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UNIFIED POWER CONVERTERS FOR BATTERY CHARGING AND TRACTION DRIVE SYSTEMS FOR ELECTRIC VEHICLES: COST AND PERFORMANCE ANALYSIS

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ABSTRACT

Electric vehicles (EVs) are a promising solution to mitigate the emission of greenhouse gases and atmospheric pollution. Although EVs existence spans from more than one century, only in the recent years there has been a considerable development in the electric mobility paradigm. This development is also verified in the operation modes for the EV, giving it an important role in smart grids. Moreover, the implementation of unified power converters for battery charging and traction drive systems is also a key topic about EVs, allowing at the same time a hardware reduction and an increasing in its functionalities. However, no economic studies about the practical feasibility of these unified systems for EVs have been reported in the literature. In this context, this paper presents a cost assessment of unified battery charging and traction drive systems for EVs focusing on practical aspects. An economic comparison is performed between a traditional EV and a unified system in order to attain a cost/performance analysis for the unified power converters that can be used in EVs.

INTRODUCTION

The rate of energy consumption has been increasing from decade to decade worldwide, which has led to a fossil fuels shortage, as well as high levels of atmospheric pollution. To contrast this trend, electric vehicles (EVs) emerge as a sustainable alternative at the utilization level to the conventional vehicles with internal combustion engine. The first commercial EVs appeared in the end of the XIX century, albeit receiving attention during little time, due to the increased reliability and low refueling cost of the fossil fuel powered vehicles. However, the interest in EVs has been renewed in the present decade, as environmental laws are becoming stricter about the pollutant particles emission by internal combustion engine vehciles (Ansari et al. 2014; Gearhart and Breitenbach 2014; Milberg and Schlenker 2011).
Besides representing a user level sustainable mobility paradigm, EVs can also play an important role in smart grids, since they are capable of providing supporting functionalities to the electrical power grid. This is possible if EVs are equipped with an on-board bidirectional battery charger, or if they are plugged to an off-board bidirectional battery charger, extending the traditional battery charging operation (grid-to-vehicle – G2V) to the injection into the power grid of part of the energy stored in the batteries (vehicle-to-grid – V2G) (Kempton and Tomić 2005; Liu et al. 2013). Furthermore, it is also possible for the EV to operate as a voltage source isolated from the power grid, an operation mode designed by vehicle-to-home (V2H) (Monteiro et al. 2017). EVs can also be used to interface renewable energy sources with the power grid (Monteiro, Pinto, and Afonso 2018) and to compensate power quality problems, such as reactive power (Kesler, Kisacikoglu, and Tolbert 2014) and harmonic currents (Hou and Emadi 2017). In addition to the possible functionalities for EVs in smart grids context, it is important to ensure that EVs do not cause grid congestion due to unrestrained or unscheduled battery charging, which can certainly happen in the near future when EVs utilization will be widespread. In this context, the impact of EVs battery charging in the power grid is addressed in (Gomez and Morcos 2003; Hattam et al. 2017; Leou, Su, and Lu 2014; Vagropoulos, Balaskas, and Bakirtzis 2017), and possible solutions are considered in (Abousleiman and Scholer 2015; de Hoog et al. 2015; Knezovic et al. 2017; Rabiee et al. 2016; Torres-Sanz et al. 2018; Vagropoulos, Kyriazidis, and Bakirtzis 2015), taking energy costs in consideration.
In addition to the on-board battery charger, an EV comprises a traction drive system to control the electric motor. Both the battery charger and the traction drive system are comprised by similar power converters and, moreover, only one of these systems is enabled at a certain time, i.e., an EV is either in movement, with operation of the traction drive system, or charging the batteries. Taking into account the separation of these two operation modes, as well as their similarities in terms of power converters constitution, a unified battery charging and traction drive system can be assembled,

maintaining the functionalities of a conventional EV, but with reduced hardware. This type of unified system is commonly entitled in the literature as integrated charger (Yilmaz and Krein 2013). The unified approach was patented in (Cocconi 1994; Rippel 1990; Rippel and Cocconi 1992) and some application examples can be found in (Chang and Liaw 2009; Haghbin et al. 2013; Kim, Kim, and Lee 2017; Liaw and Chang 2010; Lixin Tang and Gui-Jia Su 2009; Solero 2001; Subotic, Bodo, and Levi 2016a, 2016b; Thimmesch 1985), where the power grid coupling inductors can be realized with the motor stator windings or simply with external inductors. Besides reducing the required hardware, the utilization of a unified system endows an EV with an on-board fast battery charger, since the nominal power of the traction drive system is higher than the power levels of the on-board battery chargers. Furthermore, an EV equipped with this system is capable of compensating harmonic currents and reactive power, i.e., operating as a shunt active power filter (SAPF) in industrial facilities, as well as operating as a voltage source isolated from the power grid, such as uninterruptible power supply (UPS).

