High Impedance Grounding for Onboard Plug-in Hybrid Electric Vehicle Chargers

Babak Farhangi, Hamid A. Toliyat
Advanced Electric Machines and Power Electronics Lab.
Department of Electrical and Computer Engineering
Texas A&M University
College Station, TX 77843-3128, USA
farhangi@ieee.org, toliyat@tamu.edu

Ammon Balaster
Director Development
Elithion, Inc.
Boulder, Colorado, USA
ammon@elithion.com

Abstract—Plug-in Hybrid Electric Vehicles (PHEV) are currently on the early stages of production. PHEV interacts with the electric grid to exchange power through a power conditioner unit (PCU). Developing a PHEV PCU is a subject of growing interest in industry and academia. The related standards are currently under development and the required guidelines to design and develop PHEV PCU are not well established. This paper investigates the available standards regarding grounding requirements and the role of galvanic isolation among the concepts affecting the design procedure of onboard PHEV PCUs. Both isolated and non-isolated PCUs are studied in relation to operating conditions, and safety concerns. The high impedance grounding method is suggested as a possibility of grounding connection and compared to the direct grounding connection for both isolated and non-isolated PHEV PCUs.

Keywords - Plug-in Hybrid Electric Vehicle (PHEV), Power Conditioner Unit (PCU), Charger, Grounding, High Impedance Grounding, Galvanic Isolation

I. INTRODUCTION

In Hybrid Electric Vehicles (HEVs), a conventional internal combustion engine is combined with an electrical propulsion system. A Plug-in Hybrid Electric Vehicle (PHEV) is a type of HEV which has a battery storage of 4kWh or more, a means of charging the battery from an external source of electricity and the ability to drive at least 10 miles in all electric mode [1]. The HEV market has been growing in recent years and different manufacturers are launching PHEV models [2]. PHEV technology offers benefits such as improved fuel economy, reduced emissions, and energy storage for transportation and electric network, all of which are promoted in the Energy Independence and Security Act (EISA) of 2007 [3]. A PCU exchanges power between a PHEV and the electric grid. Three major functions of such a PCU are charging the vehicle batteries, supplying constant AC loads (Vehicle to Home: V2H), and injecting power into the grid (Vehicle to Grid: V2G). Onboard PCUs are the subject of the study in the present paper. The Electric Advisory Committee (EAC) 2008 report suggests full V2G implementation as a long term goal for 2020 and beyond [4]. Much like the present status of PHEVs, the related standards are either in early stages of practice or under development. Reviewing the related standards can define certain guidelines and regulations affecting the design and development of power converters used in such applications. This influences the topology, cost and efficiency of PCUs. This paper briefly overviews the available standards related to PHEV PCUs to investigate the grounding requirements when connected to the grid to perform charging, V2H and V2G functionalities. The role of galvanic isolation is evaluated by analyzing two voltage sourced charger topologies representing non-isolated and isolated PHEV PCUs. The idea of high impedance grounding of the onboard PHEV PCU to the grid is suggested by the authors in response to the associated standards. A few case studies compare fault conditions in all four possible configurations, including the isolated and non-isolated topologies for both direct and high impedance grounding.

II. GROUNDING REQUIREMENTS OF VEHICLE CHARGING SYSTEM

According to the envisioned roadmap for the PHEV PCU, the short term goal of such application is to provide a means of charging the vehicle. At the time of writing this paper, the released standards are about chargers. Chargers may be stationary or onboard on the vehicles. The onboard chargers are the subject of this paper's study. The SAEJ1772 standard covers the requirements of conductive charging of EV/PHEVs in North America [5]. FMVSS 305 [6] is another related standard. The IEEE 1547 standard [7] addresses interconnecting distributed resources with the electric grid. V2G operation of PCU is subject of this standard. Both IEEE 1547 and SAEJ1772 refer to the National Electric Code (NEC) [8] for grounding requirements in the United States. The grounding requirements of the PHEV PCU will be studied in this section.

Two nodes of an electric circuit are isolated when there is no electrical connection between them; such nodes can be separately grounded. The high voltage battery in a PHEV should be isolated from the vehicle chassis. In the connection scheme illustrated in [5], the ac ground is connected to the vehicle electric ground, which is the vehicle chassis. If the charger is a non-isolated converter, the battery terminals are connected through the charger circuit ac line terminals to the grid during normal converter operation. If there is a connection between neutral and ground, the battery terminal is electrically connected to the vehicle ground; this violates FMVSS 305 [6]. Because 240 Vac lines are never connected to ground, the battery remains isolated from the vehicle chassis. In contrast, during 120 VAC operation an ac neutral line is connected to the charger input terminal. This neutral line is often grounded (bonded) at the ac circuit breaker panel thus completing an
electrical conduction path from battery terminal to the chassis ground. If the charger is isolated, the battery terminals are isolated from the ac terminals and are therefore always isolated from the vehicle ground. When the charger is not an isolated converter, a high impedance ground may be used as described in this paper. SAE J1772 refers to NEC-article 625 for the onboard ac charging system configuration [8]. Article 625 refers to Article 250 for ground pole requirements. In a vehicular electric system it is not possible to provide an effective ground fault path to the earth. The vehicle is a mobile system on wheels isolated from the earth. The electric system is grounded to the vehicle chassis which complies with NEC-Article 250.4.B. It limits the chassis voltage to ground voltage potential. At the point of common coupling, an isolated ungrounded dc system may be grounded to ac ground through the ac neutral conductive ground path or a high impedance ground. A high impedance ground limits the ground fault current. A high impedance grounded system needs to be serviced by qualified persons, must have ground-fault detectors installed on the system, and should not serve line to neutral loads. According to [8] the low voltage electric system of vehicles with voltages less than 50 V does not need grounding. Due to the fact that the high voltage side of the vehicle electric system should not be connected to ac ground through a low impedance path, implementing a high impedance ground before the equipment ground pole achieves reference grounding as required by NEC-250.4.B. Hence a high impedance ground can isolate the vehicle electric system from the ac system satisfying all present standards. Figure 1 shows the addition of $R_{\text{GND}}$ to configuration illustrated by [5] in order to implement high impedance grounding.

