Integrated Battery Charging and Powertrain Schemes for All-Wheel Drive Electric Vehicles

A thesis submitted

in partial fulfillment for the award of the degree of

Doctor of Philosophy

by

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January 2024

Abstract

In recent decades, advancements in battery technology, huge investments in electric vehicle deployment, environmental concerns, and supportive policies by governments have spurred interest in Electric Vehicles (EVs). Two and three-wheeler EVs dominate the market in developing countries like India, Thailand, and Indonesia, while, Battery Electric Vehicles (BEVs), mostly electric-Sports Utility Vehicles (e-SUVs), which are all-wheel drive vehicles (vehicles that use motors for both axles), are popular in developed countries like the US and Europe. Different types of EVs are present on Indian roads, including electric cars such as Tata Nexon EV, Tata Tiago EV, MG ZS EV, Mahindra XUV 400 EV, electric scooters such as Ather 450X, Bajaj Chetak Electric, e-rickshaws like Mahindra Treo, Piaggio Ape E-City, and several electric buses.

With improvements in electric powertrain technology, the performance of electric cars has surpassed the capability of conventional Internal Combustion Engine (ICE) cars. However, the cost of EVs and the life cycle of batteries are issues that may be solved shortly as intense research is focused on improving battery technology, which includes the development of high-power density batteries with lower cost and extended battery life cycle.

For an EV user, the main concerns are the range anxiety and the time required to charge the battery. Presently there are two types of chargers, namely onboard AC chargers which are available up to 22 kW of power capability, and DC fast chargers with high power capability, but are available only at sparsely located charging stations. Thus there is a need for a fast onboard charger that enables charging at any location or can potentially reduce the installation cost of high-power charging stations.

In this thesis, a new Integrated (onboard) Battery Charger (IBC) capable of high power level-3 charging is proposed. Furthermore, the proposed IBC scheme is extended for All-Wheel Drive (AWD) EVs, by simultaneously utilizing both the powertrains, one on the rear-wheel axle and the other on the front-wheel axle, as a part of the integrated charger, resulting in higher power conversion capability of the system. Lastly, a driving scheme for a single-motor electric powertrain for AWD vehicles is proposed using dodecagonal, octadecagonal, and 24-sided polygonal space vector structures for

all-wheel drive EVs with the advantage of better DC bus utilization with reduced voltage harmonics.

Integrated Battery Charger Using a Split Phase Machine

An integrated battery charger is developed for EVs by re-utilizing the existing powertrain components of the vehicle. This fast on-board charger can be implemented by reconfiguring the existing three-phase machine in the EV as a split-phase machine. Moreover, the existing three-legged inverter serves a dual purpose, catering to both driving and charging modes requiring minimal additional components. During driving the inverter drives the three-phase machine, while in charging mode, the inverter functions as a grid-connected front-end converter, drawing grid currents at unity power factor. The reconfigured split-phase machine windings are connected between the grid and the inverter in such a way that it would not develop any electromagnetic torque inside the machine while charging the battery. Thus an integrated on-board charger with high power capability is developed using the existing hardware inside the vehicle. However, the utilization of asymmetrical windings of the reconfigured split-phase machine as the grid-interface inductance leads to the creation of unbalanced grid currents due to the asymmetry in the grid interface inductance and pulsating magnetic flux inside the machine. A comprehensive mathematical model has been formulated, and a novel control architecture has been implemented to address this issue. These advancements effectively mitigate the current unbalance, ensuring compliance with the IEEE-519, and IEEE-1547 standards. Furthermore, this IBC is applicable for vehicle-to-grid scenarios due to its bidirectional power handling capability. Simulation and experimental results are included to verify the proposed topology.