Although the unification of the battery charger and the traction drive system in EVs is a theoretical advantage, its practical feasibility has not been fully reported in the literature. (Woo, Joo, and Lee 2015) analyzed the practical feasibility of integrated battery chargers for plug-in hybrid EVs from the point of view of technical aspects, such as motor inductance, switching frequency and common-mode noise. However, no economic analysis seems to have been investigated in the literature until now. In this context, this paper presents an economic evaluation of a unified battery charging and traction drive systems for EVs based on practical aspects. The functionalities of the unified system for EVs are listed and an economic comparison is carried out between the unified approach and the conventional equipment employed in an EV, establishing a relation between performance and cost of the solutions.

ELECTRIC VEHICLE OPERATION MODES

This section lists the possible operation modes that can be performed by an EV endowed with unified power converters for battery charging and traction drive systems. These operation modes consist of: traction drive system, corresponding to the movement of the EV; G2V operation mode, which corresponds to the battery charging operation; V2G operation mode, which corresponds to the injection of the batteries' stored energy into the power grid; V2H, which is the operation of the EV as an isolated voltage source; and SAPF operation mode, in which the EV mitigates power quality problems related to currents, such as harmonic currents and reactive power.

Traction Mode

The traction mode is indispensable for an EV, since it is responsible for controlling the electric motor and, consequently, to perform the transportation. A block diagram of this operation mode can be seen in Figure 1. This operation mode is performed by the traction drive system, which is composed by a dc-ac converter whose power rating should be higher than the nominal power of the electric motor. Besides, this system also comprises a dc-dc converter that is used to adapt the batteries voltage to the dc-link of the dc-ac converter, as well as to perform regenerative braking, i.e., to transfer energy back to the batteries when the electric motor acts as a generator, such as in cases of deceleration or when travelling downhill. Therefore, the traction drive system is comprised by bidirectional converters in order to allow bidirectional power flow, as suggested by the double arrows in the figure.

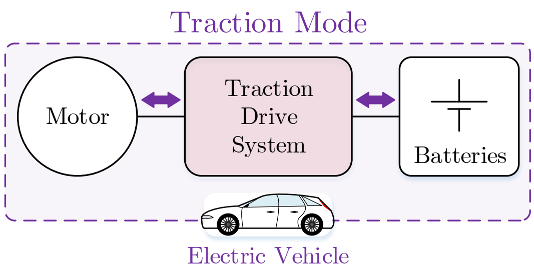


Figure 1: Block diagram of the traction operation mode of an EV.

Grid-to-Vehicle (G2V) Mode

The G2V operation mode corresponds to the battery charging operation of the EV, which is accomplished with its on-board battery charging system. A block diagram of this operation mode is presented in Figure 2. Comparatively to the traction drive system, the battery charging system presents a low power rating, since the maximum on-board battery charger power level is 19.2 kW (Yilmaz and Krein 2013). Therefore, an EV endowed with the traditional equipment, i.e., traction drive system plus battery charging system, can only perform slow battery charging. However, for an EV endowed with a unified system for battery charging and traction, fast battery charging is possible, since the power limit for the battery charging operation is defined by the traction drive system power rating. Consequently, an EV with this equipment can charge its batteries from a three-phase power grid instead of single-phase only. Similarly to the traction drive system, the battery charging system is comprised by two power converters, namely an ac-dc converter to interface the power grid and a dc-dc converter to control the charging process of the batteries. These converters can be either unidirectional or bidirectional in a traditional EV, but only bidirectional in an EV with unified power converters in order to allow the traction operation mode.

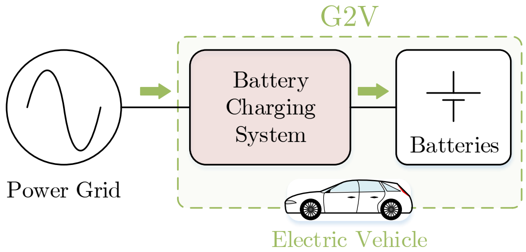


Figure 2: Block diagram of the G2V operation mode of an EV.

Vehicle-to-Grid (V2G) Mode

Figure 3 shows a block diagram of the V2G operation mode, which corresponds to the complementary operation of G2V, i.e., the energy stored in the EV batteries can be injected into the power grid, which is a relevant feature towards smart grids. Accordingly, this operation mode is also accomplished with the battery charging system, and it is only feasible for EVs with bidirectional battery charging systems. This increases the sophistication of the battery charging system of a traditional EV, but does not carry additional costs to an EV endowed with unified power converters, provided that the traction mode and the battery charging operation already require bidirectional power converters. Moreover, in a similar way to the G2V operation, a traditional EV has limited V2G capacity, while an EV with unified power converters is capable of injecting higher amounts of power into the grid. Besides, it can perform V2G operation in three-phase power grids.

