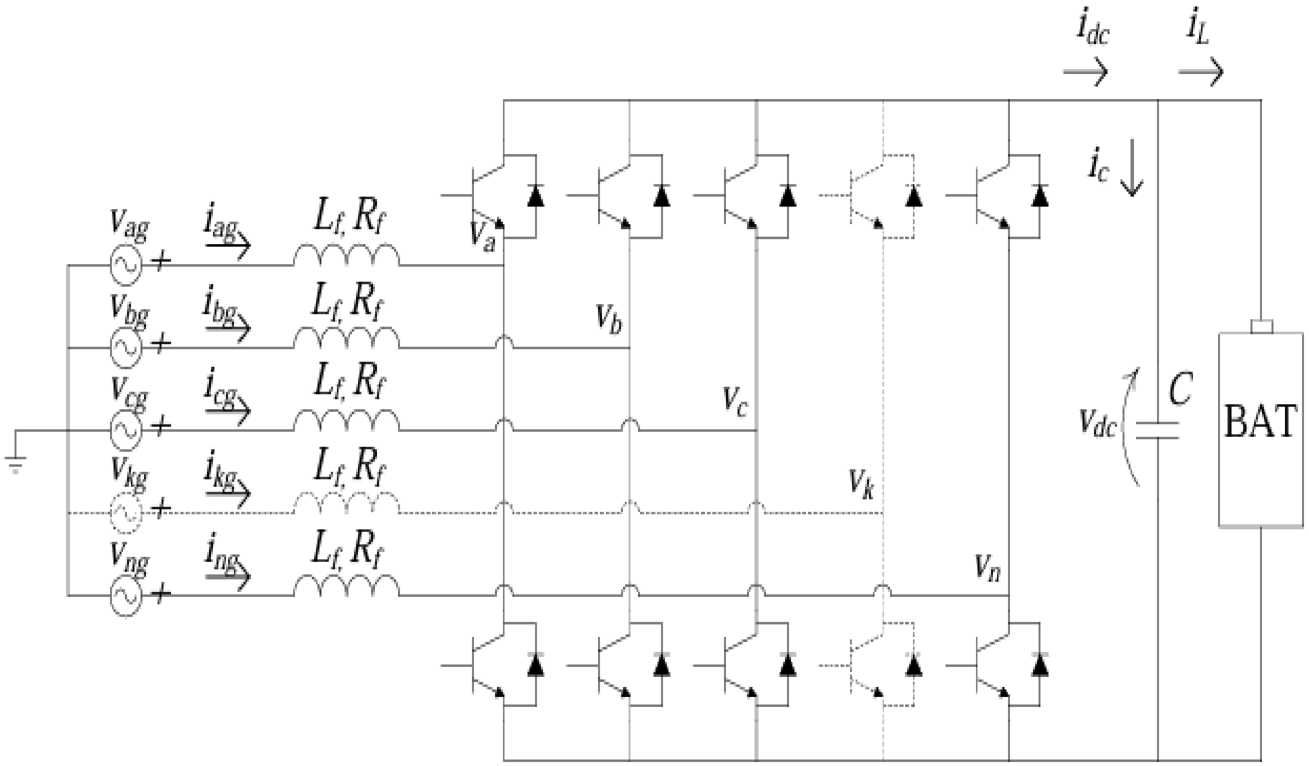


Literature Review

01. Another integrated OBC consists of traction inverters, a motor and an active front end for a two-stage conversion [3]

02. Vehicle motor's leakage inductance used as the magnetic component

03. The implementation of the active frontend increases the system size



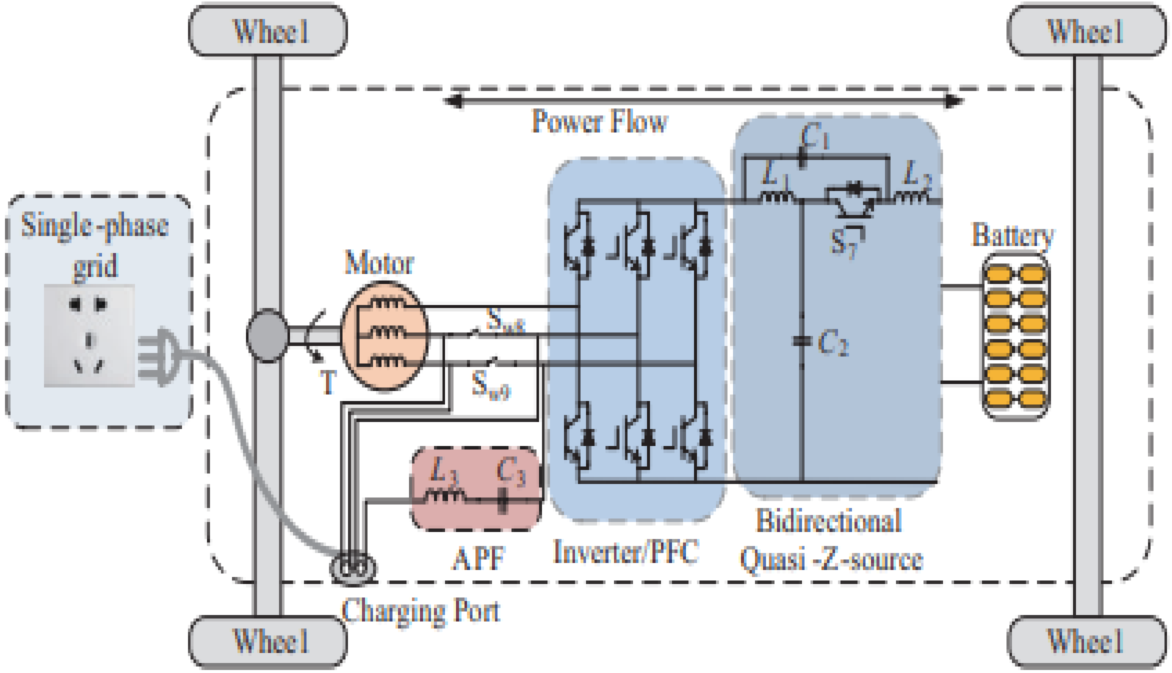
Literature Review

01. A very simple design comprising a single-phase inverter, a PMSM, an active power filter and a quasi-z-source inverter [4]