Parallel Operation of IBCs using Split Phase Machines for All-Wheel Drive EVs

All-Wheel Drive EVs have two powertrains, one in the front-axle and the other in the rear-axle for improved drive performance. An IBC of high power capability can be developed by using the two powertrains simultaneously, in parallel operation for charging the battery. The two existing three-phase motors can be reconfigured as

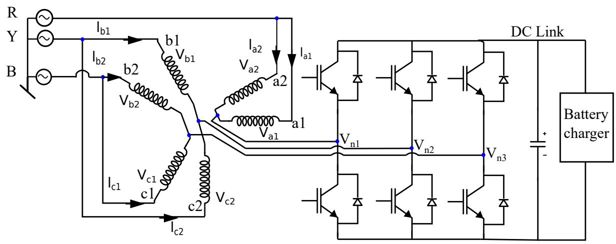

Fig. 1. Schematic of the proposed IBC using a split-phase machine.

split-phase machines. Also in this work, a new winding arrangement for the two split-phase machine windings is proposed for the parallel combination, such that the current in each of the individual IBCs will be unbalanced, but the grid current which is the sum of the two IBC currents will be balanced naturally without any additional control effort. The mathematical proof for the cancellation of unbalance with the proposed winding configuration is included in this thesis.

Also, it is found through mathematical derivation, that there is a flow of zero sequence circulating current through the two inverters, due to the difference in inductance value in each phase of IBC-1 compared to the same phase in IBC-2 leading to a difference in pole voltage of each phase of inverter-1 of IBC-1 and inverter-2 of IBC-2. This low-frequency circulating current is limited by introducing a zero-sequence current controller.

Furthermore, the proposed IBC configuration showcases bidirectional functionality, thereby allowing for its application in vehicle-to-grid scenarios.

Simulation and experimental results are included to verify the proposed concepts.

An Advanced Modulation and Driving Scheme for All-Wheel Drive EVs

In an AWD EV, even though it has two powertrains, predominantly for normal running conditions, only one primary drivetrains will be energized, and the secondary drive is mostly turned off. Both the drivetrains are used only when there is a need for extra torque, like while driving on a slippery road or through muddy terrain. In this thesis, a new driving scheme during normal running conditions is proposed, where in the

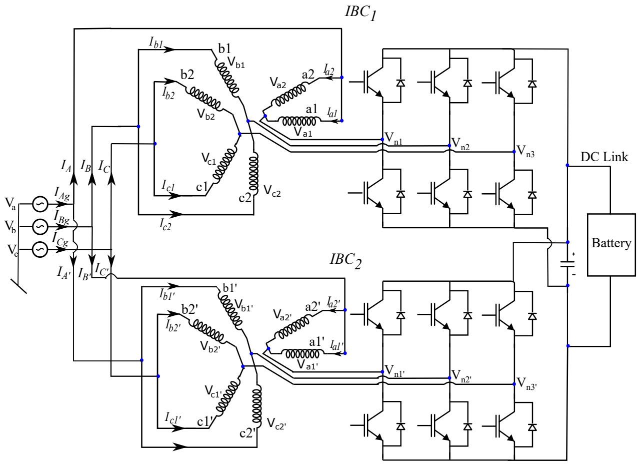

Fig. 2. Proposed configuration of parallel IBCs for AWD vehicles; (R-Y-B and Y-R-B phase sequences for IBC1 and IBC2 respectively are shown.)

primary motor is driven as an open-end wound machine by utilizing the inverters of both the powertrains. This reconfiguration helps in implementing multi-sided space vector schemes like dodecagonal, octa-dodecagonal, and 24-sided polygonal space vector schemes, with the same hardware resulting in better utilization of the battery voltage with reduced harmonics.

Also in this topology, the secondary inverter acts as a switched capacitor without any DC source. The voltage across the capacitor can be maintained constant without needing any closed-loop voltage control. For each multi-sided space vector scheme, there is a different magnitude of stable capacitor voltage, where the capacitor will go and settle naturally using the switching scheme presented in this thesis. The mathematical analysis for the stability of the capacitor voltage is derived in detail for the different multi-sided space vector schemes in this thesis.

