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Evolution of Integrated Battery Charging Technology in e-mobility applications

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Abstract

This paper presents an initiative, progress, and development of battery charging techniques in electric driven vehicles extensively, with respect to the demanding needs for addressing the issues of exhaustible fuel resources, environmental hazards due to carbon emission etc. Alerted by the haunting issues of conventional IC engine vehicles, manufacturers are making significant attempts to reduce the dependency on IC engines by converting the vehicles to Hybrid Electric, Plug-in Hybrid Electric and Electric Vehicles. Battery is a prime source for driving the traction circuit in Electric Vehicles (EVs), due to rapid change in standard of living, it is required to adopt an adequate technology to charge the battery of Hybrid Electric Vehicles (HEVs), Plug-in Hybrid Electric Vehicles (PHEVs) and Electric Vehicles (EVs). Basically, charger can be a standalone or onboard. The merits of the standalone (external) chargers are potentially feasible for higher power rating, no limitation of size and weight. The limitations of onboard charger are size, space and weight. To overcome the limitations of onboard charger, the existing power electronic traction circuit of the vehicle is used as a charging circuit and motor winding as an input inductor, when the vehicle is at halt. The evolution of battery charging technology is presented by comparing different integrated

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battery chargers based on their topologies and their additional potential to support the grid is explored based on various factors.

Keywords: Integrated Charger, Plug-in Hybrid Electric Vehicles, standalone charger, onboard charger..

1.1 Introduction

Depletion of fossil fuels, environmental hazards due to carbon emission, etc. compelling the user to switchover to (fossil- fuel free) electric driven vehicles. Which in turn open a way to replace IC (Internal Combustion) engine driven vehicles gradually by Hybrid Electric Vehicles (HEVs), Plug-in Hybrid Electric Vehicles (PHEVs) and Electric Vehicles (EVs). Due to inadequate charging facilities, idea of integrating the charger to Plug-in Hybrid Electric Vehicles (PHEVs) and Electric Vehicles (EVs) is initiated. This integration led to increased weight, space, and cost. Most of these issues are resolved by effective use of existing traction circuitry as a battery charging circuit. Since this drive train is idle when the vehicle is at halt. This idea was initiated more than three decades ago [1]. This paper presents the evolution of integrated charger extensively in electric driven vehicles also explores the potential of integrated chargers in V2G (Vehicle to Grid) integration to support the grid capability. Basically, EV battery chargers are presumed to be unidirectional, which accounts for less component count, reduced risk of inter connection and ease of control.

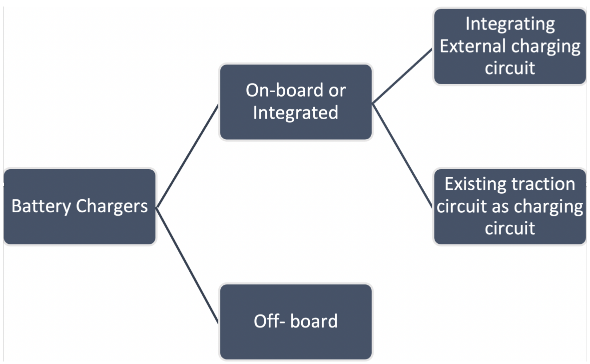

Figure 1.1 Classification of Battery Chargers

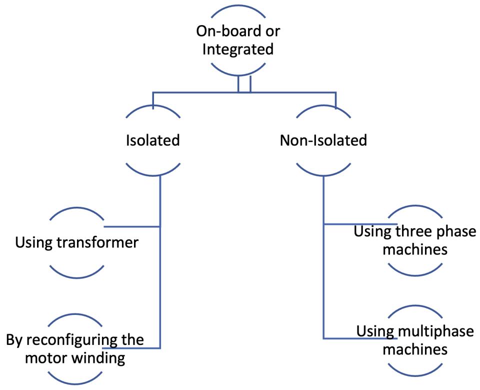

Figure 1.2 Classification of Integrated Battery Chargers

1.2 CLASSIFICATION OF BATTERY CHARGERS

Basically, EV-battery chargers are classified as on-board and off-board chargers. In onboard charging, external charging circuit can be integrated with the vehicle, in recent developments, to overcome the burden of external integration, the existing traction circuitry is used as a charging circuit, the block diagram of the basic classification of battery chargers is as shown in the Fig. 1.1

1.3 ON-BOARD OR INTEGRATED CHARGERS

The integrated chargers can be classified based on the isolation of input and output ports to ensure the safe operation as isolated and non-isolated is shown in Fig 1.2. In the existing power electronic drive circuit, the motor is connected to the traction circuit, the motor winding can be utilized to provide isolation between input and output. In doing so, there would be a chance of torque production which is addressed by reconfiguring the motor winding [7-8]

As per the literature [4] the integrated chargers can be listed separately based on the isolation between input and output as shown in the Fig 2. The galvanic isolation was achieved by using a transformer on the AC input side [5] or by using reconfigured machine winding. The major obstacle in the machine winding during charging is generation of torque, to nullify the torque developed, the machine winding is reconfigured suitably [16].