02. The design is compact due to the smaller passive components used in the quasi-z-source inverter

03. Design has an improved current ripple

04. Design has issues relating to size

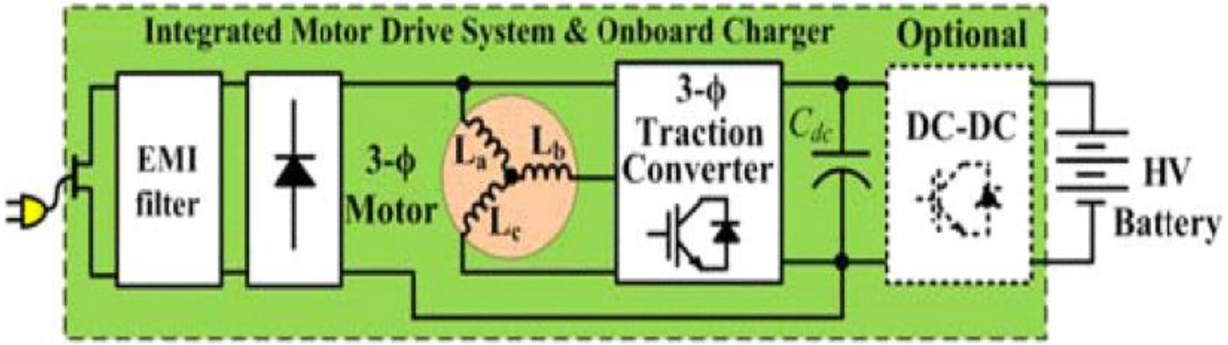


Literature Review

01. A different design uses only a PMSM and the traction converter to solve the size issue [5]

02. The charger can handle high-power levels of charging with minimal losses

03. Major drawbacks include in-rush current problems and high voltage stress on the switches.



The Hidden Problem in Integrated Charging

01. Charging via motor may generate undesired torque.

02. Traditional topologies suffer from high current ripple, poor power factor, and control complexity.

03. Need to ensure zero torque generation during charging, high efficiency and power factor.

04. Complexity of charging designs

05. High in-rush current

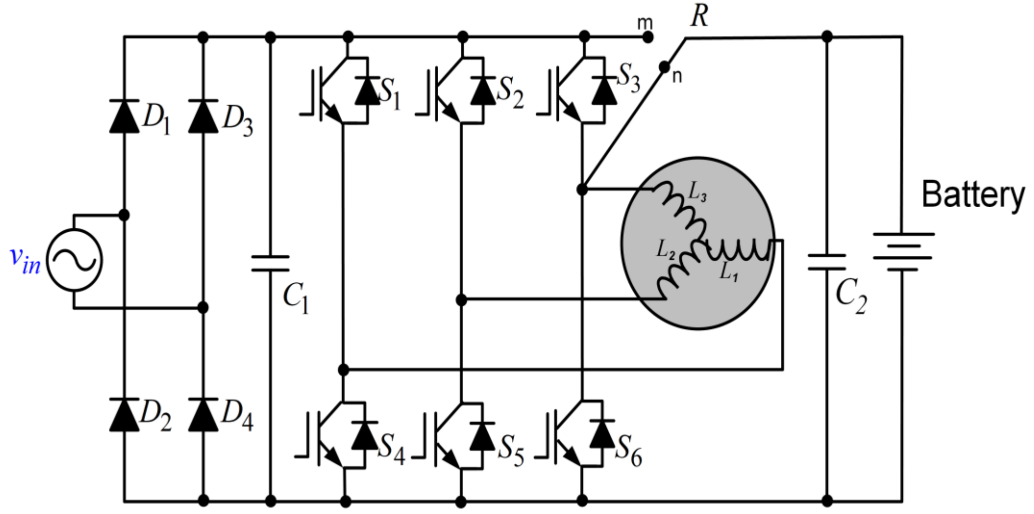
The Proposed Charger I

01. What if we could use the vehicle's drivetrain system to do the charging?

02. Uses PMSM stator windings as coupled inductors with the inverter as the full converter.

03. Comprises a PMSM, an inverter and a single-pole double-throw switch (R).

04. Has zero torque, high power factor, minimized hardware, and reduced current ripples.



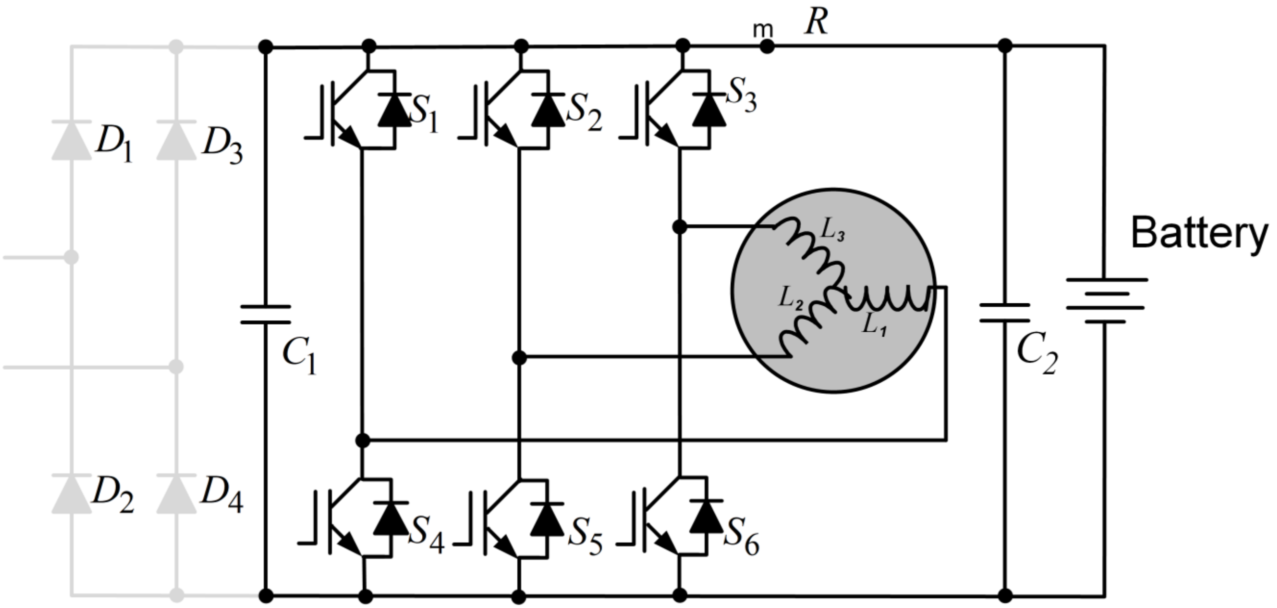
Vehicle Driving Mode

01. No AC supply from the grid

02. Battery is the primary power source to drive the vehicle's motors

03. Switch *R* closes at m, and path n is opened

04. All switches of the inverter are activated by Space Vector PWM signals



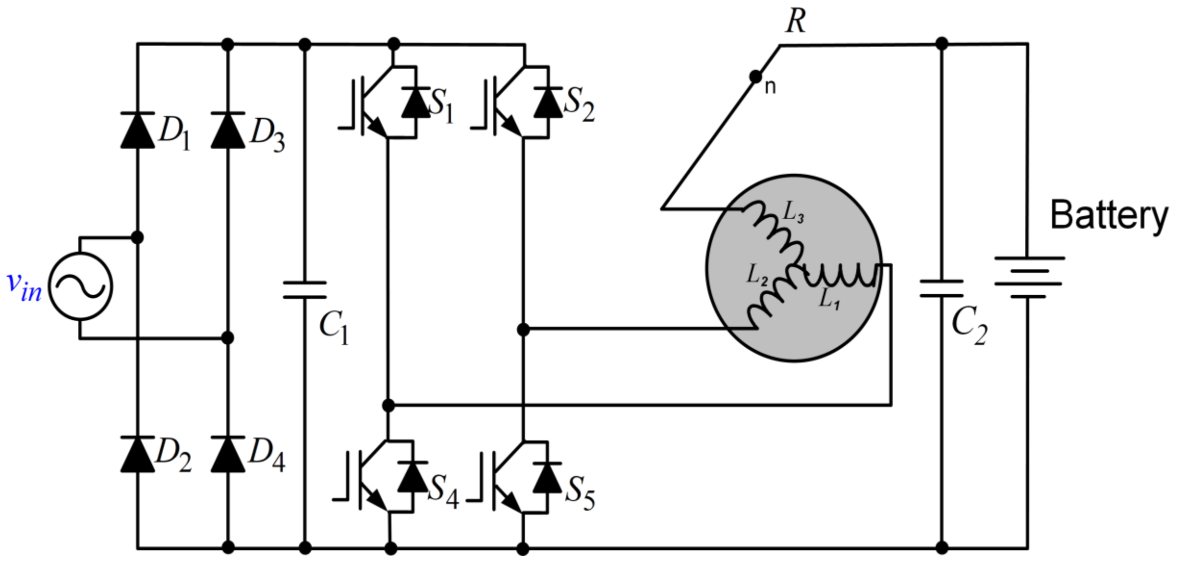
Vehicle Charging Mode

01. AC to DC rectification stage to regulate DC link voltage

02. Switch *R* connected at point n

03. Switches S_3 and S_4 stay in the OFF position

04. Switches S_1, S_2, S_4 *and* S_5 operate according to the charging operational mode



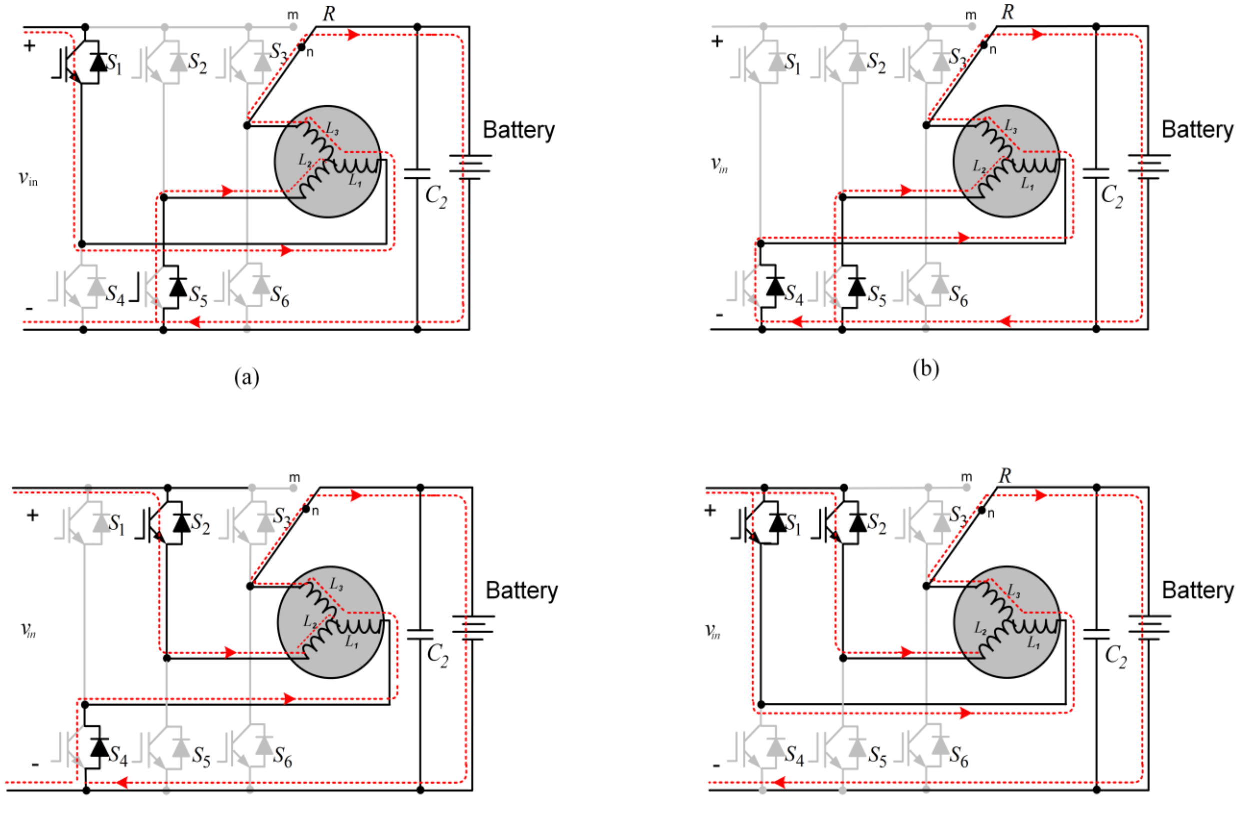
Modes of Operation

01. The charger operates based on an interleaved buck converter

02. The operational modes are categorized into four distinct modes

03. Sequential order for duty cycle less than 0.5 is I, II, III and II

04. For a duty cycle greater than 0.5, the sequential order is IV, I, IV and III



(a) (b) (c) (d)

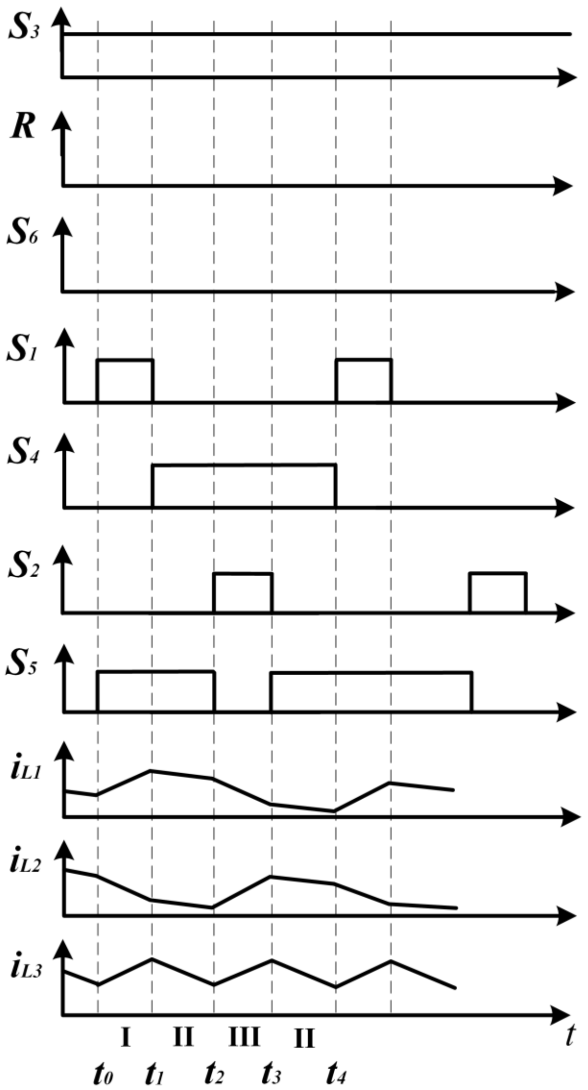
Modes of Operation

01. S_6 is OFF throughout the charging operation

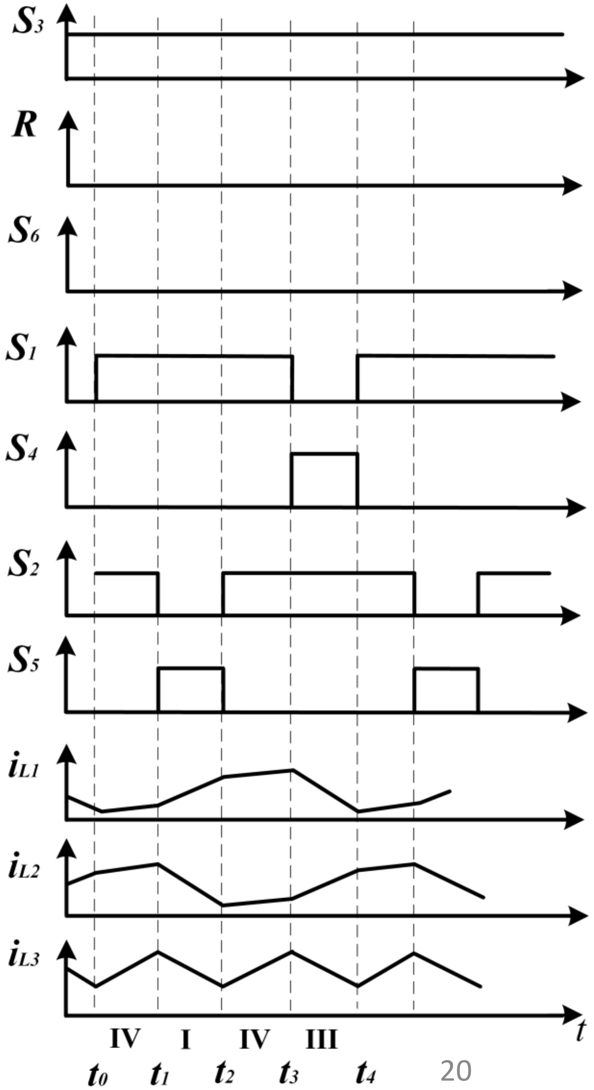
02. S_1 and S_2 form the interleaving network

03. Two distinct steady-state operations: $0 < D < 0.5$, for $V_o < 2v_{in} < 2V_o$ and $0.5 < D < 1$, for $V_o > 2v_{in}$

04. A mode repeats in the charging cycle depending on the duty cycle

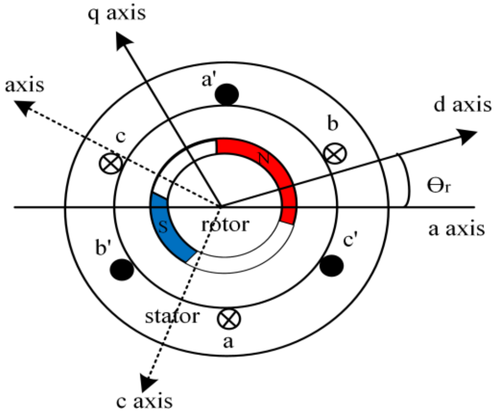


a. Less than 0.5

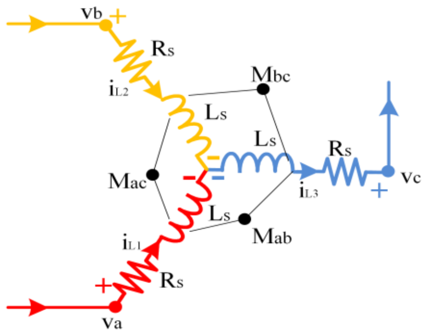


b. Greater than 0.5

Mathematical Modeling



(a)



(b)

01.
$$v_a = Ri_a + L_{eq}\frac{di_a}{d_t}$$
$$v_b = Ri_b + L_{eq}\frac{di_b}{d_t}$$
$$v_c = Ri_c + L_{eq}\frac{di_c}{d_t}$$

02.
$$v_d = R_s i_d + L_d\frac{di_d}{d_t} - N\omega i_q L_q$$
$$v_q = R_s i_q + L_q\frac{di_q}{d_t} + N\omega(i_d L_q + \Phi_m)$$
$$v_o = R_s i_o + L_o\frac{di_o}{d_t}$$