III. TOPOLOGY COMPARISON OF ONBOARD CHARGERS

A PCU employed in a PHEV is a two-port power converter. It has an ac port at the line side and a dc port at the high voltage battery side. In V2G and V2H applications, bidirectional power flow is required; whereas, a charger needs only a unidirectional power flow from the line to the battery. This power converter is placed where the charger block is located in Figure 1. Figure 2 shows a realization of a non-isolated charger using voltage source converters. This topology includes a boost rectifier with unity power factor control and a regulated DC link from the ac power. If the minimum battery voltage is less than the peak amplitude of the ac line voltage a buck dc/dc converter is required to charge the battery from the dc link. Replacing the dc/dc converter with an isolated converter results in an isolated PCU as it is shown in Figure 3. Compared to the non-isolated converter the isolated topology adds complexity and cost, and may lower conversion efficiency. More examples of non-isolated and isolated PHEV PCU can be found in [9-17].
This section studies isolated and non-isolated PHEV chargers both during normal operation and when the ground is connected to the neutral. Both conductive and high impedance grounding are investigated. Figure 4 shows the block diagram of the simulation test bed implemented in MATLAB SIMULINK. The charger block contains the converters presented in Figure 2 and Figure 3. The rectifier stage is identical in both converters and it has a closed loop controller to deliver unity power factor. The non-isolated charger uses a current controlled buck converter and the isolated charger uses a dual active bridge as the dc/dc stage. The battery is modeled as a 350 Vdc source and an internal resistance. The simulation test bed includes a human body model as it is shown in Figure 5 [18]. This model is used to investigate what happens when a human touches the line. The switches marked 1 to 4 are used to configure different case studies. Arranging these switches as shown in Figure 4 makes a vector representing each simulation case study. If the switch value is 1 it means the switch is connected. Each case study will be described verbally in the text, and the respected readers may refer to Figure 4 according to the case study vector to determine how the simulation test bed is configured.

A. Neutral not Grounded: Case Study (0010)

In the first case study both chargers operate at 6 kW, 240 Vac line. The line and neutral ports are connected to the charger; the chassis is grounded while the neutral is not bonded to the ground (0010). Both chargers operate properly as the rectifier stage waveforms are presented in Figure 6.

B. Neutral is Grounded: Conductive Ground Case Study (1010) vs. High Impedance Ground Case Study (1100)

In the second case study, the neutral is bonded to ground, and ground is connected to the chassis, (1010). This may be due to a fault or a practice in wiring the single-phase 120 Vac panel. The non-isolated charger cannot operate in this condition while the isolated charger works fine as shown in Figure 7. The charger protection mechanism will shut down in this case for the non-isolated charger. In contrast, when the neutral is connected to the chassis through a 5 MΩ high impedance ground both chargers operate well, case study (1100), Figure 8.
Human safety is an important concern for the onboard PHEV PCU. It is common to relate the isolation requirements to the safety issues. The following case studies analyze how these facts are related. The next case studies investigate the outcome of a human touching the line while he/she is connected to the chassis ground. As a residential line is more accessible, compared to a PHEV battery which is sealed, there is a higher chance of occurrence for this fault, as compared to a fault on the battery side. The SAEJ1772 connection plug prevents such an event when the person does not work with any other ac equipment and the ground fault indicator can shut down the charger before neutral current exceeds a safe limit of 5 mA if the charger follows SAEJ1772 requirements.

According to simulations whenever someone touches the line in the case of non-isolated charger, he/she can get shocked. While for the isolated charger, if there is no connection between the neutral and the ground or the chassis has a high impedance ground connection, the person is not shocked, even though there is no ground fault indicator installed. The details are provided in the following case studies.

C. Human to Line Fault, Grounded Chassis, (1011)

The neutral is bonded to the ground and the chassis is directly grounded. Referring to the case study A only the isolated charger is able to operate in this configuration. If someone touches the line, as can be seen in Figure 9, a high current would shock the person if this fault happens. The high frequency isolation of the onboard charger is placed in the middle of PHEV PCU and does not help in this case. The current $I_H$ and the voltage $V_H$ can be seen in Figure 9. Figure 5 shows where these meters are located.

D. Human to Line Fault, High Impedance Grounded Chassis, (1101)

The same fault is simulated when chassis is connected to the neutral through a $5 \, \Omega$ resistor (1101). If the charger is non-isolated the current shocks the person as shown in Figure 10, while if the charger is isolated the current is controlled below 0.1 mA and would not shock the person, Figure 11.
The brief introduction to the status of PHEVs and the PHEV PCU roadmap described the importance of this product. Reviewing the related standards provided guidelines for the design procedure of the PHEV PCU. Grounding schemes and isolation requirements of PHEV PCUs also were investigated. The main contribution of this study evaluates the idea of implementing a high impedance reference grounding connection at the point of common coupling between the vehicle chassis and the electric network ground which is not foreseen in the latest edition of SAEJ1772 standard. This approach lets a non-isolated converter operate with both 240 Vac and 120 Vac plugs regardless of whether or not neutral is bonded to ground. The provided case studies offer a tool to compromise between protection facilities and selected power converter topologies to achieve a cost effective PHEV PCU for different applications. This is important to increase market penetration of PHEV and their functionalities. The suggested grounding scheme may be further evaluated by different standards before utilization.

**REFERENCES**