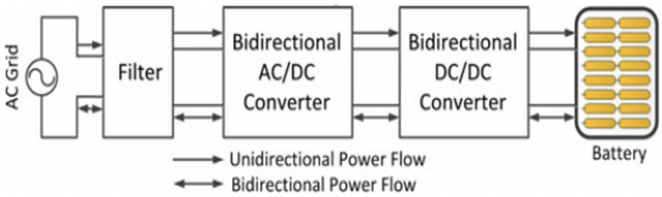

Figure 1.3 Typical two stage Battery Charger

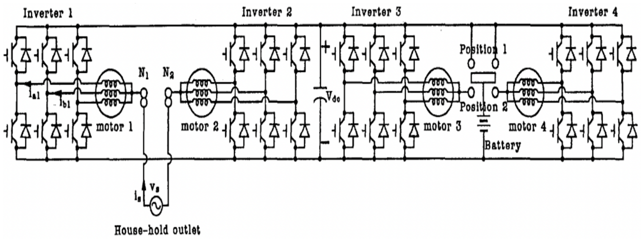

Figure 1.4 Integrated Battery Charger for four-wheel drive EV as in [2]

1.4 TOPOLOGICAL DEVELOPMENTS

The conventional battery charger for EVs generally consists of ac-dc converter, dc-dc converter to facilitate the transfer of power from source to load (battery) based on the nature (unidirectional or bidirectional). There would be two power stages. First stage takes care of unity power factor operation by sinusoidally shaping grid current, and second stage plays a role of regulating the battery charging current or voltage.

A battery charger plays a crucial role in the development of PHEV'S EV's. An integral battery charger, which uses traction circuit of four-wheel drive, is proposed with no additional components except a transfer switch [2] A battery charger plays a crucial role in the development of PHEV'S EV's. An integral battery charger, which uses traction circuit of four-wheel drive, is proposed with no additional components except a transfer switch [2].

Here equivalent power circuit is comprised of ac-dc boost converter and a dc chopper (Fig 3), in the charging mode, the utility source is connected between the neutral points of two motors, ac source voltage can be converted to desired dc link voltage and dc link supplies constant current or voltage to the battery through two phase shifted choppers. At each inverter the upper three IGBT's and lower three IGBT's are on and off simultaneously as a single power switch to make the current in each phase identical without any phase displacement to avoid the generation of torque in the motor. The idea

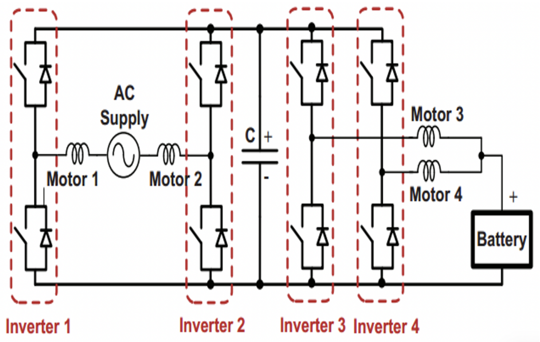

Figure 1.5 Fig 5. Equivalent circuit during charging

was validated by presenting experimental results. Since idea of two-wheel drive dominates over the four-wheel drive-in terms of cost and other factors. By utilizing the available power electronic components and motors a low-cost integrated charger is proposed which uses a digital controller to regulate the converter

Fig 6. Integrated charger with two motors – two inverters configuration as in [4], [9] and [10]

Here existing two inverters are used as ac/dc converters and two motors as inductors of converters. The control signals for two inverters are set to generate similar zero sequence currents in the windings of the motors. The equivalent circuit of the charger is as shown in Fig 7. Two neutral points of three phase motors are connected to ac source to charge the battery, as per the control scheme adopted only bottom switches are used to regulate the input current, top switches are kept off to minimize the switching loss. Gradually the number of converters and motors used in the integrated charger circuit is reduced, which accounts for less weight, space, cost, and ease of control. An integrated charger with one motor and two converters is proposed in [4] as it involves two converters, control complexity increases, required contact switches are an additional hardware. One motor with one power converter is proposed in [5] here the motor used is special type called switched reluctance motor its special winding configuration helps to provide isolation as these motor windings can be used as an isolated transformer during charging mode. But some of the limitations of this topology are under utilization of copper per phase and increased per phase mmf losses. Since isolation between input and output is an essential feature for the safe operation of the charger, the prioritized isolation was provided by reconfiguring the machine winding,