03.
$$T_r = \frac{3}{2}N(i_q(i_d L_d + \Phi_m) - i_d i_q L_q)$$

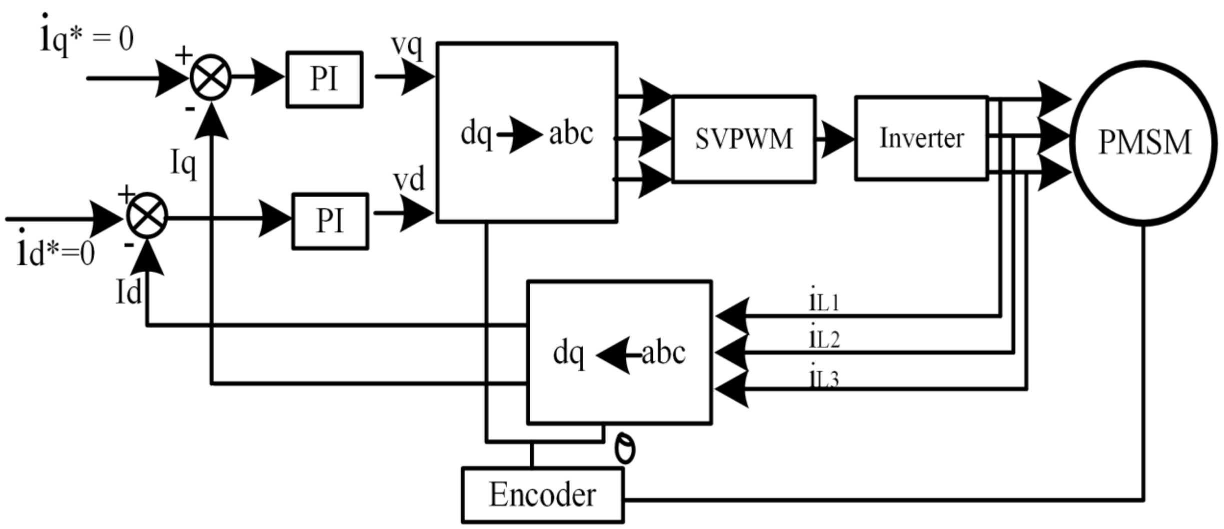
Torque Cancellation

01. The i_q current impacts the torque generated

02. The i_q current is controlled using Field Oriented Control as shown in the diagram

03. The i_q current is set to zero to generate zero torque

04. $\tau = \frac{3}{2}N\left(i_q(i_d L_d + \psi_m) - i_d i_q L_q\right) = 0$



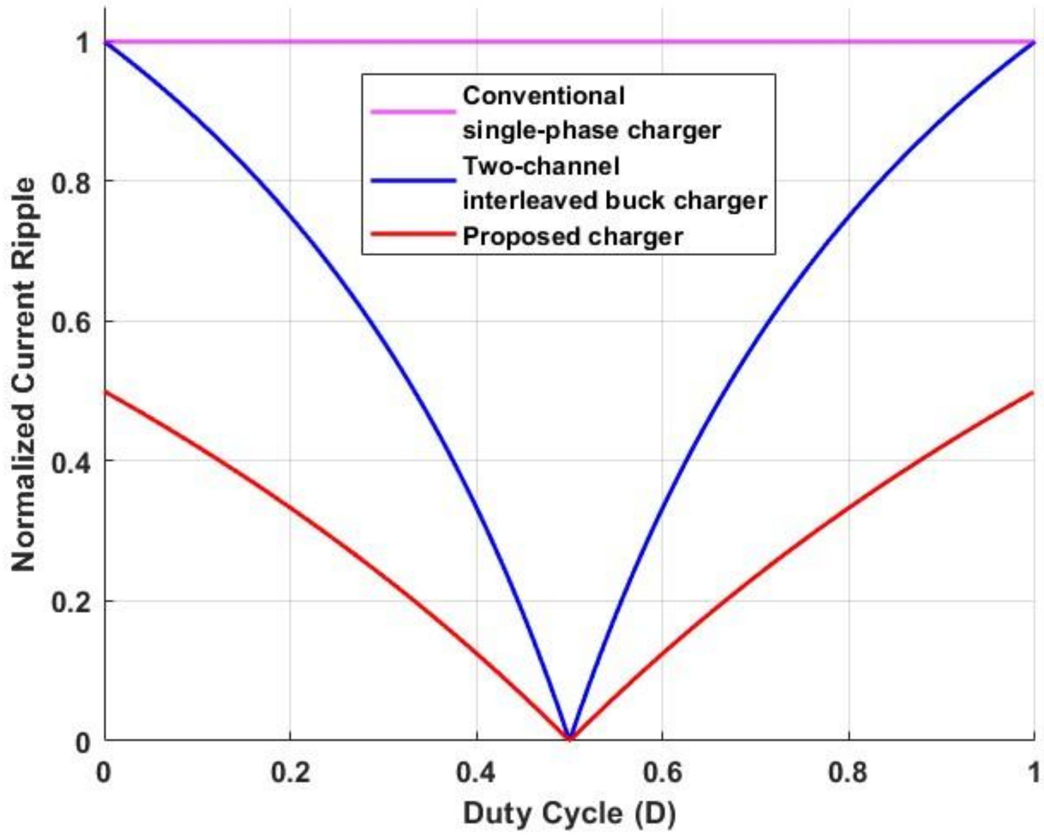
Output Current Ripple Analysis

01. High ripple stresses the battery and electrolytic capacitor

02. Ripples increase EMI, reduce charger lifespan

03. Winding ripples partially cancel out at the output

04. Lower motor winding ripple means smaller filter size, reducing losses



Component Design

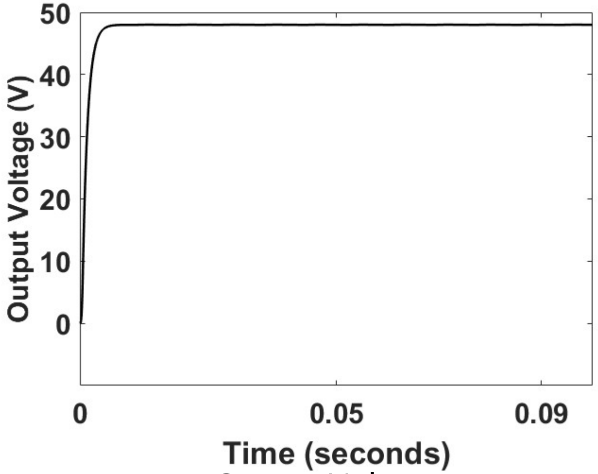
01. *Switches* S_1 , S_2, S_4 and S_5 are selected based on their voltage and current stress (V_{DC} & $I_o/2$)

02. *Switches* S_6 and S_3 *based on* V_o *and* $V_{DC} - V_o$, respectively

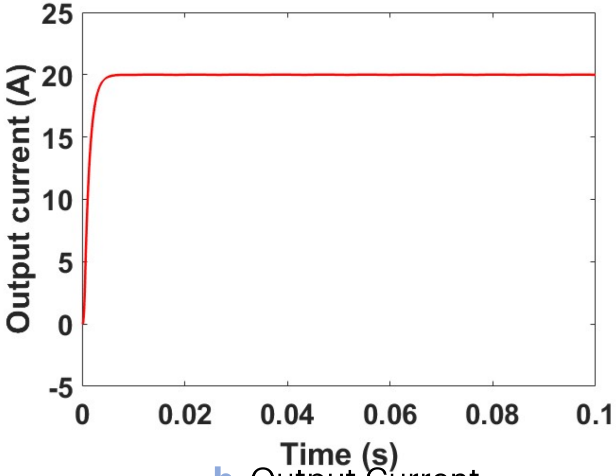
03. Input and output capacitors: $C_1 = \frac{DI_o}{f_l \Delta V_{DC}}$; $C_2 = \frac{P_{max}}{2\Delta V_{out} .\omega .V_o}$

04. Equivalent inductance and resistance: $L_{eq} = \frac{V_{DC}.(1-D)}{i_{o_{rip}}.f_s}$; $R \le \frac{P_{max}(1-\eta)}{\eta.D^2 I_o^2}$

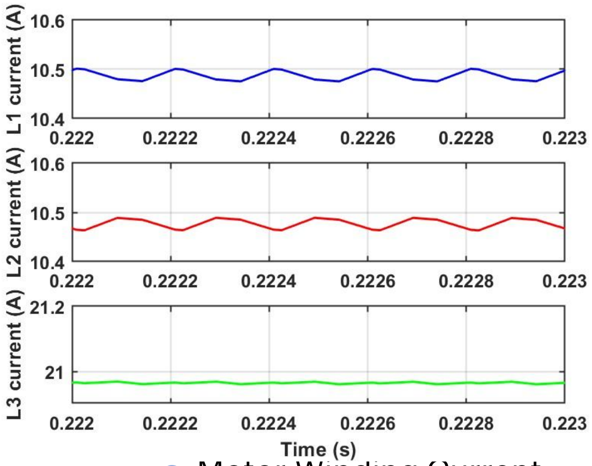
Simulation Results



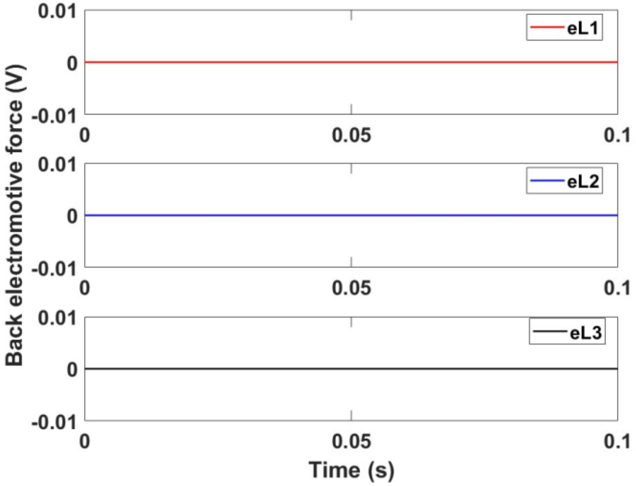
a. Output Voltage



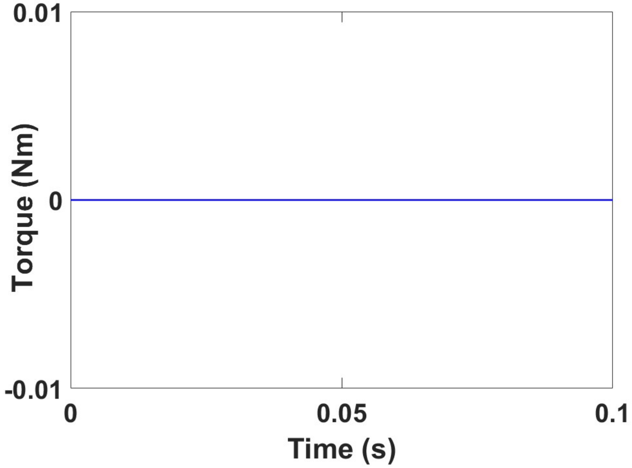
b. Output Current



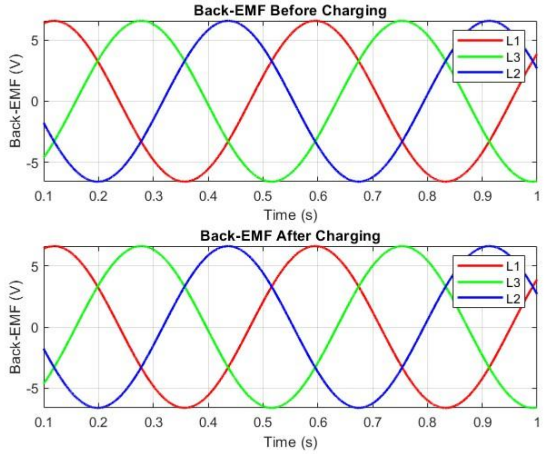
c. Motor Winding Current



d. Back emf in charging mode



e. Motor Torque



f. Driving mode back EMF before and after charging

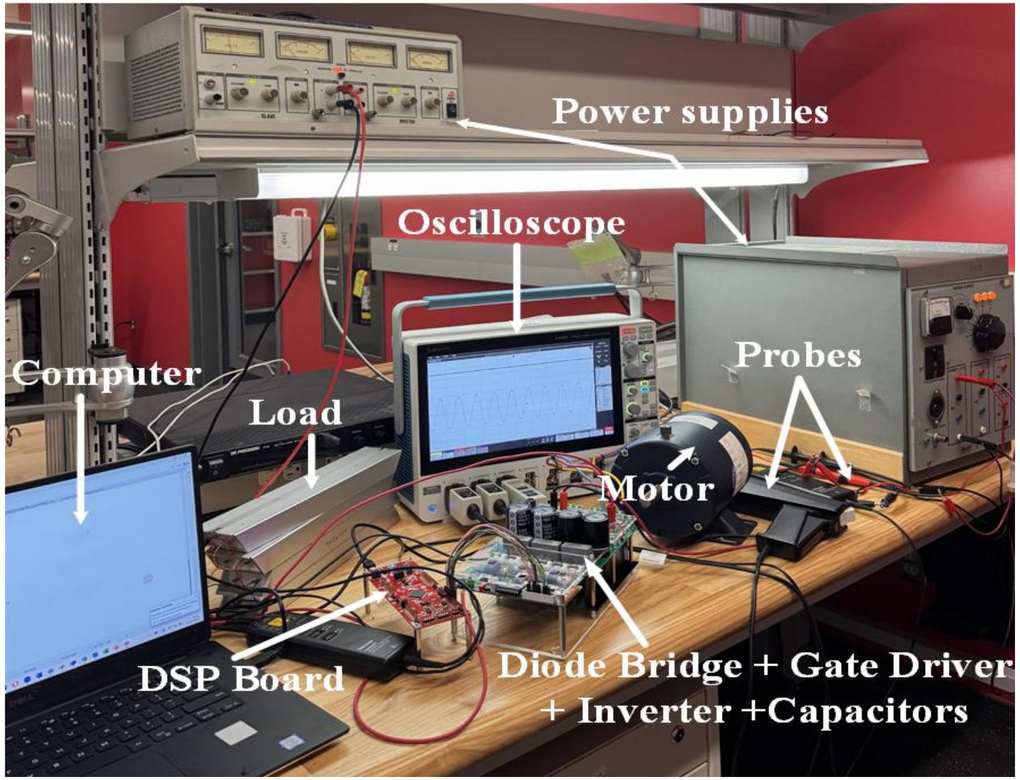
Experimental Setup

01. Made up of an AC power supply, an inverter, a diode bridge rectifier, an ACS712 current sensor

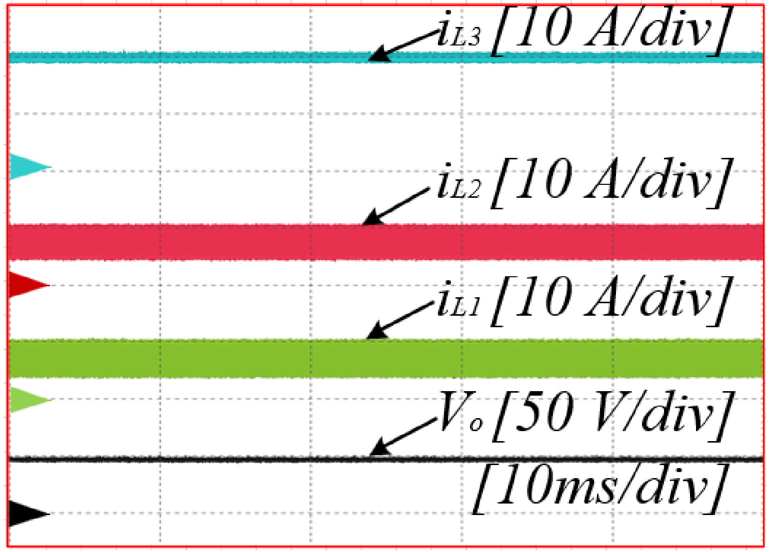
02. Also has a voltage divider network, a PMSM, two capacitors and a TMS320F280049C microcontroller.

03. Motor parameters: 3kW rated power, 4 pole pairs, 0.5-ohm resistance, 2mH equivalent inductance

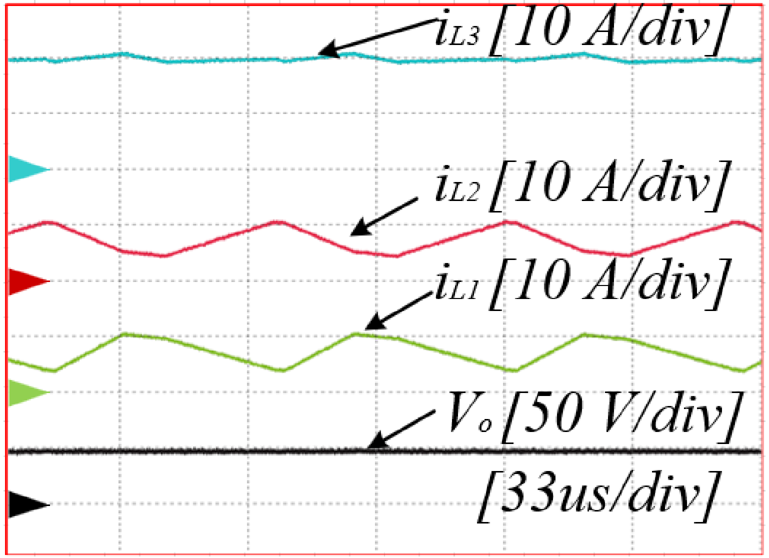
04. Data acquisition via Oscilloscope



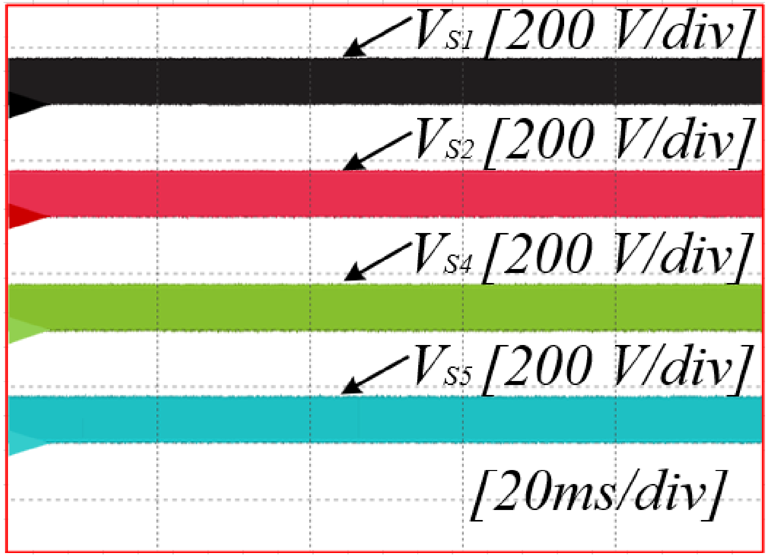
Experimental Results



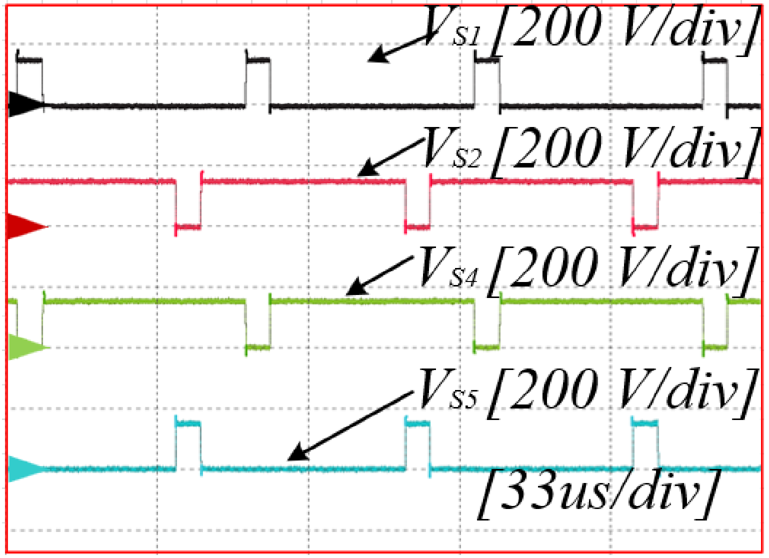
a. Winding currents and output voltage(Zoomed out)



b. Winding currents and output voltage (Zoomed in)

