Integrated Motor Drives and Battery Chargers for Plug-in Hybrid Electric Vehicles

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Summary

Plug-in vehicles, electric vehicles or plug-in hybrid electric vehicles use grid power to charge the battery. The components in the traction circuit, like the electric motor and the inverter, are not used during the battery charging, so there is a possibility to use them in the charger circuit to reduce the size, weight and price of the on-board charger; that is called an integrated motor drive and battery charger or simply an integrated charger which can be galvanically isolated or non-isolated from the utility grid.
The main objective of the project was to enhance the research area for the integrated motor drives and battery chargers.

Within this project, different examples of integrated chargers reported by academia or industry, isolated or non-isolated, have been reviewed and compared in terms of circuit configuration, control strategy, degree of integration, and efficiency. Moreover some new isolated and non-isolated solutions are presented and explained. A patented integrated motor drive and isolated battery charger based on a split-phase permanent magnet (PM) motor is described where the motor windings are reconfigured for the traction and charging mode by using a relay based switching device. To reduce the magnetization current due to the motor air gap, the motor rotates at synchronous speed during the battery charging. So, an extra clutch is used in the system to disconnect the motor from the vehicle transmission during the charge operation. The mathematical model of the split-phase PM motor based on a double dq approach, the developed controllers, and the system functionality are explained. Moreover, simulation and experimental results show that the system has a good performance in terms of system efficiency and dynamic response with two PM motor alternatives in two separate practical systems. Two new categories of integrated motor drives and non-isolated battery chargers are presented and explained. The first scheme is based on the winding's reconfiguration of a split-phase PM motor which simulation and practical results are provided. The second scheme is a single-phase solution where a split-phase PM motor and two inverters enable battery charging.

The project was part of the theme 2 (Electric machines and drives) consisting of the three research groups in electrical drives from KTH, Chalmers and Lund University. The project was lead by a reference group with all industrial partners represented. In the Theme 2 reference group, it was decided to put the focus on research efforts aimed at cutting cost of the electric drive system. Three main focus areas were identified where the area "Low add-on cost for charging" was addressed in this project. The project was financed from 1st of May 2008 to 1st of May 2013 and the dissertation was 1st of April 2013. The project cost was 1220 kSEK/year.

Background

The battery has an important role in the development of EVs or PHEVs as an energy storage device. The performance of battery modules depends not only on the design of modules, but also on how the modules are used and charged. In this sense, battery chargers play a critical role in the evolution of this technology.
The on-board battery charger gives flexibility to charge anywhere where there is an electric power outlet available. However, the on-board type has the drawback of adding weight, volume and cost to the vehicle, thus it is usually made for lower powers (< 3.5 kW). When higher charging power is needed, the size and weight of the charger is easier to handle with an off-board charger. Vehicles with a longer EV-range (e.g. > 100 km) may require filling large amounts of energy (e.g. > 20 kWh) in reasonably short time. Even a 30 minute charging time would require a charging power of 40 kW or more, which is on the high side and very

well may be limited by the maximum allowed continuous battery power. With a significantly increased fleet of EV's, the need for long charging times, compared to filling e.g. gasoline, implies the need for an un-proportionally large amount of charging stations, that will be expensive. Then, high power on-board chargers are attractive if the weight, volume and cost can be handled. In that case the infrastructure requirement would be reduced to rather simple high power outlets and thus the cost would be significantly lower than that of off-board chargers.
Different types of integrated chargers are reported by academia or industry that are reviewed and compared in this project. Moreover, as a main result of this thesis, a high-power integrated motor drive and isolated battery charger based on a split-phase PM motor is presented and explained. The main idea is to use the motor as a grid-connected generator with extra terminals. The concept of this rotary transformer or motor/generator for this application is the subject of a Swedish patent that is extended to an international patent.