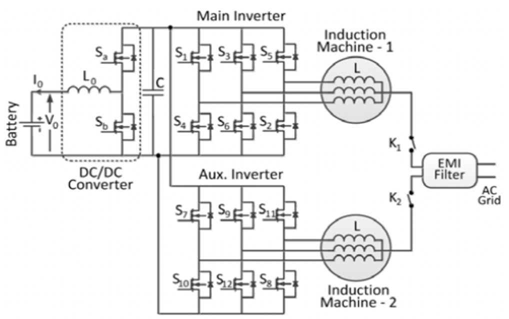

Figure 1.6 Integrated charger with two motors – two inverters configuration as in [4], [9] and [10]

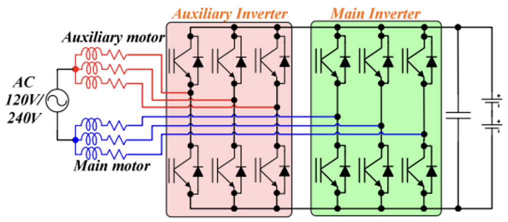

Figure 1.7 Low-cost charger circuit diagram: utilizing the available power electronics systems to charge the batteries of PHEV/EV as in [3]

which led to increased number of motor phases [14], [16]. In the literature attempts were made to increase i. The charging efficiency, ii. Input-power factor, iii. User safety

To reduce i. Number of components ii. Power loss iii. Cost iv. Extra hardware requirement

By looking at various factors which help the most economic and efficient operation of the integrated charger, different available topologies are reviewed extensively and some of the performance parameters of various integrated topologies are tabulated in the Table-I

1.5 BIDIRECTIONAL TOPOLOGY

Most of the integrated charger topologies uses bi-directional switches, which facilitates the flow of power in either direction, this feature will enhance the ability of the charger to feed power back to grid if needed. This really helps in strengthening the grid capability to cater to loads locally. In this direction

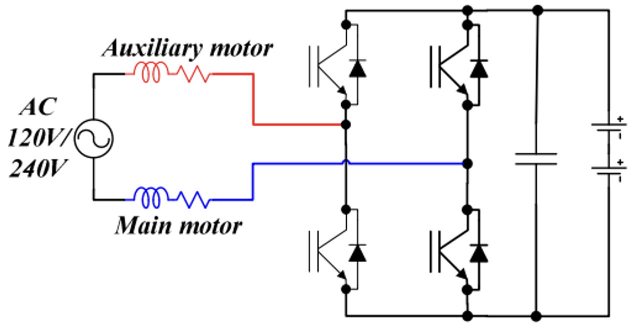

Figure 1.8 Equivalent circuit low-cost charger a PHEV/EV as in [3]

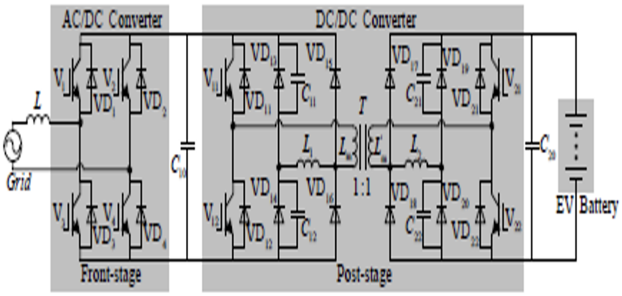

Figure 1.9 Two stage charger topology for V2G as in [22]

a two-stage bidirectional converter topology is proposed for Vehicle to Grid (V2G) system [22]