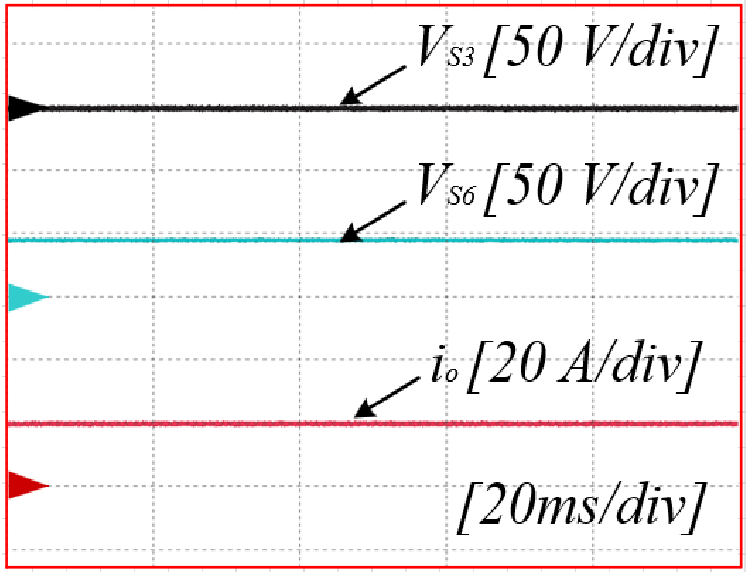


c. Switches voltage stress (Zoomed out)

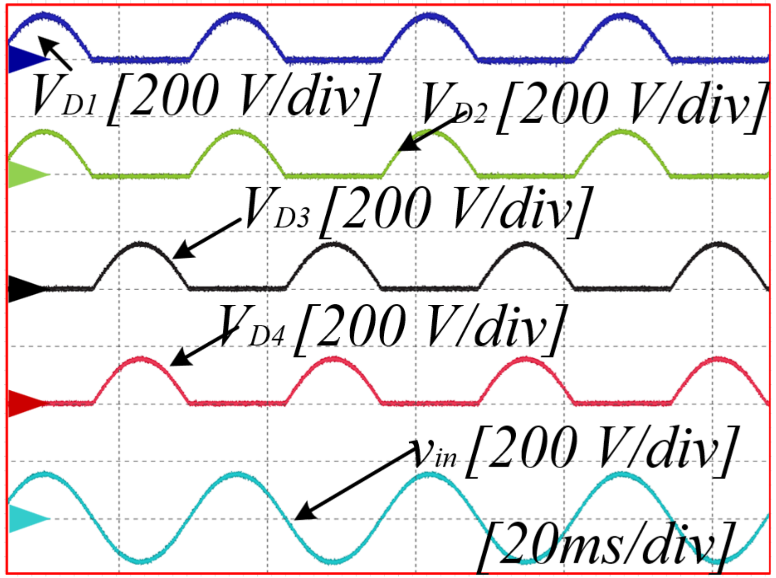


d. Switches voltage stress (Zoomed in)

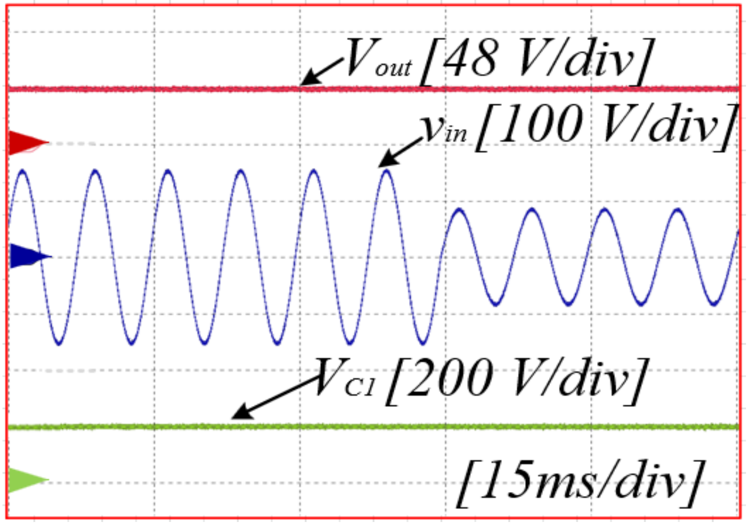
Experimental Results



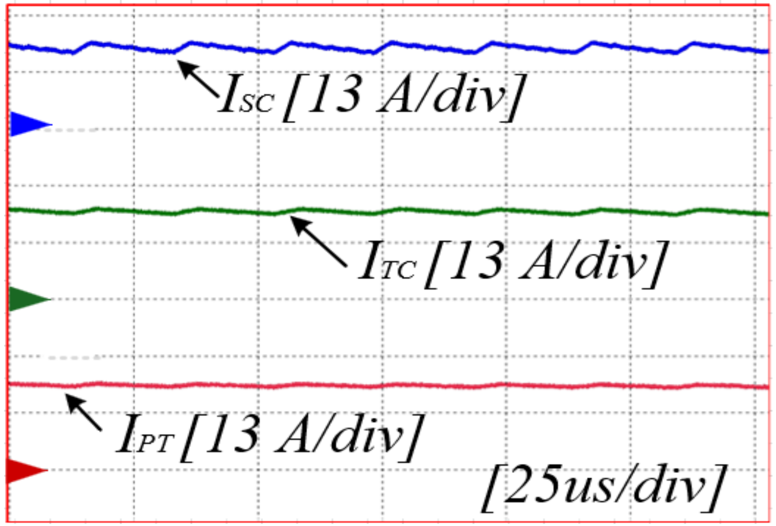
a. Switches voltage stress and output current



b. Input and diode voltages



c. Step change and its effect



d. Output current ripple comparison

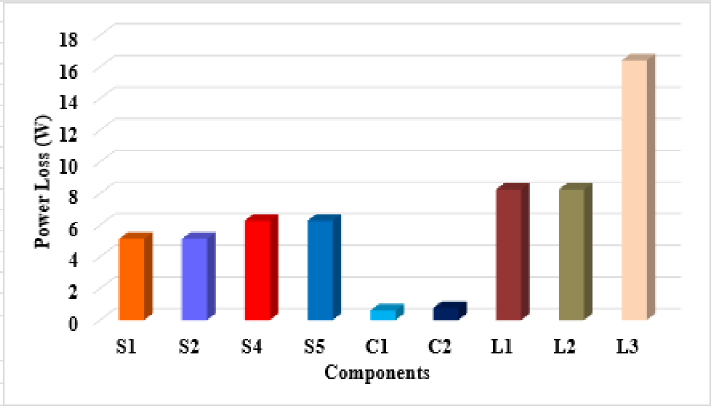
Power Loss Analysis

01. Switching losses resulting from the ON and OFF turning of the switches

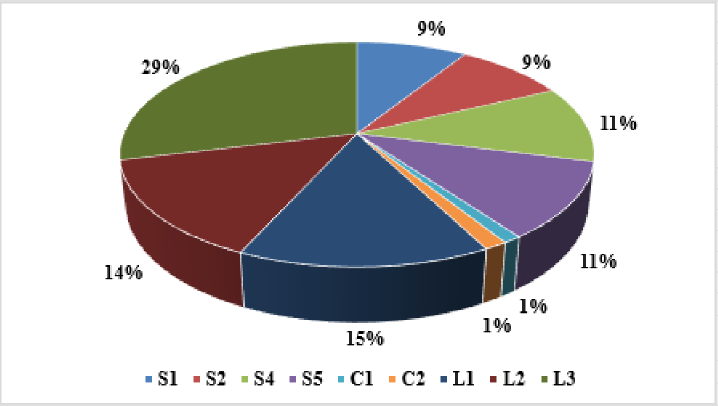
02. Conduction Losses resulting from the motor windings and the switches

03. Core Losses resulting from only the motor windings

04. Efficiency of 94% at rated power



(a)



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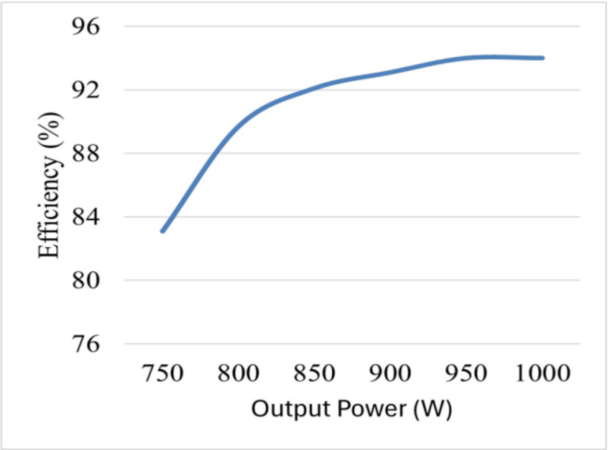