General project description

The main objective of the work reported in this thesis is to enhance the research area for the integrated motor drives and battery chargers. So different types of integrated chargers are proposed and described including experimental results to validate the proposed schemes. Moreover, in the context of the integrated chargers, modeling and control of the split-phase PM motors are investigated and explained.
In summary, the main contributions can be itemized as:

- A comprehensive review and comparison of available integrated chargers reported by industry or academia.
- Mathematical modeling of the split-phase motor using a double dq approach with an extended Park transformation for an arbitrary phase-shift between two sets of stator three-phase windings.
- Proposition, simulation, analysis, control development, and implementation of a high-power motor drive and isolated battery charger based on a split-phase PM motor.
- Proposition, simulation, control development and partial implementation of high-power motor drives and non-isolated battery chargers for two different configurations of the drive system.
- Proposition, analysis and simulation of a decoupled control strategy for a drive system based on a split-phase PM motor and dual inverters using the eigenvalue decomposition of the state-space model. Development of a maximum torque per ampere control strategy for a drive system based on the split-phase PM motor and dual inverters using the double dq approach.

Achieved results

Different examples of integrated motor drive and battery chargers introduced by academia or industry have been reviewed and compared. Circuit configuration, traction/charging functionality, charging features like bidirectional capability or unity power factor operation capability, control strategy for the traction and charging and the degree of integration are the main aspects of this review and comparison. Table 2.1 in the PhD Thesis[1] shows a summary of these solutions including the comparison results.

A novel integrated motor drive and isolated battery charger based on a split-phase PM motor is presented in the thesis, see also Fig. 1. The charger is a high-power high-efficiency device which uses an extra clutch and a relay-based switching device to reconfigure the traction circuit from the traction mode to the charging mode. The motor is rotating during the charging operation which implies that the system efficiency in the charging mode is lower than the efficiency in the traction mode. On the other hand, a separate battery charger with a high power is eliminated from the system. The control strategy is developed for the battery charging mode for the grid synchronization and battery charging. The motor first synchronizes itself to the grid and then starts to charge the battery. The control algorithm, system functionality, simulation results, and experimental results are provided to verify the proper operation of the system. Two experimental setups have been designed and implemented to verify the proposed scheme. The first system is based on a 20 kW PM motor with a charging power of 3 kW and an efficiency close to 80% is measured. The measured system efficiency is shown in Fig. 2 for different power levels, and the measurement set-up is shown in Fig.3. The optimal current trajectory for the motor during the charge operation and the loss analysis is performed and

[1] Saeid Haghbin, Integrated Motor Drives and Battery Chargers for Electric or Plug-in Hybrid Electric Vehicles, PhD Thesis, Chalmers University of Technology, 2013.

presented for this case. The second system is based on a split-phase PMSM motor with two identical windings that are not shifted in the space. The practical results for the second system show that the integrated charging is feasible in this scheme as well.

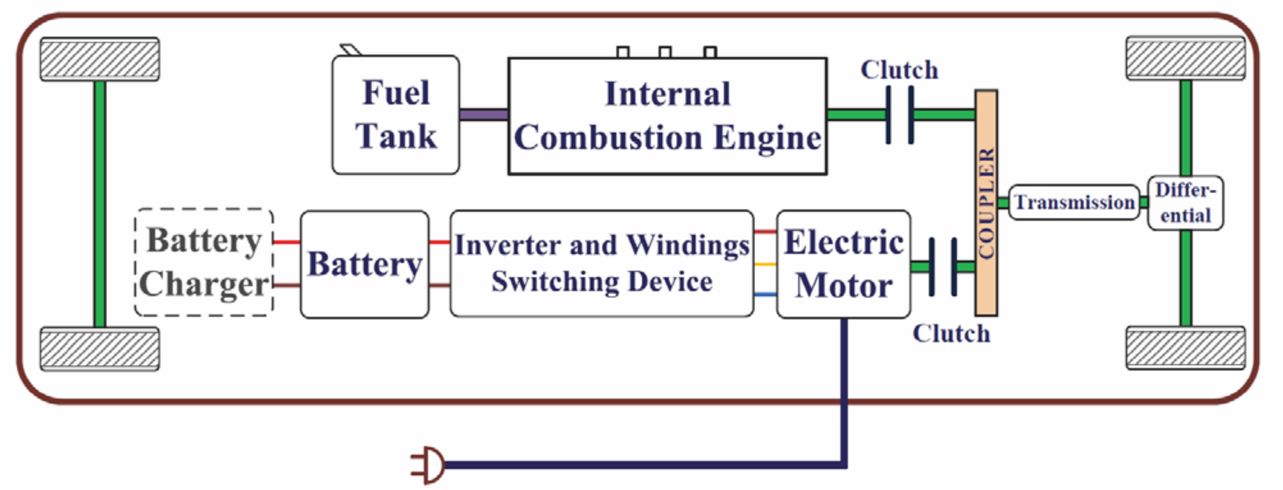

Figure 1: Integrated motor drive and isolated battery charger based on the split-phase PM motor for a PHEV