Table 1.1 Performance comparation of different integrated charger topologies

Integrated charger topology	**References**	**Bidirectional or unidirectional**	**Power stages**	**Type of motor**	**Isolated or Non- isolated**	**Extra hardware required**	**Charging efficiency**	**Discharging efficiency**	**Advantages**	**Limitations**	Applications
Four motors with four converters	[2]	Bidirectional	2	Induction motors	Non- isolated	Control circuits for 24 power switches, and contact switches	Not reported	Not reported	1. Can be operated almost at unity power factor 2. No extra filter inductor	1. Complexity of control. 2. Comparatively high cost.	Plug-in Electric Vehicles
Two motors with two converters	[20]	Bidirectional	2	Induction motors	Non- isolated	Control circuits for 24 power switches, and contact switches	Not reported	Not reported	1. Can be operated almost at unity power factor 2. No extra filter inductors	1. Complexity of control 2. Comparatively high cost	Plug-in Hybrid Electric Vehicles
	[4]	Bidirectional	2	Not reported	Non- isolated	Contact switches	Not reported	Not reported	1. Can be operated almost at unity power factor	1. Complexity of control 2. Comparatively higher cost	Plug-in Hybrid Electric Vehicles
	[21]	Bidirectional	1	Induction motors	Non- isolated	Contact switches	93.60%	Not reported	1. Can be operated almost at unity power factor 2. No extra filter inductors	1. Cannot be applied for delta connected motors 2. Fixed value of motor leakage reactance	Plug-in Hybrid Electric Vehicles
	[17]	Bidirectional	2	Not specified	Isolated	1. More number of switches 2. Requirement of HF transformer	Not reported	Not reported	1.Can be operated almost at unity power factor 2. No extra filter inductors	1. Cost is more compared to one motor, one converter topology 2. Complexity of control	Plug-in Hybrid Electric Vehicles
	[18]	Bidirectional	2	Not specified	Isolated	Requirement of HF transformer	Improved efficiency due to low switching losses	Not reported	1. Can be operated almost at unity power factor 2. No extra filter inductors 3. Absence of DC-link capacitor	1. Modified circuit configuration 2. Cost is more compared to one motor, one converter topology	Plug-in Hybrid Electric Vehicles
One motor with two converters	[9]	Bidirectional	2	Induction motors	Non- isolated	Two dedicated converters	Not reported	Not reported	1. Comparitively less cost, less space and weight	1. Complexity of control. 2. Cost is more compared to one motor, one converter topology.	Plug-in Hybrid Electric Vehicles
	[11]	Unidirectional	1	Induction motors	Non- isolated	Control circuits for 12 power switches	86%	Not reported	1. Close to unity power factor operation 2. No independent ac/dc converter	1. Complexity of control. 2. Cost is more compared to one motor, one converter topology	Plug-in Hybrid Electric Vehicles
	[14]	Bidirectional	2	Induction motors	Non- isolated	Two set of stator windings, control circuits for 12 power switches	Not reported	Not reported	1. Close to unity power factor operation. 2. No independent ac/dc converter	1. Complexity of control. 2. Cost is more compared to one motor, one converter topology	Plug-in Hybrid Electric Vehicles
One motor with one converter	[13]	Bidirectional	2	Induction motors	Non- isolated	Extra Contact switches	Not reported	Not reported	1. Reduced complexity of control. 2. Reduced size and weight.	1. Increased magnetizing currents. 2. Expensive wound rotor induction motor	Electric Vehicles
	[20]	Bidirectional	2	Induction motors	Non- isolated	Extra Contact switches	Not reported	Not reported	1. Reduced complexity of control. 2. Reduced size and weight.	1. Increased magnetizing currents. 2. Expensive wound rotor induction motor	Plug-in Hybrid Electric Vehicles
	[15]	Unidirectional	2	Permanent magnet motor	Isolated	Need of extra capacitor	Not reported	Not reported	1. Reduced complexity of control 2. No need of extra filtering	1. Increased magnetizing currents. 2. Need of center tapped stator winding	Electric Vehicles

Many attempts are being made to utilise the stored vehicle battery energy to increase the grid capability by means of V2G power transaction [23-25]

1.6 Conclusion

This article is mainly focused on intensive analysis of some of the EV Battery charging topologies and comparing them to explore their potential in charging the Electric Vehicle battery with most efficient and economical way without much extra cost at the same time to expose the potential of EV chargers in V2G operation to strengthen the grid in supplying the local load.

References

[1] D. Thimmesch, “An SCR Inverter with an Integral Battery Charger for EVs,” IEEE Trans. Ind. Appl., vol. 21, no. 4, pp. 1023-1029, August 1985.

[2] S.-K. Sul and S.J. Lee, ”An integral battery charger for four-wheel drive electric vehicle”, IEEE Tran. on Industry Applications, Vol. 31, No 5, September/October 1995.

[3] Lixin Tang and Gui-Jia Su “Low cost digitally controlled charger for plug in hybrid electric vehicles” IEEE Energy Conversion Congress and Exposition pp. 3923-3929, Sep. 2009.