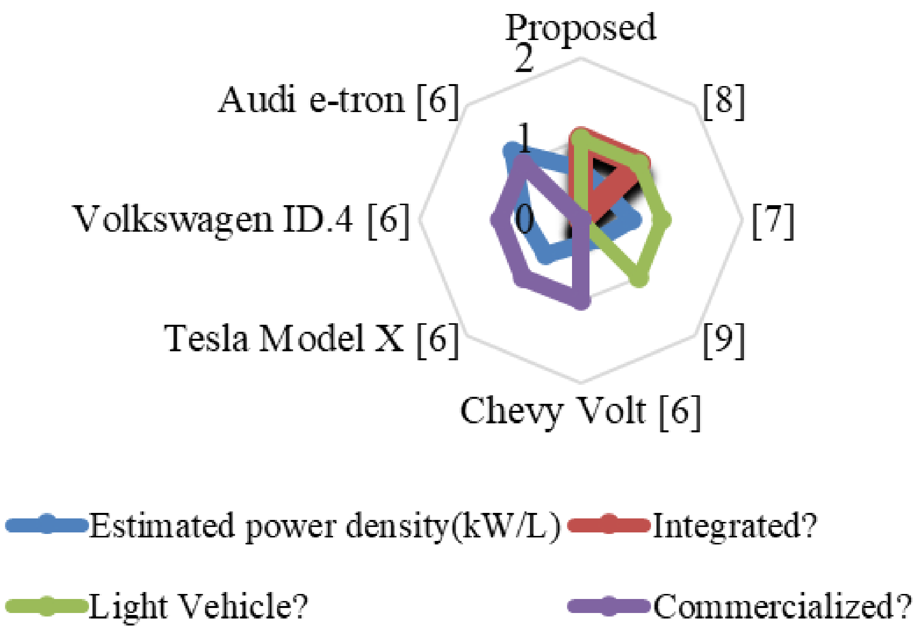
Comparison with Existing Chargers

01. Fewer components used.

02. High power density

03. Comparison made to assess the power density of integrated and non-integrated

04. Comparison made to assess the topology with other existing chargers for light, medium and heavy-duty EVs



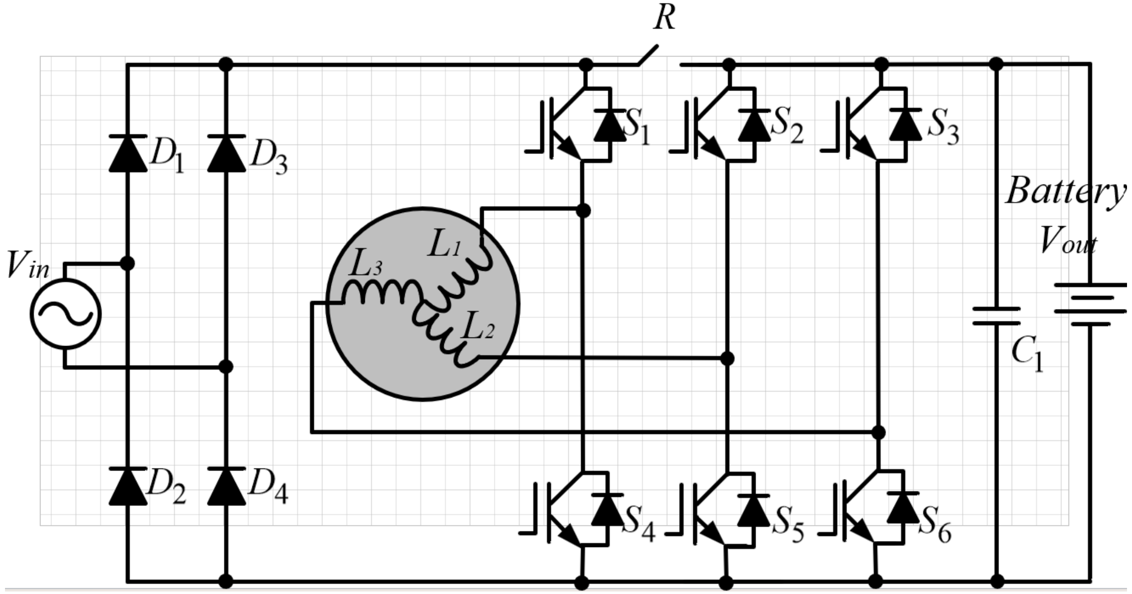
The Proposed Charger II

01. What if we could use the vehicle's drivetrain system to do the charging?

02. Dual-purpose use of PMSM as interleaved coupled inductors

03. Comprises a single-phase AC input, diode bridge, and interleaved boost PFC.

04. Has zero torque, high power factor, minimized hardware, and reduced current ripples.



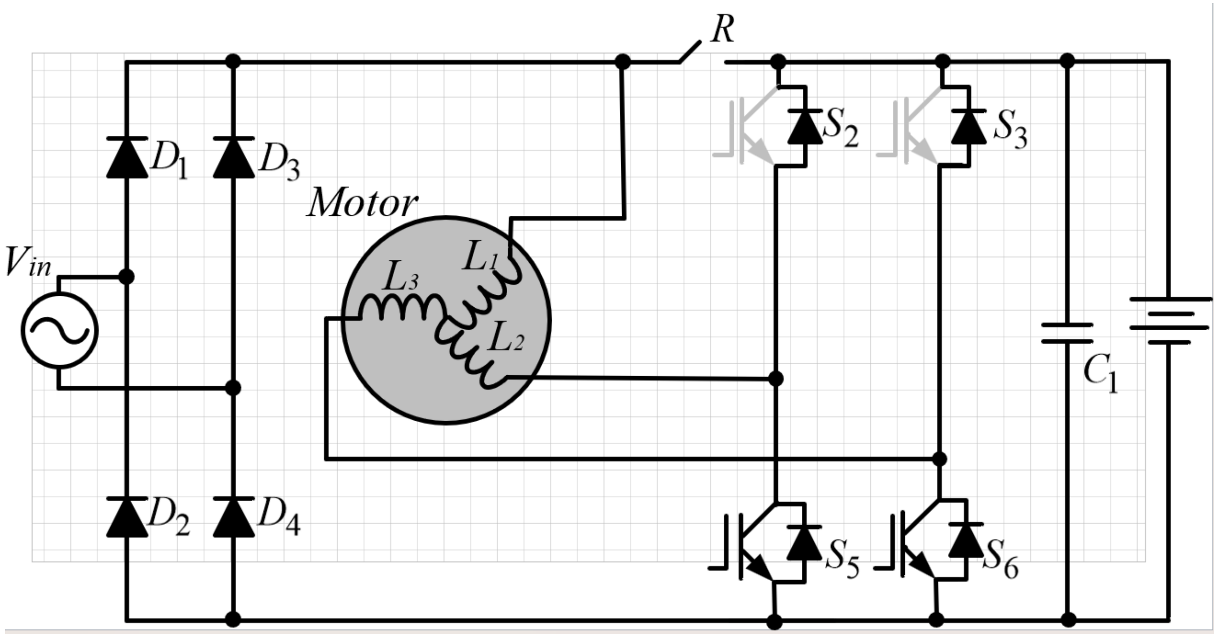
Vehicle Charging Mode

01. AC to DC rectification stage for PFC and DC link voltage regulation

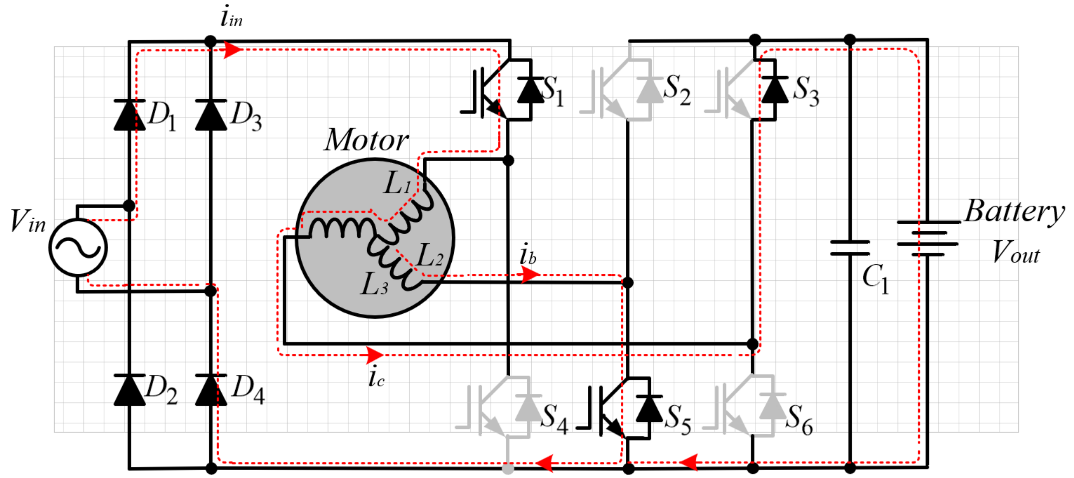
02. Switch *R* is opened throughout the operation

03. Switch S_1 stays ON, while S_4 goes OFF completely

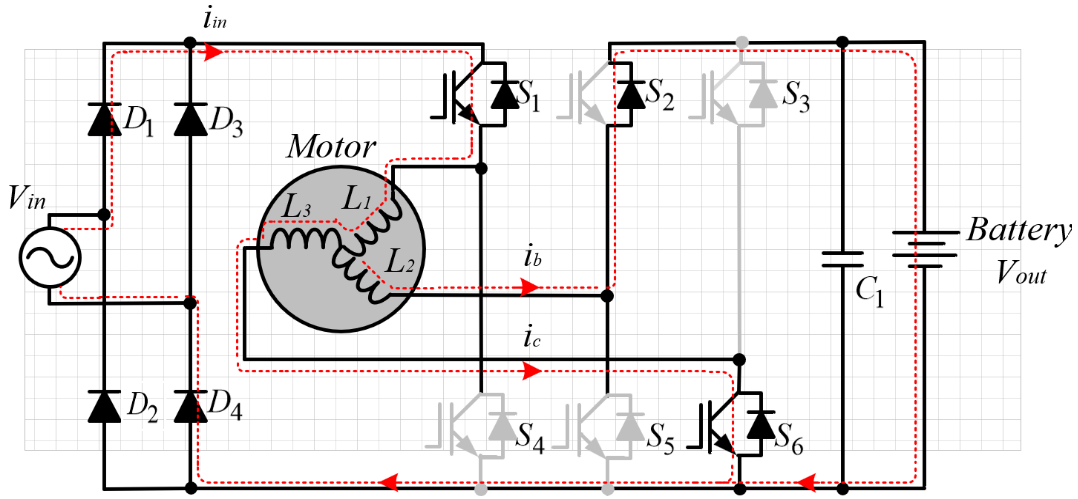
04. Switches S_2, S_3, S_5, S_6 operate according to the charging operational mode



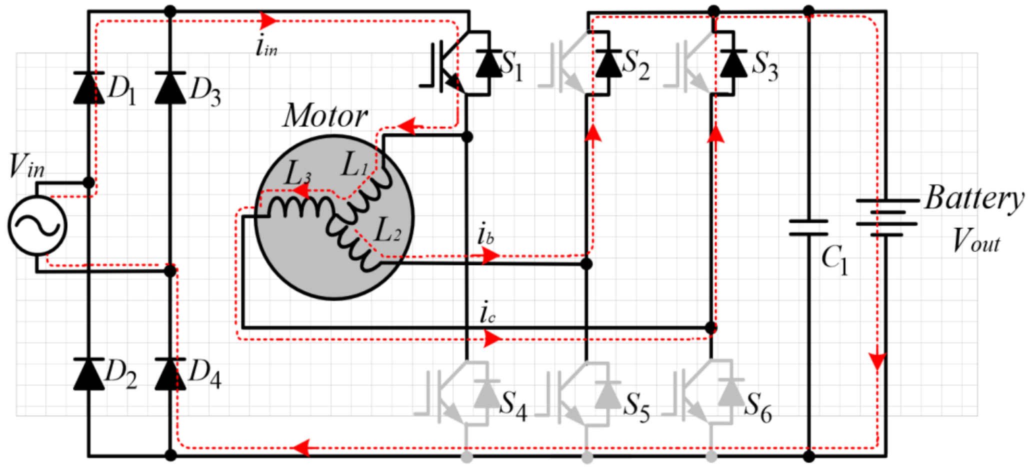
Modes of Operation



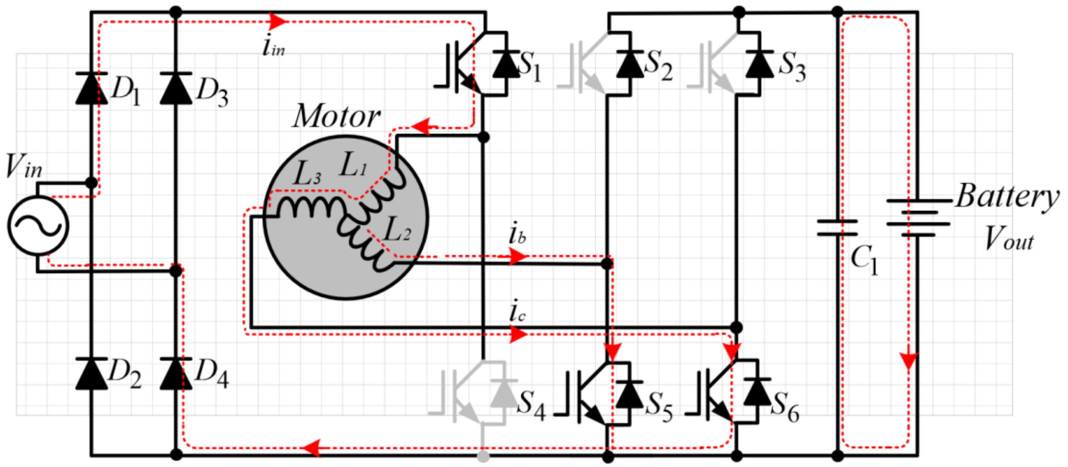
a. Mode I



b. Mode II



c. Mode III



d. Mode IV

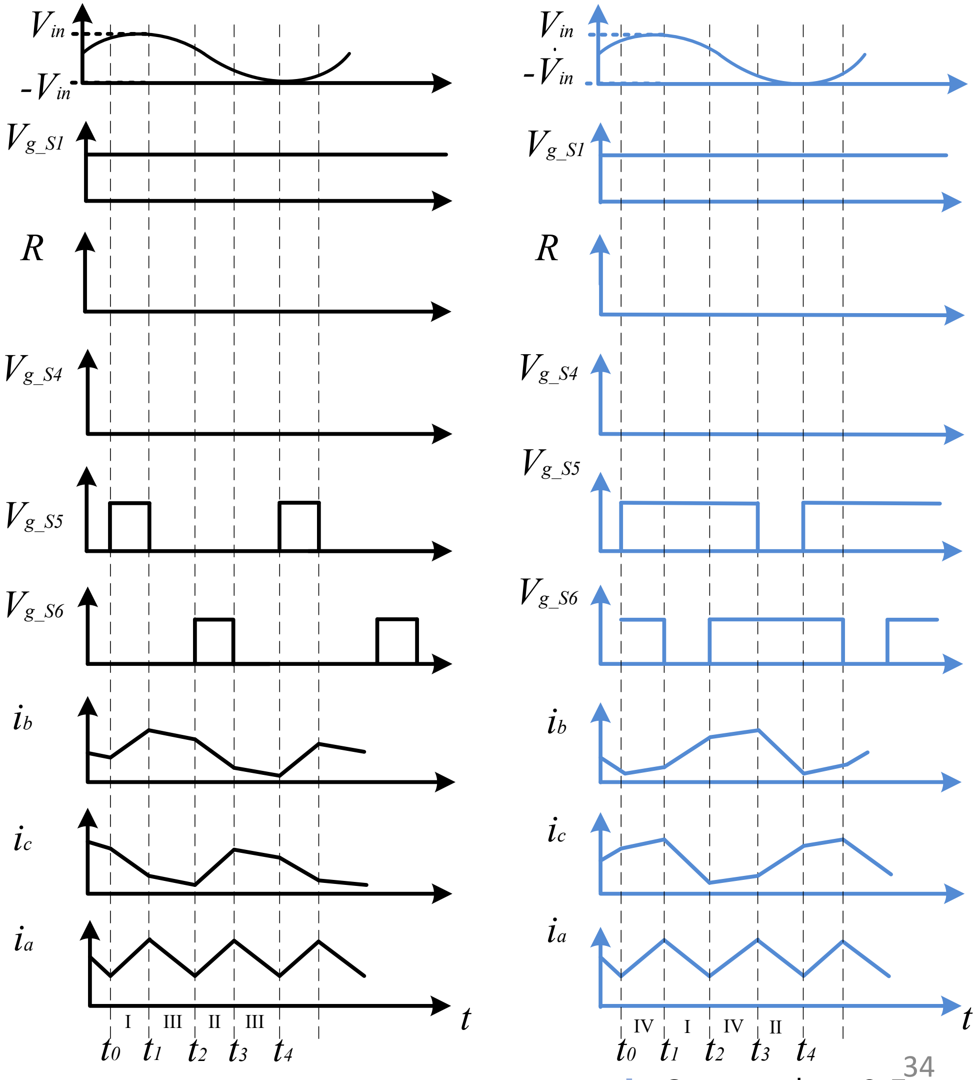
Modes of Operation

01. S_1 is ON while S_4 is OFF throughout the charging operation

02. S_5 and S_6 form the interleaving network

03. Two distinct steady-state operations: $0 < D < 0.5$, for $V_o < 2v_{in} < 2V_o$ and $0.5 < D < 1$, for $V_o > 2v_{in}$