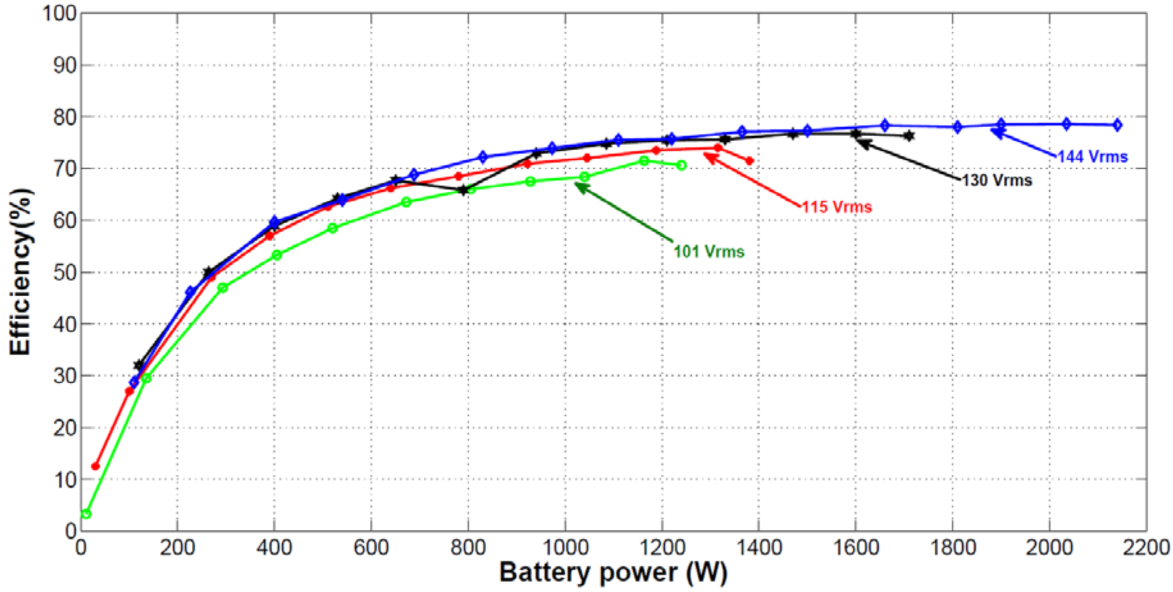

Figure 2: Measurement: system efficiency in charging mode for different power levels.

The galvanic isolation is the main advantage of the proposed integrated charger in this thesis compared to other types of integrated chargers. However, because of using an extra clutch, extra switching relays, and lower efficiency compared to other types of integrated chargers, more investigations are needed with respect to the total cost of the system. It seems that this solution is an attractive option in higher power levels, in bus or truck applications for instance but non-isolated integrated chargers are the mostly used solutions in industrial applications so far. The motor is then mainly used as inductances in the charging circuit and developed torque in the motor should be zero to be able to use the motor in the charger circuit.

Consequently, two main categories of non-isolated integrated motor drive and battery chargers are presented and explained in this project. The first solution uses the motor windings midpoints to cancel out the motor mutual flux to be able to use the leakage inductances in the battery charger. The second solution is presented for a split-phase PM motor with dual inverters.

For the first solution, it is possible to charge the battery with a single-phase supply and/or a three-phase supply, however a single switch is needed to reconfigure the system for the traction and charging mode operation. The second solution just uses a single-phase power source for the battery charging and there is no need for any extra component. The proposed non-isolated integrated chargers have a good potential to be utilized as a product because of the low price, simple structure and easy control

A double dq model is developed for the split-phase PM motor using an extended Park transformation. Consequently, the modeling and control of split-phase PM motors that are a type of multi-phase motors are investigated in this context. As an example, a modal FOC-based drive system is presented for the split-phase PM motor. There is a tight coupling between the stator windings that needs a suitable decoupling scheme in the drive system.