[4] L. Shi, A. Meintz, and M. Ferdowsi, “Single-Phase Bidirectional AC-DC Converters for Plug-in Hybrid Electric Vehicle Applications,” in Proc.IEEE VPPC, 2008.

[5] M. Barnes and C. Pollock, “Forward converters for dual voltage switched reluctance motor drives,” IEEE Trans. Power Electronics., vol.16, no.1,pp.83–91, Jan. 2001

[6] Subotic et al., “Isolated chargers for evs incorporating six-phase machines,” 653–664 63 IEEE Trans. Ind. Electron., 2015.

[7] S. Haghbin et al., “An isolated high-power integrated charger in electrified-vehicle applications,” 4115–4126 60 IEEE Trans. Veh. Technol., 2011.

[8] A. S. Abdel-Khalik et al., “Interior permanent magnet motor-based isolated on-board integrated battery charger for electric vehicles,” 124–134 12 IET Electr. Power Appl., 2017.

[9] G. Pellegrino et al., “An integral battery charger with power factor correction for electric scooter,” 751–759 25 IEEE transactions on power electronics, 2009.

[10] C. Shi et al., “A three-phase integrated onboard charger for plug-in electric vehicles,” 4716–4725 33 IEEE Trans. Power Electron., 2017.

[11] S. Loudot et al., “Fast charging device for an electric vehicle,” Sep. 30 2014, uS Patent 8,847,555.

[12] I. Subotic et al., “An ev drive-train with integrated fast charging capability,” 1461–1471 31 IEEE Trans. Power Electron., 2015.

[13] I. Subotic et al., “Integration of six-phase ev drivetrains into battery charging process with direct grid connection,” 1012–1022 32 IEEE Trans. Energy Convers., 2017.

[14] M. S. Diab et al., "A nine-switch-converter-based integrated motor drive and battery charger system for evs using symmetrical six-phase machines," 5326–5335 63 IEEE Trans. Ind. Electron., 2016.

[15] L. De Sousa et al., "Method and electric combined device for powering and charging with compensation means," Oct. 6 2015, uS Patent 9,153,996.

[16] I. Subotic et al., "Onboard integrated battery charger for evs using an asymmetrical nine-phase machine," 3285–3295 62 IEEE Transactions on industrial electronics, 2014.

[17] T. Na et al., "A review of on-board integrated electric vehicles charger and a new single-phase integrated charger," 288–298 4 CPSS Transactions on Power Electronics and Applications, 2019.

[18] I. Subotic et al., "Isolated chargers for evs incorporating six-phase machines," 653–664 63 IEEE Trans. Ind. Electron., 2015. 34 12 IET Electr. Power Appl., 2017.

[19] N. Bodo et al., "Efficiency evaluation of fully integrated on-board ev battery chargers with nine-phase machines," 257-266 32 IEEE Trans. Energy Convers., March 2017.

[20] D. G. Woo, G. Y. Choe, J. Kim, B. Lee, J. Hur, G. Kang, "Comparison of Integrated Battery Chargers for plug-in electric vehicles: Topology and Control," in Proc. IEMDC, 2011, pp. 1294-1299.

[21] L. Tang, G. J. Su, "A Low-Cost, Digitally-Controlled Charger for Plug-in Hybrid electric Vehicles," in Proc. IEEE ECCE, 2009, pp. 3923-3929.

[22] Yan, Xiangwu, Bo Zhang, Xiang Ning Xiao, Huichao Zhao, and Liming Yang. "A bidirectional power converter for electric vehicles in V2G systems." In 2013 International Electric Machines Drives Conference, pp. 254-259. IEEE, 2013.

[23] Foti, S., Testa, A., Scelba, G., De Caro, S., Tornello, L. D. (2020). A V2G Integrated Battery Charger Based on an Open End Winding Multilevel Configuration. IEEE Open Journal of Industry Applications, 1, 216-226.

[24] Quispe, B. B., e Melo, G. D. A., Cardim, R., Ribeiro, J. M. D. S. (2021, March). Single-Phase Bidirectional PEV Charger for V2G Operation with Coupled-Inductor Cuk Converter. In 2021 22nd IEEE International Conference on Industrial Technology (ICIT) (Vol. 1, pp. 637-642). IEEE.

[25] Luh, M., Blank, T. (2021, September). Auxiliary Resonant Commutated Pole Inverter (ARCPI) with SiC MOSFETs for efficient Vehicle-to-Grid (V2G) charging. In 2021 23rd European Conference on Power Electronics and Applications (EPE'21 ECCE Europe) (pp. P-1). IEEE.