04. A mode repeats in the charging cycle depending on the duty cycle



a. Less than 0.5 **b.** Greater than 0.5

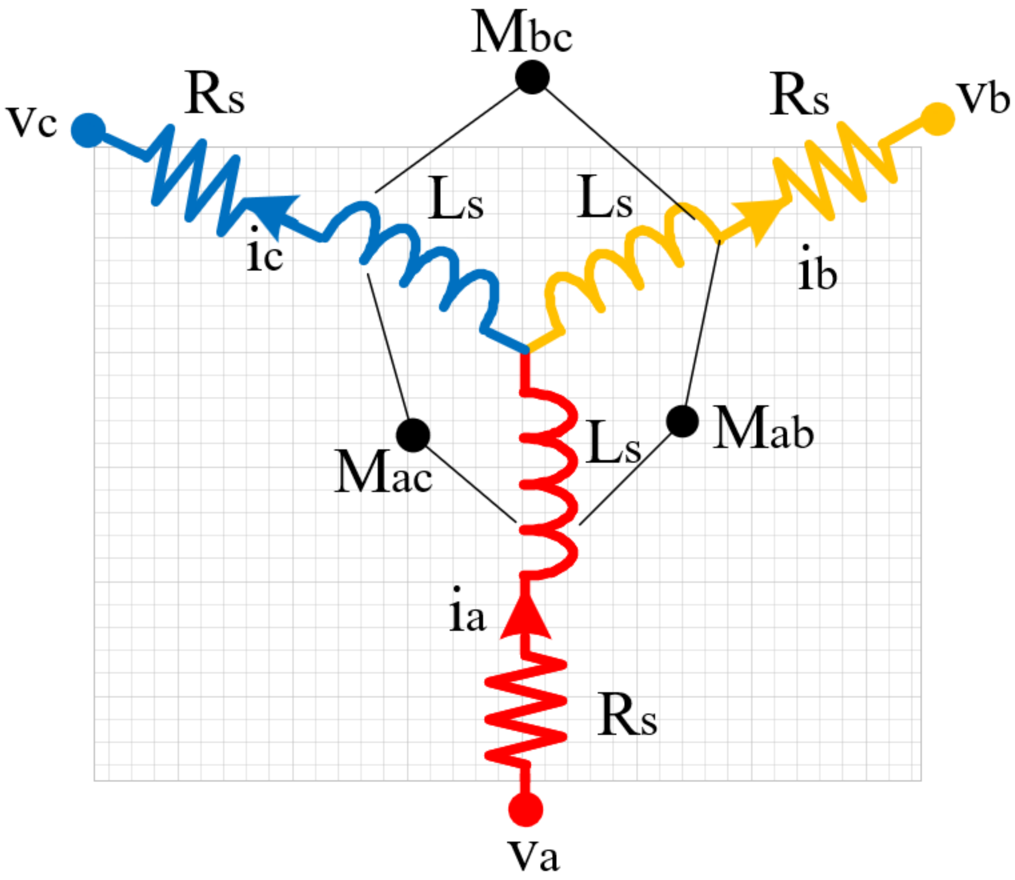
Mathematical Modeling

01. Modeling is based on electrical, back-emf, torque and mechanical models.

02. Assumptions are made to model the PMSM as a coupled inductor

03. Mathematical analysis done in d-q frame for accuracy and simplification

04. Direct and quadrature axes inductance are the same for a round rotor



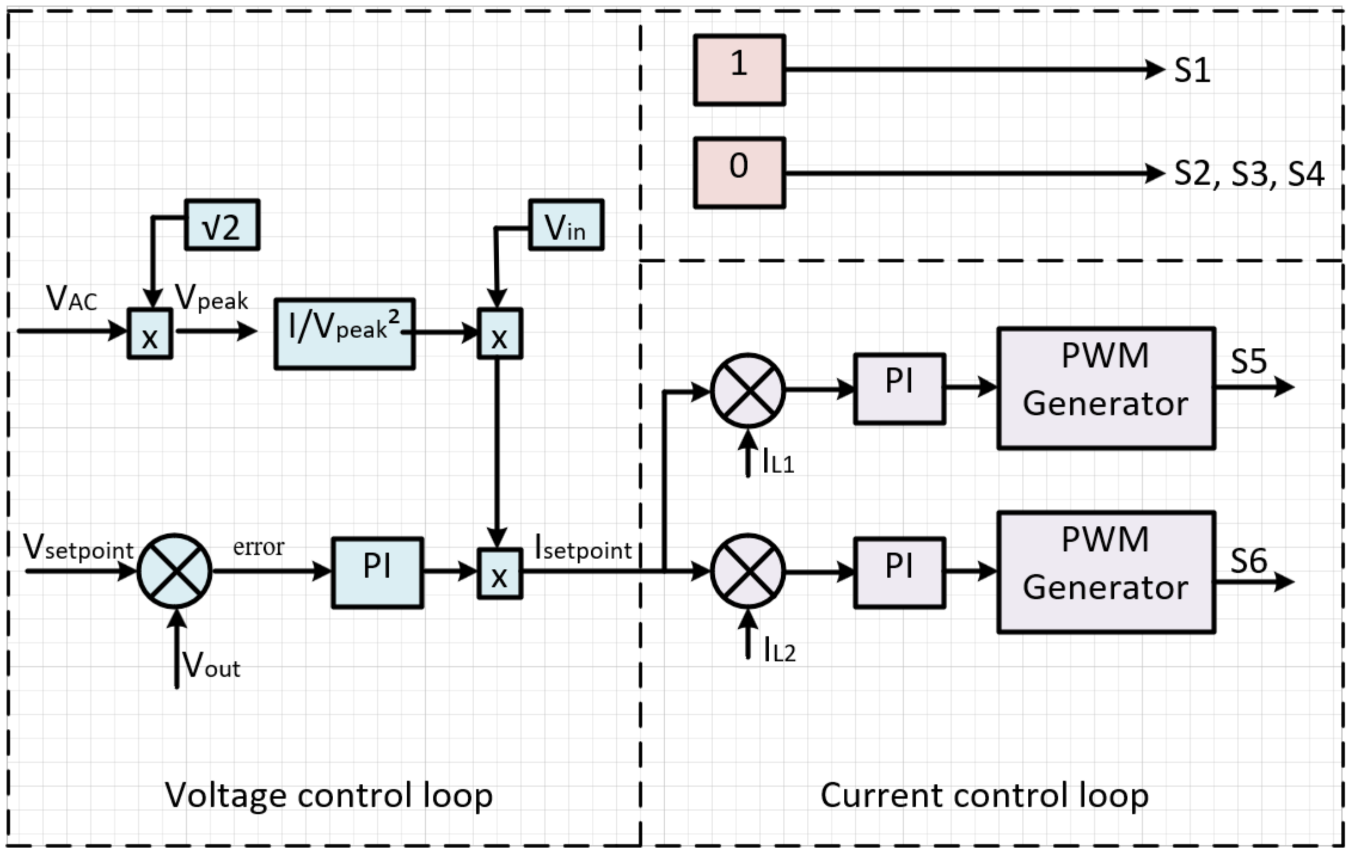
Battery Charging Control

01. The control of the PFC boost charger configuration regulates output voltage

02. Control consists of voltage and current loops

03. Three PI blocks compensate for the errors from the compensation

04. S_1 is turned ON, while S_2, S_3 and S_4 are turned OFF

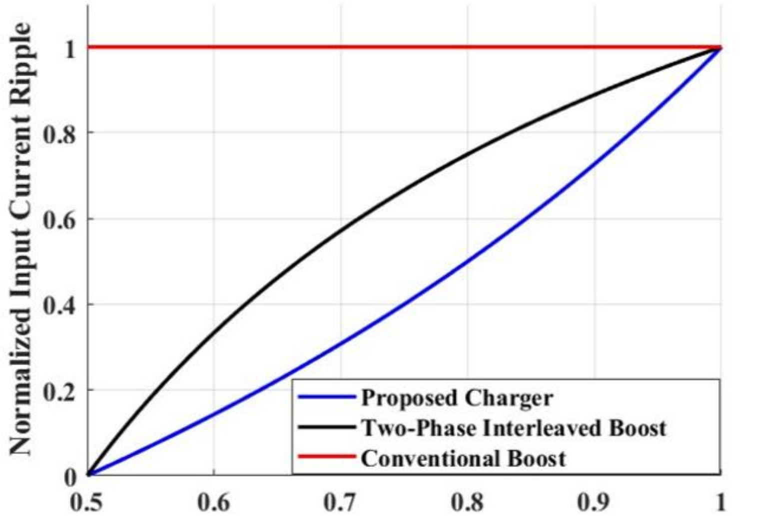


Output Current Ripple Analysis

01. Maximum and minimum input current ripple for $0 < D \leq 0.5$

$$I_{in_{\min}} = V_{in}\left[\frac{1}{(1-2D+D^2)R_L} - \frac{D(1-2D)}{6(1-D)L_{eq}}\left(\frac{1}{f_s}\right)\right]$$

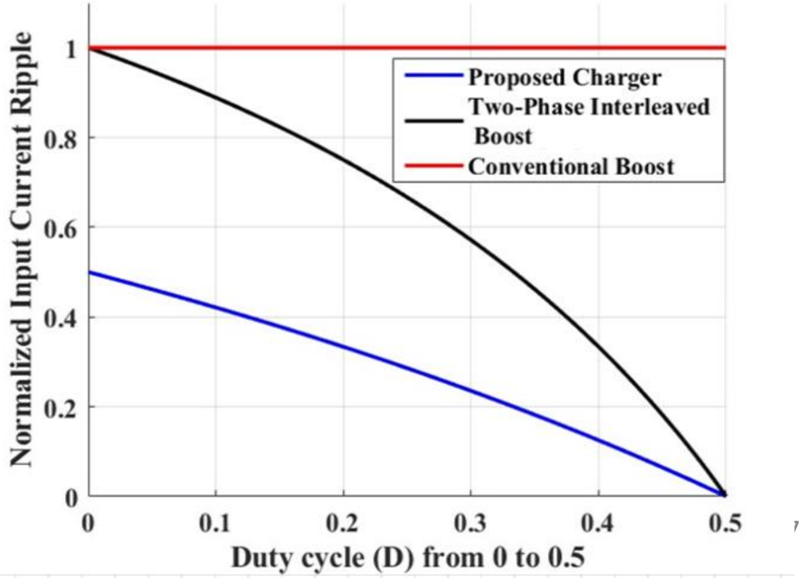
$$I_{in_{max}} = V_{in}\left[\frac{1}{(1-2D+D^2)R_L} + \frac{D(1-2D)}{6(1-D)L_{eq}}\left(\frac{1}{f_s}\right)\right]$$



02. Maximum and minimum input current ripple for $0.5 < D \leq 1$

$$I_{in_{min}} = V_{in}\left[\frac{1}{(1-2D+D^2)R_L} - \frac{2D-1}{6L_{eq}}\left(\frac{1}{f_s}\right)\right]$$

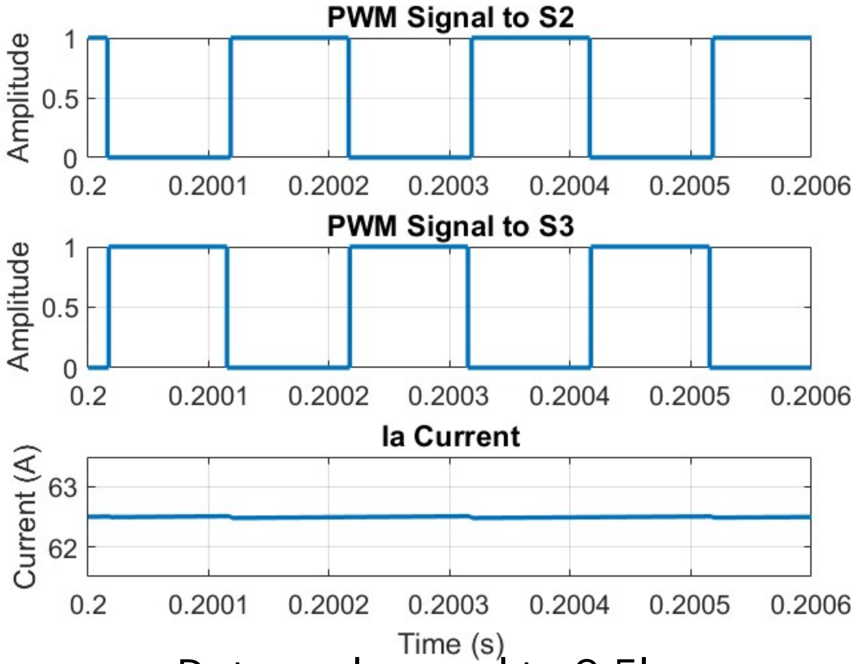
$$I_{in_{max}} = V_{in}\left[\frac{1}{(1-2D+D^2)R_L} + \frac{2D-1}{6L_{eq}}\left(\frac{1}{f_s}\right)\right]$$



Simulation Results

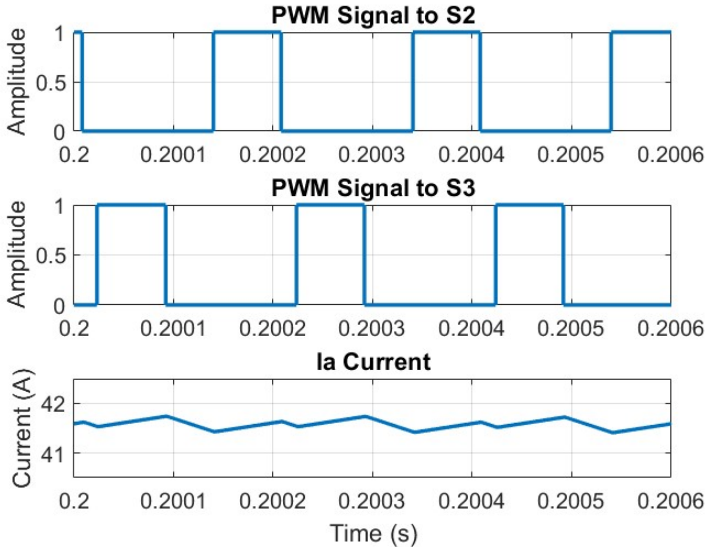
01. Made Ripple present for D greater than 0.5 and less than 0.5