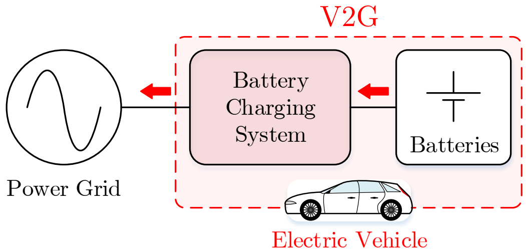


Figure 3: Block diagram of the V2G operation mode of an EV.

Vehicle-to-Home (V2H) Mode

Figure 4 shows a block diagram of the V2H operation mode within an EV. In this operation mode, the EV acts as an isolated voltage source, using the energy stored in its batteries to feed home loads through a controlled sinusoidal voltage. In order to accomplish this feature, both the EV and the home loads should be disconnected from the power grid. This operation mode can be useful for load shift purposes, supplying the home loads during higher demand periods. On the other hand, the V2H operation can also endow the EV with UPS features, supplying the home loads if a power outage occurs, i.e., the EV acts as an off-line UPS. Similarly to the G2V and V2G operation modes, the V2H operation is accomplished with the battery charging system and, in a similar way, it is limited by the power rating of this system. Consequently, an EV endowed with unified power converters is capable of operating as a load shift system or as a UPS for higher power levels and in three-phase power grids. Considering that UPSs are an important asset in industrial facilities, an EV with a unified system can have a significant role in this type of installation, and it can even discard the utilization of dedicated UPSs in the facility, which is not possible with an EV endowed with the traditional equipment.

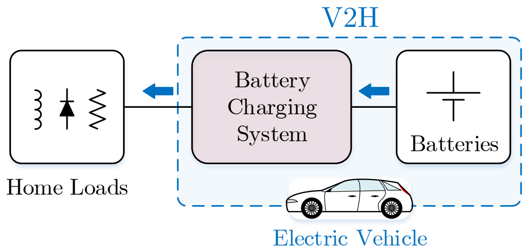


Figure 4: Block diagram of the V2H operation mode of an EV.

Shunt Active Power Filter (SAPF) Mode

Figure 5 shows a block diagram of the SAPF operation mode. A SAPF is used for compensating power quality problems related with currents, such as harmonics and reactive power, that are caused by the connection of certain electrical loads to the power grid. Since a SAPF is connected in parallel to the power grid, its functionalities can be accomplished with the battery charging system, using the same connection than the one used for the G2V and V2G operation modes. However, since a SAPF is comprised by a bidirectional ac-dc converter, the battery charging system should comprise this type of converter in order to operate as a SAPF. Besides, the SAPF operation can be performed simultaneously with either the operation modes G2V or V2G, basically differing in the ac-dc converter control. In this way, it is possible to plug-in the EV battery charger and charge its batteries while the power quality problems related to currents are being compensated in the home. These advantages can be further increased by employing unified power converters in the EV, since the SAPF compensation features can be extended to three-phase installations. Considering the previous example for the V2H operation mode, an EV with this type of system can charge its batteries and compensate power quality problems related to currents while parked in the industrial facility, and, in case of power outages, it is able to switch its operation mode from SAPF to UPS.

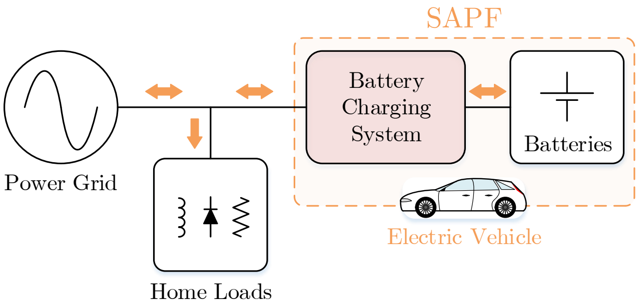
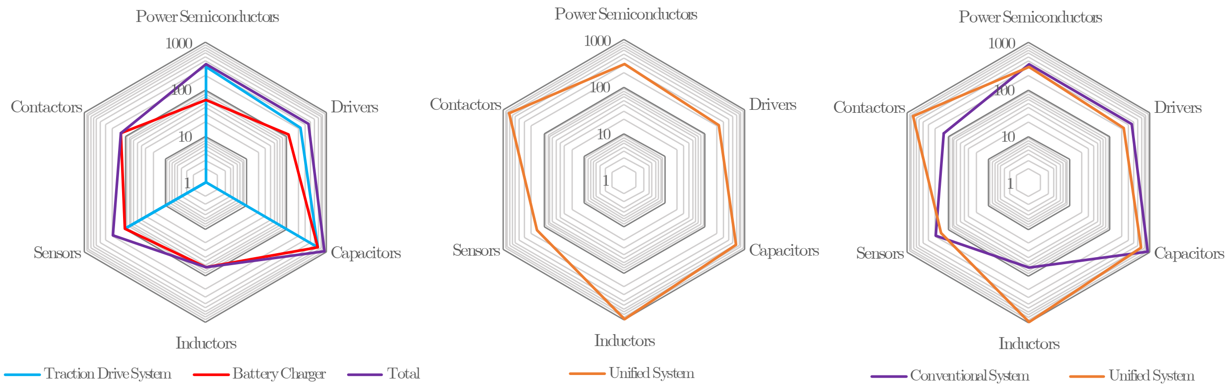


