Modeling of PV based Bidirectional Battery Charger for Electric Vehicles

Moturu Arun Bhargav[1], Dr. Gadi Venkata Siva Krishna Rao[2]

[1]*Post graduate scholar, Dept. of Electrical Engineering, Andhra University, Visakhapatnam, Andhrapradesh, India*
[2]*Professor, Dept. of Electrical Engineering, Andhra University, Visakhapatnam, Andhrapradesh, India*

---***---

Abstract - *As hybrid vehicles gain popularity among the consumers, current research initiatives are focused towards developing plug-in electric and hybrid vehicles that can exploit utility power to charge vehicle batteries and therefore less dependent on the gasoline usage. Power electronic systems are being developed to allow plug-in vehicles to be vehicle-to-grid (V2G) capable where the vehicles can work as distributed resources and power can be sent back to the utility. In this paper a review of different plug-in and V2G capable vehicles are given along with their power electronics topologies. The economic implication of charging the vehicle or sending power back to the utility is described in brief. Finally, all vehicles with V2G capability must meet the IEEE Standard 1547 for connecting to the utility. Brief descriptions of the requirements and testing that must be followed for V2G vehicles to conform the IEEE 1547 standards are also discussed.*

Key Words: Autonomous energy management system, plugin electric vehicle, energy storage, bidirectional charger, grid-to-vehicle, vehicle-to-grid.

1. INTRODUCTION

The continuous rise in gasoline prices along with the increased concerns about the pollutions produced by fossil fuel engines are forcing the current vehicle market to find new alternatives to reduce the fossil fuel usage. Along with the research on bio-fuel driven engines; different electric vehicles and hybrid electric vehicles are evolving as viable alternatives to replace, or at least reduce, the current fleet of fossil fuel driven vehicles. Although current manufactured electric/hybrid vehicles are being marketed as a way to reduce fossil fuel usage, several promising technologies are being demonstrated that can utilize power electronics to charge the battery from the utility using plug-in vehicles or act as a distributed resource to send power back to the utility with vehicle-to-grid capabilities.

In this paper, different plug-in vehicle topologies are described to review the power electronics required for them. The newly evolving V2G technology is also discussed along with economics and compliance requirements to allow the vehicle to be connected to the grid. Before going into the details of power electronics required for the electric/hybrid vehicles, the common forms of these vehicles are described next to get accustomed with the terminologies.

1.1 Electric Vehicles

A typical electric vehicle (EV) has a battery pack connected to an electric motor and provides traction power through the use of a transmission. The batteries are charged primarily by a battery charger that receives its power from an external source such as the electrical utility. Also during regenerative braking, the motor acts as a generator which provides power back to the batteries and in the process slows down the vehicle. The primary advantage of an EV is that the design is simple and has a low part count. The primary disadvantage is that the driving range of the vehicle is limited to the size of the battery and the time to re-charge the battery can be from 15 minutes to 8 hours depending on how far the vehicle was last driven, the battery type and battery charging method.

1.2 Hybrid Electric Vehicles

The components that make up a typical hybrid electric vehicle (HEV) include a battery pack, motor controller, motor/generator, internal combustion engine, transmission and driveline components. The batteries are charged through the use of the on-board internal combustion engine and generator. In a plug-in hybrid electric vehicle (PHEV), the batteries can also be charged through the use of a battery charger that receives its power from the utility. The best PHEV design will allow the vehicle to operate on electric power only reducing the amount of time that the engine runs. When the vehicle is not operating, the battery can be charged through the use of a battery charger that is "plugged in" to the electrical utility or other energy sources. A PHEV normally has a larger battery pack than a HEV. The advantage of a PHEV over an HEV is that due to external battery charging, the vehicle can run longer on electric power which in-turn reduces engine fuel consumption.

1.3 Fuel Cell Vehicles

The prototype fuel cell vehicles (FCV) that are currently under development mostly utilize an on-board tank to store pressurized hydrogen. Hydrogen and conditioned air are fed to a proton exchange membrane (PEM) stack to develop DC power. The configuration is very similar to the electric vehicle configuration in which a electric motor/generator provides the mechanical power for traction. The on-board batteries allow the energy to be stored during regenerative braking and provide peak power to the motor controller during vehicle acceleration. A plug-in fuel cell vehicle (PFCV) has a battery pack and a fuel cell that is connected to an electric motor that provides traction power to the wheels through a transmission. The batteries can be charged by the use of a battery charger that receives its power from the utility but can also be charged by using the fuel cell.

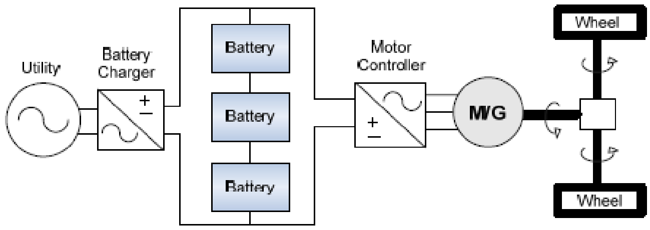

Fig -1: Typical EV configuration

2. PLUG-IN VEHICLES

According to the Electric Power Research Institute (EPRI), more than 40% of U.S. generating capacity operates overnight at a reduced load overnight, and it is during these off-peak hours that most PHEVs could be recharged. Recent studies show that if PHEVs replace one-half of all vehicles on the road by 2050, only an 8% increase in electricity generation (4% increase in capacity) will be required. Most of the electric vehicles that are of plug-in type, utilize on-board battery chargers to recharge the batteries using utility power. The simplest form of a plug-in electric vehicle is shown in Fig. 1. This configuration consists of a battery system and a motor controller that provides power to the motor, which in-turn supplies power to the wheels for traction. Many of today's EVs use a permanent magnet electric motor that can also act as a generator to recharge the batteries when the brakes are applied. During regenerative braking, the motor acts as a generator that provides power back to the batteries and in the process slows down the vehicle. Friction brakes are used when the vehicle must be stopped quickly or if the batteries are at full charge.