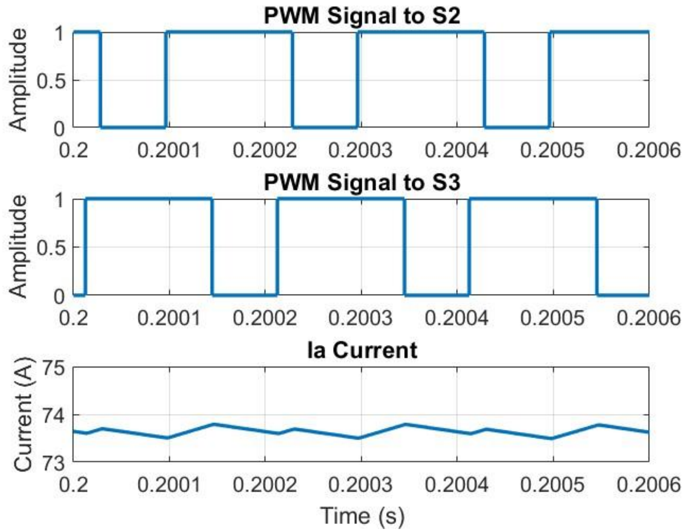
02. At 0.5, only two modes occur, and output current ripple is zero



a. Duty cycle equal to 0.5I

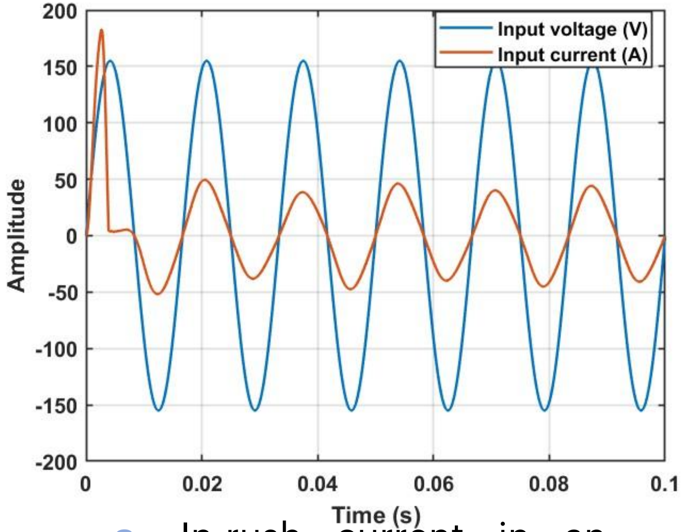
b. Duty cycle less than 0.5



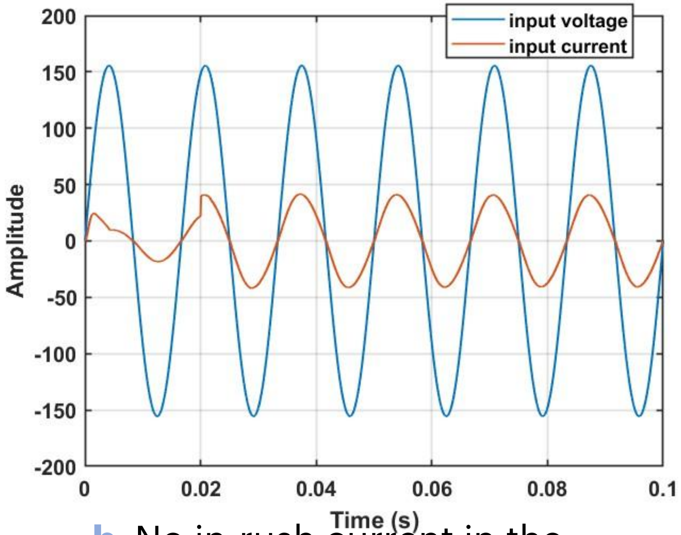


c. Duty cycle greater than 0.5

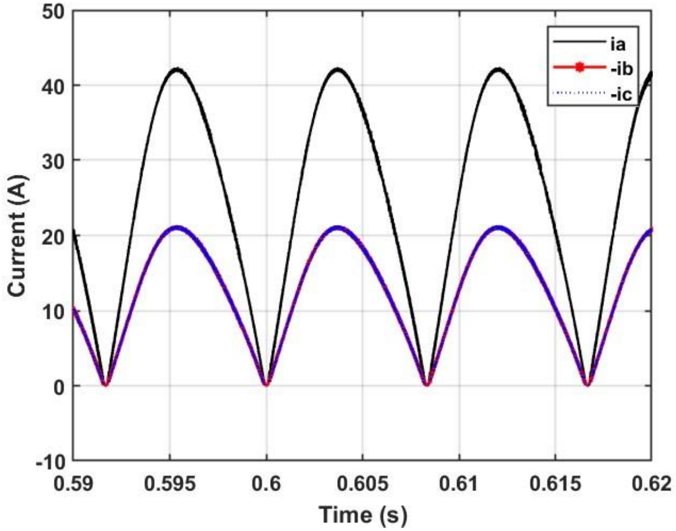
Simulation Results



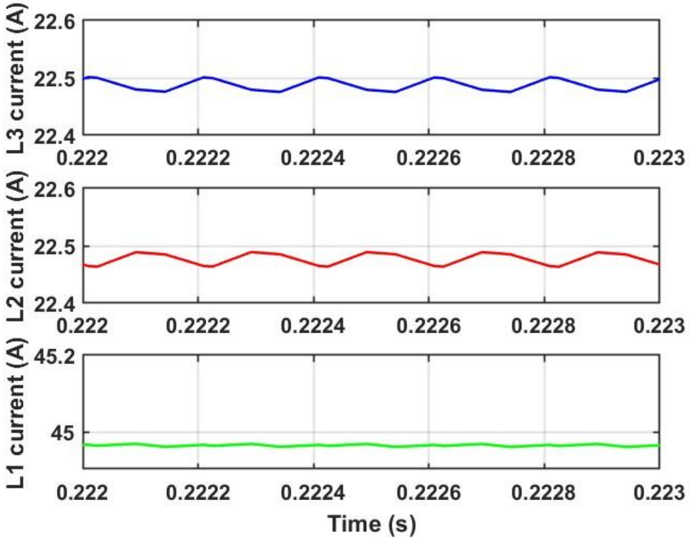
a. In-rush current in an existing model



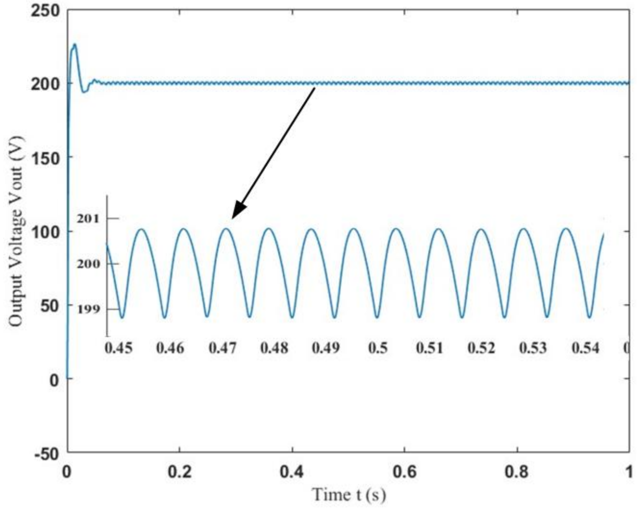
b. No in-rush current in the proposed model



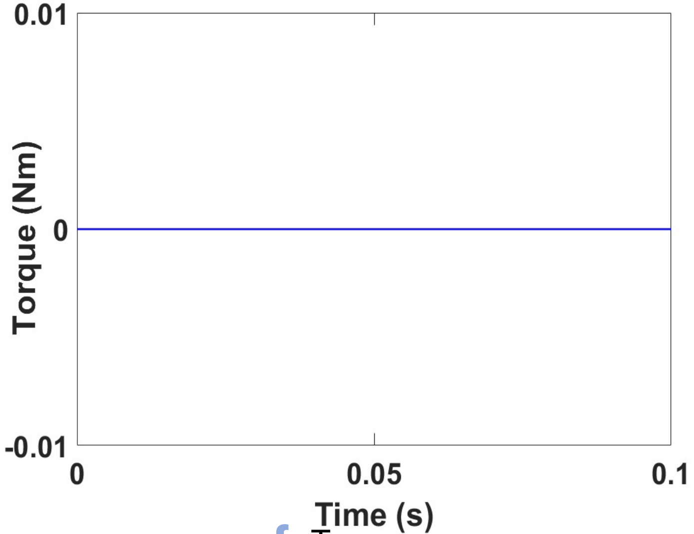
c. Winding currents



d. Winding currents zoomed in



e. Output voltage



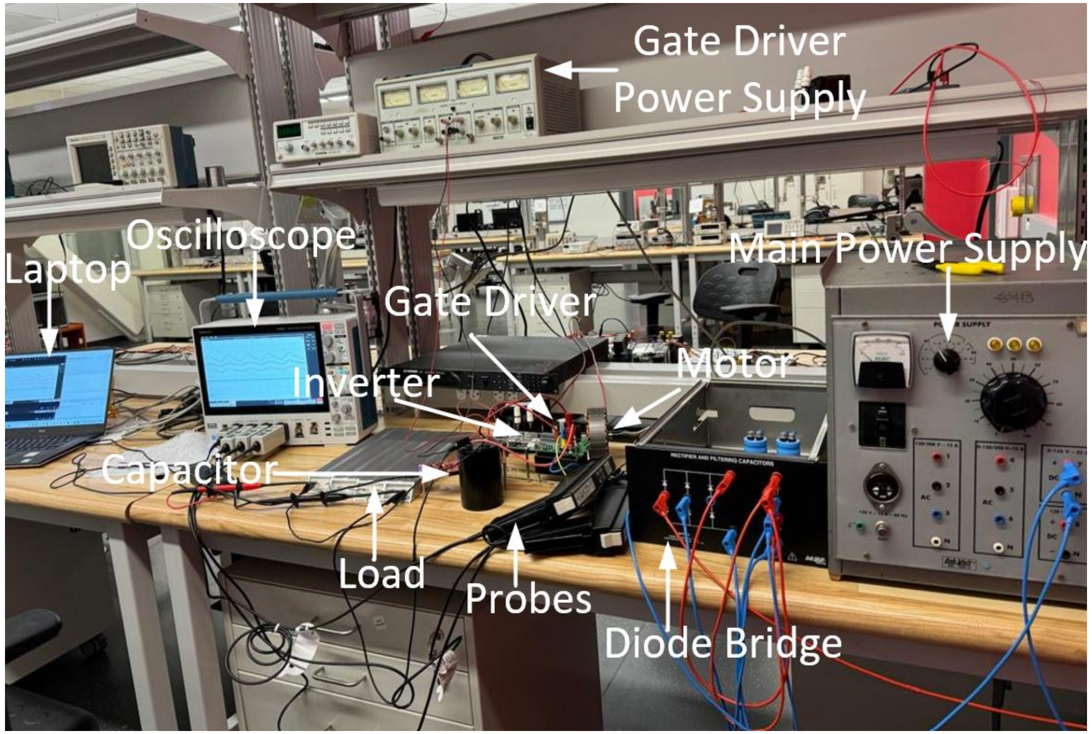
f. Torque

Experimental Setup

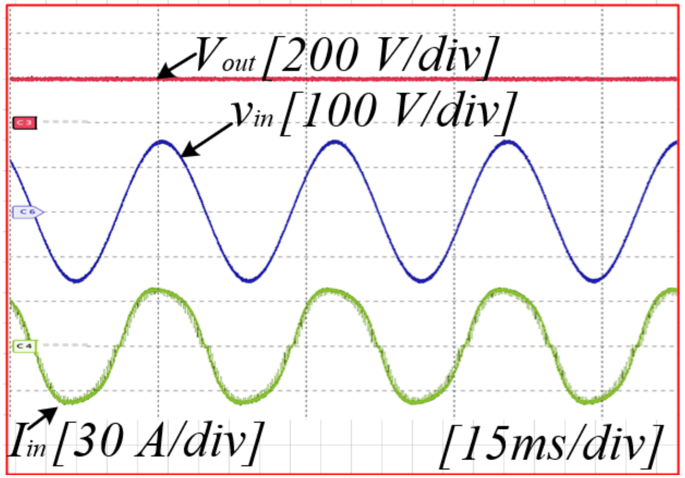
01. Made up of an AC power supply, an inverter, a diode bridge rectifier, an ACS712 current sensor

02. Also has a voltage divider network, a PMSM, two capacitors and a TMS320F280049C microcontroller.

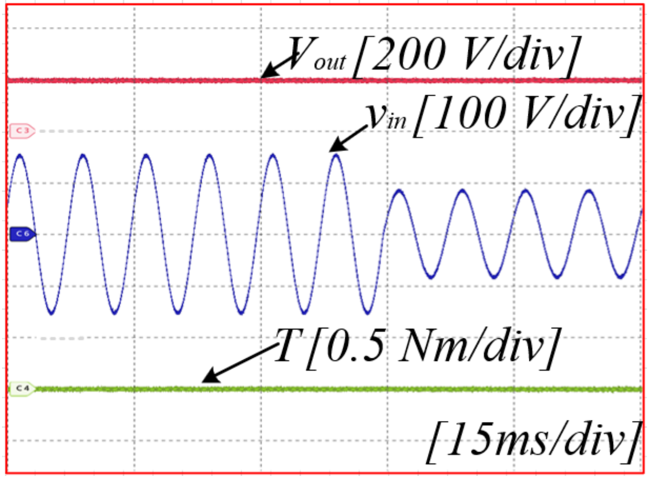
03. Data acquisition via Oscilloscope



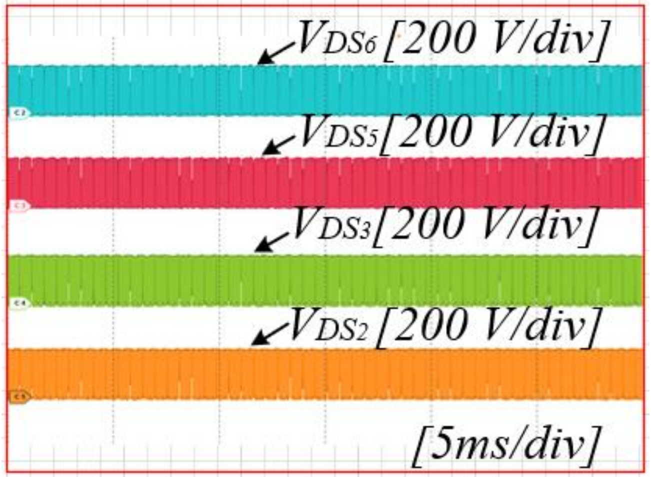
Experimental Results



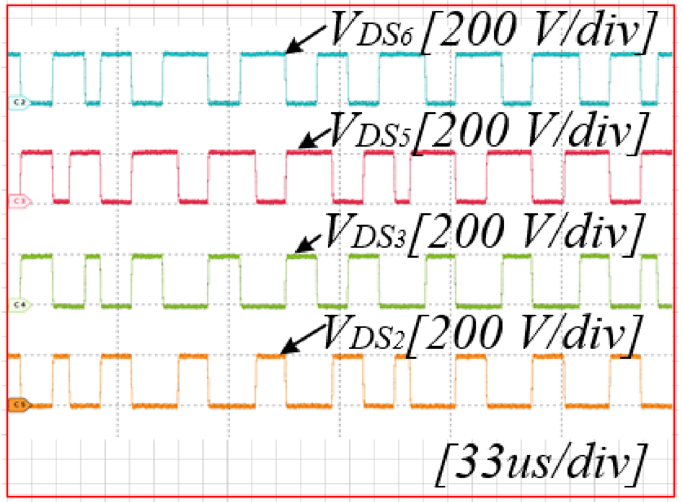
a. PFC



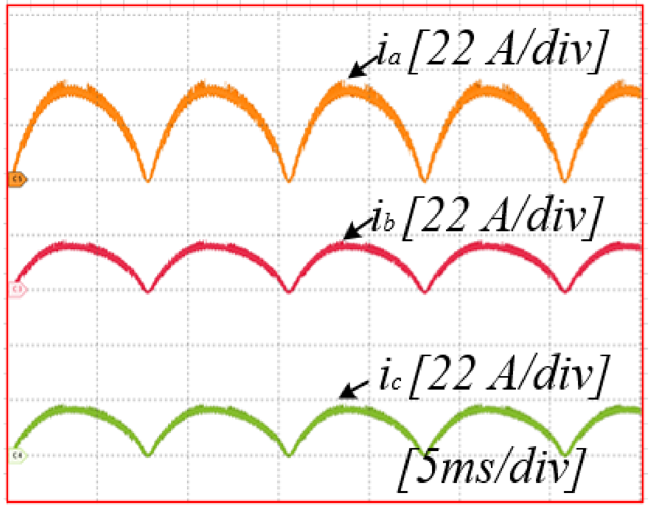
b. Input voltage step change



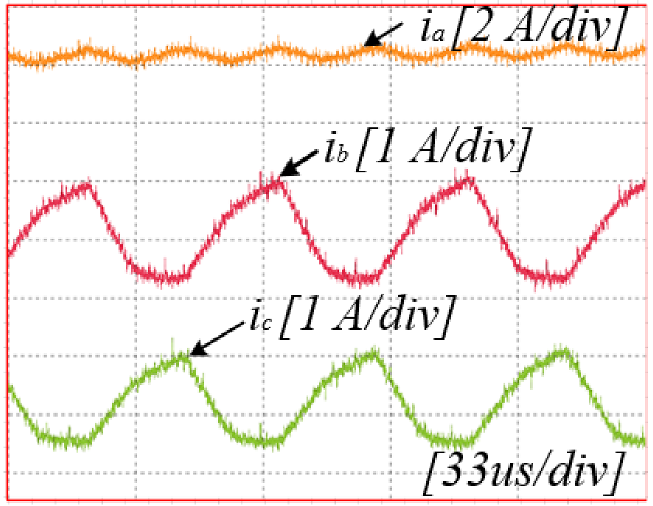
c. Voltage stress on switches (zoomed out)