Furthermore, a switching scheme is implemented to linearize the inverter gain between the input voltage and the fundamental component of output voltage in the over-modulation region. This is important when operating at higher speeds, as the main advantage of a multi-sided space vector scheme is the reduction in voltage harmonics when operating in the extreme modulation region. The mathematical expressions for the different regions in each of the multi-sided space vector schemes are included in the thesis. Simulation and experimental results are included to verify the proposed concepts.

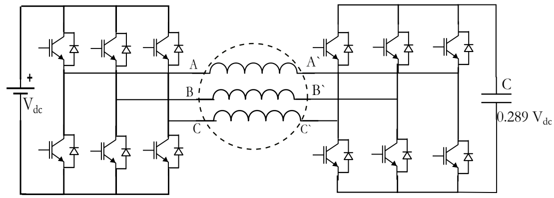

Fig. 3. Schematic for dodecagonal space vector scheme using one DC source.

Summary and Critical Overview of the thesis

A new and fast integrated battery charging scheme is developed for EVs with the existing three-phase machine and three-legged powertrain inverter. The proposed scheme is the only scheme reported that can reuse the three-phase inverter in the vehicle. All other reported works require five or six-legged inverter to operate as IBC using the multiphase machine. Currents are drawn from the grid at a unity power factor with lower THD (within the IEEE-519 standards). The proposed scheme can be used to charge the EV from any place where AC power is available and is limited to the power capability of the Electric Vehicle Supply Equipment (EVSE) and the maximum power of the inverter. Furthermore, the power rating of the IBC can be up to twice the power rating of the motor in the vehicle. As the proposed IBC scheme is bidirectional, the system can also be used for vehicle-to-grid applications. Further research can be done for implementing this topology using permanent magnet synchronous machines as it has become a popular motor in EVs.

The concept of IBC is then introduced for AWD EVs. A high-power integrated charging scheme is proposed for All-Wheel Drive EVs, using the two motor drives inside the vehicle. This charging scheme can also be implemented for heavy-duty electric trucks, which are always on the run, and it helps users to charge the battery from any location where the AC supply is available. Furthermore, by implementing the proposed parallel IBC winding configurations, the distortions in the grid currents can be inherently reduced without using any additional control effort. This scheme can also be used for vehicle-to-grid applications because of its bidirectional nature. In cases where front axle and rear axle powers are different, unbalance in the current is mitigated as opposed to complete elimination.

Furthermore, a driving scheme with better inverter DC voltage utilization for AWD EVs is proposed by engaging the two inverters (present on both the front axle and rear axle) inside the vehicle. The motor (front/ rear axle) is run as an open-end winding motor along with the two inverters inside the vehicle. Three space vector modulation schemes, namely the 12, 18, and 24-sided polygonal space vector structures, are implemented using the same hardware, that is, the open-end winding motor with the two two-level inverters. The main advantage is the reduction in voltage harmonics in the phase voltages of the motor, resulting in reduced torque pulsations.

This scheme is implemented using a single DC source, with the second inverter fed by a DC link capacitor (operating as a switched capacitive filter). A switching scheme is implemented, where the capacitor voltage is regulated naturally without any closed-loop control. Furthermore, linearization of the overmodulation region is developed to utilize the existing battery voltage to its maximum limit effectively.

This work aims to solve a few significant problems that impede EV adoption. An IBC to enable high-power (level-3) charging wherever AC power is available is attempted. This charging method will also effectively reduce the capital cost of EV charging facilities as powertrain equipment is reused as the AC-DC converter. A decrease in capital cost will increase the number of charging stations. The proposed scheme is adaptable to be used for AWD vehicles. As e-SUVs typically have larger batteries, high power capabilities of e-SUV powertrains as parallel IBCs should be exploited for the benefit of fast charging. Lastly, by using the dual inverter topology for the open-end wound motor, the efficiency of the powertrain can be improved. In summary, this thesis proposes methods to use existing power electronic hardware in an EV for charging and driving motors more efficiently. As the cost of adopting these schemes is relatively minimal, the proposed schemes are a viable alternative to traditional charging and driving methods. The proposed methods are validated through simulations and exhaustive experimental results.