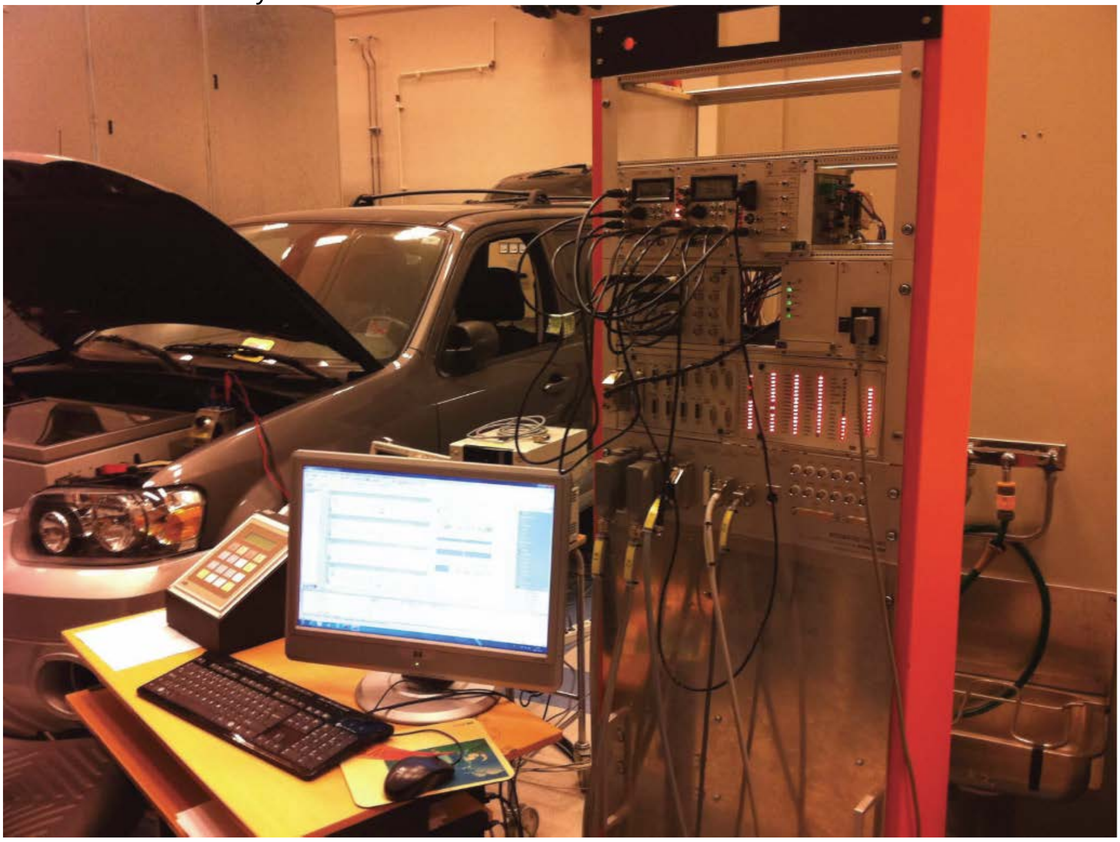

Figure 3: The experimental setup including the vehicle.

Contribution to hybrid vehicle technology

New isolated and non-isolated integrated motor drives and battery chargers have been proposed, designed, simulated, implemented and verified. This work has laid a foundation for further work within the area for the industrial partners. The project has also contributed to the academia as it allowed development of the research personnel (yielding one PhD degree and contributing to one position as Assistant Professor). The work has also played an important role in the teaching activities at the division of Electric Power Engineering, such as development of the electric drives courses, and of several master thesis projects.

Uniqueness and news value

The isolated integrated charger has been introduced in several news and media at a national and international level. For instance, in Sweden in Nyteknik it was reported and in US it was part of the US Department of Energy annual report.

Timing and finance

The project was financed from 1st of May 2008 to 1st of May 2013, the licenciate thesis was 2011 and the dissertation was 1st of April 2013.

The total project budget is SEK 6.1 million, all funded by SHC.

Executors and collaboration

The project was part of a collaboration with Chalmers, Lund and KTH, and it was lead by a reference group with all industrial partners represented.

Papers and publications

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