d. Voltage stress on switches (zoomed in)

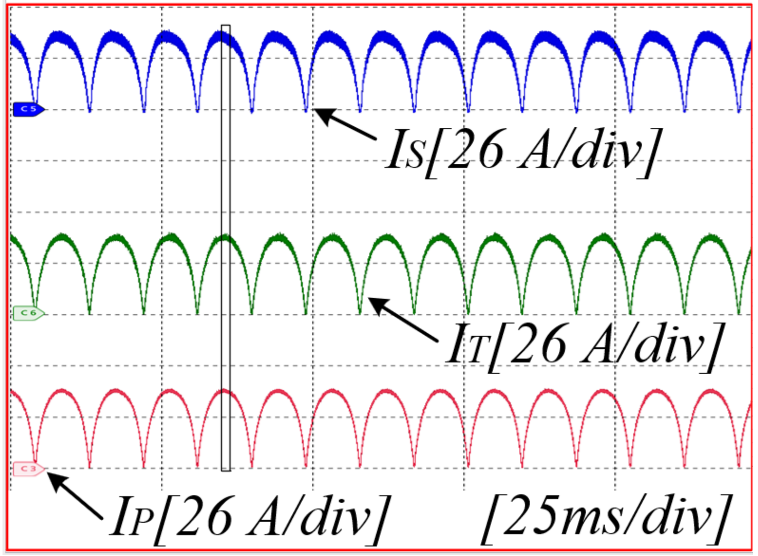


e. Motor winding current (zoomed out)

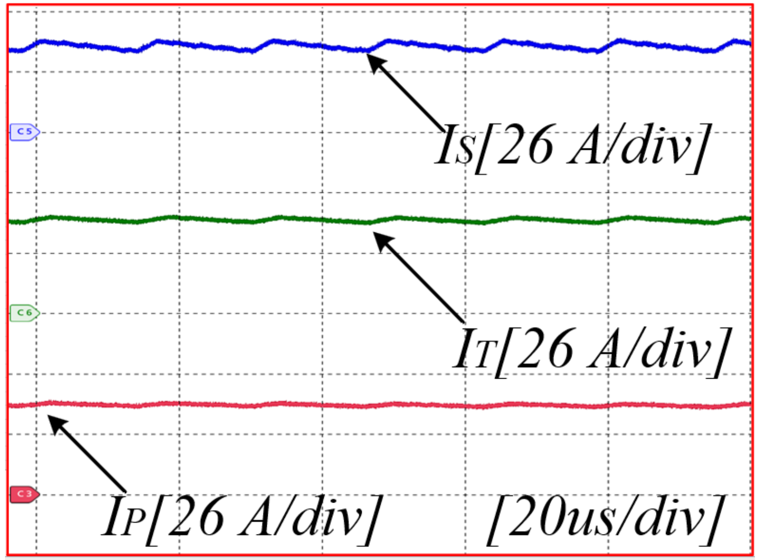


f. Motor winding current (zoomed in)

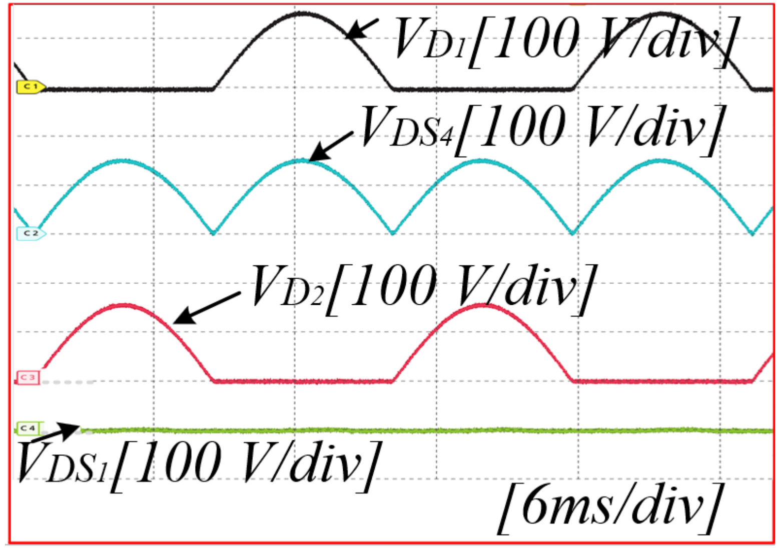
Experimental Results



a. Input Current Ripple Comparison (zoomed out)



b. Input Current Ripple Comparison (zoomed in)



c. Switch Voltage stress and diode voltage

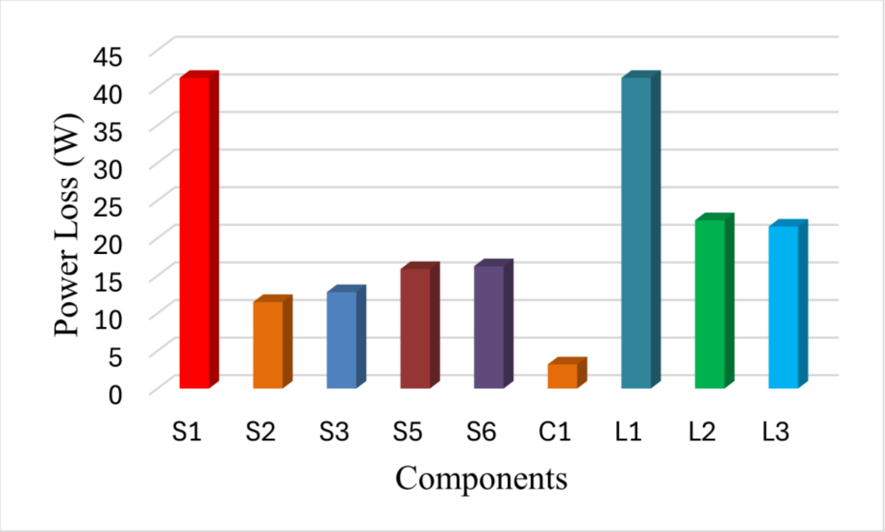
Power Loss Analysis

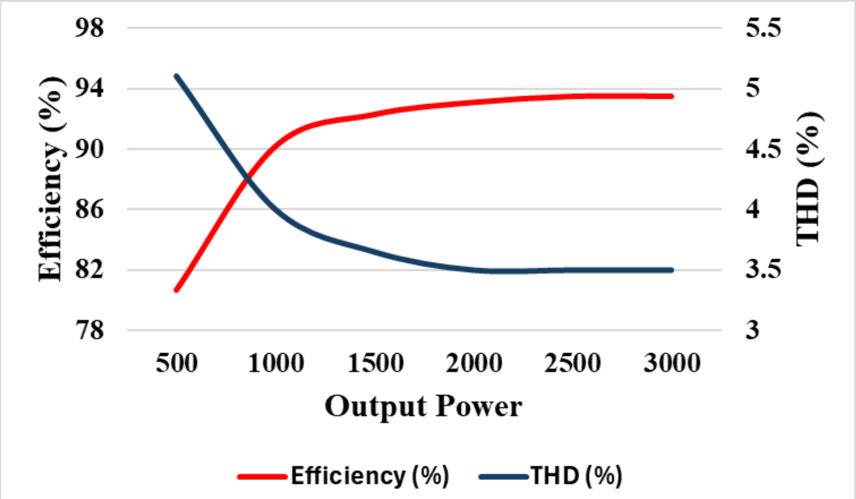
01. Switching losses resulting from the ON and OFF turning of the switches

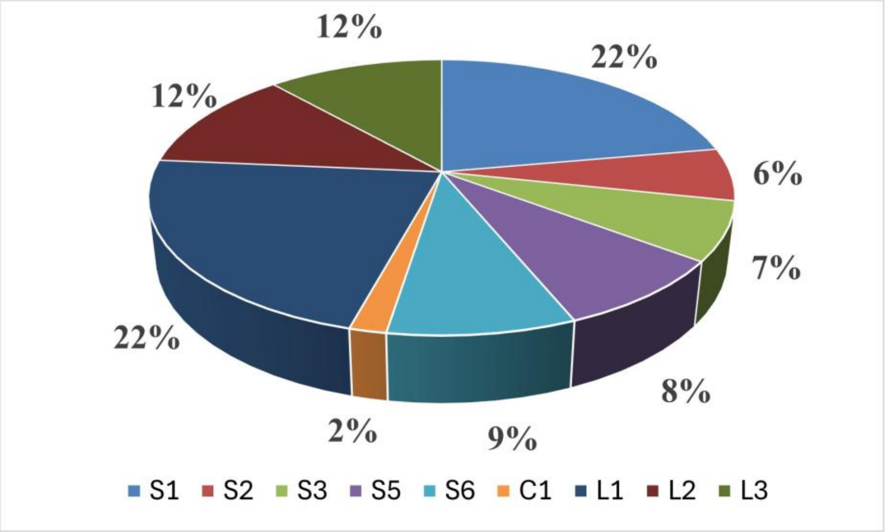
02. Conduction Losses resulting from the motor windings and the switches

03. Core Losses resulting from only the motor windings

04. Efficiency and THD of 93.9% and 3.5%







Conclusion and Future Work

01. A magnetically coupled integrated onboard EV charger has been presented

02. Configuration of the charger does not require rewinding of motor windings

03. Charger has no in-rush current, torque generation, and bulkiness issues

04. Comprehensive analysis, simulation, and experiments done to prove the stability, robustness and high-power density of the charger

Conclusion and Future Work

01. Integration of both the output and input current ripple into the same OBC topology.

02. Extension of the charger's functionality to do V2H, V2G and V2X

03. Extension of the proposed charger to vehicles with more than one motor

04. Solve the industry-wide pain point

List of Publications

01. **D. Afriyie**, A. A. Khan and M. Tariq Iqbal, "Magnetically Coupled Interleaved Buck Integrated On-Board Charger for Light Electric Vehicles," in IEEE Transactions on Transportation Electrification.

02. **D. Afriyie**, A. A. Khan and M. Tariq Iqbal, " A Single-Phase Integrated On-Board Charger with Minimal Current Ripple for Electric Vehicles Having at Least One Motor," in IEEE Journal of Emerging and Selected Topics in Power Electronics (under review).

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[1] S. Wang and P. W. Lehn, "A Three-Phase Electric Vehicle Charger Integrated With Dual-Inverter Drive," in IEEE Transactions on Transportation Electrification, vol. 8, no. 1, pp. 82-97, March 2022.

[2] V. Vidya and R. S. Kaarthik, "Parallel Operation of Integrated Battery Chargers for All Wheel Drive Electric Vehicles," in IEEE Transactions on Transportation Electrification, vol. 9, no. 2, pp. 3106-3114, June 2023.

[3] I. Subotic, E. Levi, M. Jones and D. Graovac, "Multiphase integrated on-board battery chargers for electrical vehicles," 2013 15th European Conference on Power Electronics and Applications (EPE), Lille, France, 2013

[4] T. Na, X. Yuan, J. Tang and Q. Zhang, "A review of on-board integrated electric vehicles charger and a new single-phase integrated charger," in CPSS Transactions on Power Electronics and Applications, vol. 4, no. 4, pp. 288-298, Dec. 2019.

[5] Shi, C., Tang, Y. and Khaligh, A., “A single-phase integrated onboard battery charger using propulsion system for plug-in electric vehicles,” IEEE Transactions on Vehicular Technology, vol. 66, no.12, pp.10899-10910, 2017.

[6] A study of rotational movement and motor torque during charging process of reconfigured on-board charger,” IEEE Trans. Power Electron., vol. 35, no. 10, pp. 10720–10728, Oct. 2020.

[7] H. Wouters and W. Martinez, "Bidirectional Onboard Chargers for Electric Vehicles: State-of-the-Art and Future Trends," in IEEE Transactions on Power Electronics, vol. 39, no. 1, pp. 693-716, Jan. 2024.

[8] R. Pandey and B. Singh, "A Power Factor Corrected LLC Resonant Converter for Electric Vehicle Charger Using Cuk Converter," 2018 IEEE International Conference on Power Electronics, Drives and Energy Systems (PEDES), Chennai, India, 2018

[9] G. Pellegrino, E.Armando and P. Guglielmi, "An Integral Battery Charger With Power Factor Correction for Electric Scooter," in IEEE Transactions on Power Electronics, vol. 25, no. 3, pp. 751-759, March 2010

Integrated Onboard Chargers (OBCs) for Electric Vehicles (EVs)

Presented by: Daniel Afriyie

Supervisors: Dr. Ashraf Khan
Dr. Tariq Iqbal

Thank You