Figure 5: Block diagram of the SAPF operation mode of an EV.

COST ANALYSIS

This section presents the cost analysis of unified power converters for battery charging and traction drive systems for EVs. The diagrams of Figure 6 show the estimated average cost (in euros) of a traction drive system (rated between 50 kW and 75 kW, three-phase) and a battery charger (rated between 3 kW and 6 kW, single-phase), as well as the cost of the two systems combined (as in a traditional EV) and the cost of a unified system. The analysis only comprises the power stage of the equipments, since it is more expensive than the control stage, besides the fact that the control stage is similar between the analyzed equipments. Moreover, it should be referred that the spectrum of the estimated average cost is large for each component, since it depends on the component itself, the type of implementation and commercial price, besides the fact that the analysis considers not a specific power value but a power range instead. In the scope of this paper, this analysis only considers bidirectional battery chargers, meaning that all the operation modes presented in the previous section are possible.

In Figure 6 (a) it can be seen that the traction drive system (in green) comprises more costly components than the battery charger (in red), which is expected considering the larger power rating. However, the traction drive system does not use contactors or inductors. According to the performed estimation, the total average cost is 1230 € for the traction drive system and 1060 € for the battery charger. The combination of the two systems can be seen in the same figure (in purple), representing the equipment present in a traditional EV. It should be referred that this cost is not simply the sum of the two equipments, since some components can be shared, such as capacitors. In Figure 6 (b) it can be seen the estimated average cost of a unified system for the same conditions of the previously considered traction drive system (in orange), and Figure 6 (c) shows the overlapping of this curve with the total cost curve of the traditionally separated systems. As it can be seen, the inductors are the main drawback of the unified approach, which are expensive due to the fast battery charging capability of this system. Besides, the contactors to interface the system with the power grid are also more costly due to the same reason. In terms of total average cost, the conventional equipment is estimated to cost 1990 €, while the unified system is 3030 €. Despite having fewer power semiconductors, drivers, capacitors and sensors, the inductors contribute heavily for the higher cost of the unified approach (1000 € of estimated average cost), followed by the contactors (750 €). However, it should be noted that on-board fast battery charging is possible with this type of system, representing a charging power around 10 times higher for a cost that is only circa 52% higher than the traditional equipment that only offers slow battery charging. Therefore, the unified approach offers a better price/performance ratio than the equipment traditionally employed in an EV.



(a) (b) (c)

Figure 6: Cost analysis of power electronics systems for EVs: (a) Estimated average cost of a traction drive system, a battery charger and the total system; (b) Estimated average cost of a unified system; (c) Cost comparison between a conventional system and a unified system.

CONCLUSIONS AND FURTHER RESEARCH

This paper presented an economic assessment of unified power converters for battery charging and traction drive systems for electric vehicles (EVs) focusing on implementation aspects. Four operation modes were considered within unified systems for battery charging and traction drive of electric vehicles in a context of smart grids, namely: (1) Grid-to-vehicle (G2V), meaning the traditional battery charging operation; (2) Vehicle-to-grid (V2G), meaning the energy injection from the EV into the power grid; (3) Vehicle-to-home (V2H), in which the EV operates as an isolated voltage source, acting as a load shift system or as an off-line uninterruptible power supply (UPS); and (4) Shunt active power filter (SAPF), in which the EV compensates power quality problems in terms of currents, and that can be combined with either the G2V or the V2G operation modes. All the referred operation modes can be employed in power systems with higher power ratings than homes, such as industrial facilities, if the EV is equipped with a unified system, while maintaining the possibility of operating at homes. As demonstrated by the cost analysis that has been carried out, the main monetary issue of having a unified system is related to the inductors and contactors, despite having less power semiconductors, drivers, capacitors and sensors, which makes a unified system to cost 1.5 times more than a traditionally separated equipment. However, from the price/performance ratio point of view, the unified system offers better results, since the referred operation modes can be employed in power levels around 10 times higher than the typical on-board slow battery chargers.

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