The components that make up a typical HEV include a battery pack, motor controller, motor/generator, internal combustion engine, transmission and driveline components. The primary power electronics include a DC-AC motor controller which provides three-phase power to a permanent magnet motor. The Toyota Prius HEV configuration is given in Fig. 2. The Prius design uses two permanent magnet motors/generator, one of 10kW and the other of 50kW. The battery is connected to a booster and inverter before feeding to the motor/generators. The power electronics are bidirectional and used for both charging the battery and powering the motors. The motor/generators and gasoline engine feed into a planetary gear set. The system operates in a continuously variable transmission (CVT) mode where the gear ratio is determined by the power transfer between the battery, motor/generators and gasoline engine. The batteries can also be charged using regenerative braking of the large motor/generators. There is no provision to charge the batteries externally. For plug-in hybrid electric vehicles, batteries are charged when they are not being driven. This is normally accomplished through a utility connected AC-DC converter to obtain DC power from the grid. The batteries can also be charged directly from a solar resource using a DC-DC converter or from a wind source using an AC-DC converter. Energy flow is unidirectional as power is taken from the utility to charge the battery pack. A Toyota Prius configuration with PHEV conversion is shown in Fig. 2. The battery voltage for most converted PHEVs are maintained at the same level as the original design (typically 200-500 VDC) and battery modules are added in parallel to increase the energy capacity of the battery pack, thus allowing the electric motor to run more often than the original HEV design. Some of the PHEV conversion companies include: CalCars, Energy CS, Hymotion, Electrovaya, and Hybrids Plus, and most of them use lithium batteries.

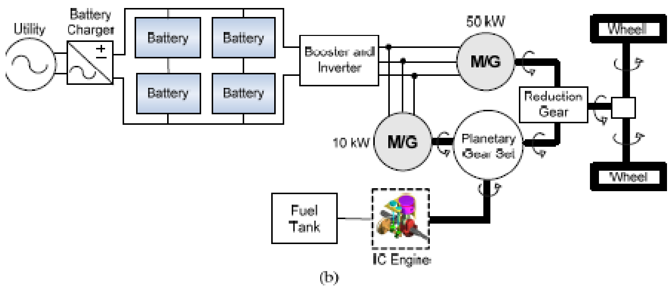

Fig -2: Configurations of converted PHEV

Table -1: Average Cell Voltage during Discharge in Various Rechargeable Batteries

Electrochemistry	Cell Volts	Remark
Lead-acid	2.0	Least cost technology
Nickel-cadmium	1.2	Exhibits memory effect
Nickel-metal hydride	1.2	Temperature sensitive
Lithium-ion	3.6	Safe, contains no metallic lithium
Lithium-polymer	3.0	Contains metallic lithium
Zinc-air	1.2	Requires good air management to limt self-discharge rate

2.1 Plug-in Electric Vehicle Charger Topology

The desirable characteristics for the charger are power bi-directionality (V2G and G2V), power factor equal to one, capability of performing power control, low PQ impact, construction and topology simplicity, and regular 16 A single-phase plug compatibility. This charger does not allow performing fast charge, being 2.3 kW (10 A, 230 V) the advisable maximum power for a single-phase household-type plug. This power range is defined based on EU standards and power grid restrictions, since higher power ranges could represent a negative impact on the low voltage (LV) grid in terms of PQ and EMS requirements [22]–[24]. Regarding the voltage level of the battery pack, the proposed design is focused on L-category vehicles (two-, three- and four-wheel vehicles such as motorcycles, mopeds, quads, and minicars), as the one studied in [25], but could be extended to other voltage levels.

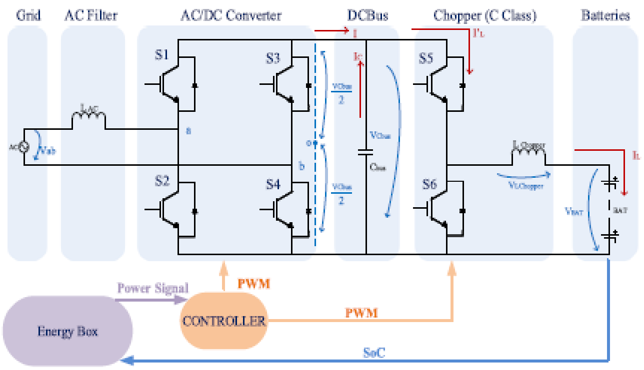

Fig -3: PEV charger topology

The topology presented in Figure 3 is formed by three legs of two Insulated Gate Bipolar Transistors (IGBT), denoted by $S_j \in \{1, \ldots, 6\}$. The IGBTs are used due to their good compromise characteristics associated with voltage, switching frequency and current limits. These power switches are used for an AC/DC converter that operates as a controlled rectifier or as an inverter for G2V or V2G operation modes, respectively, and for a DC/DC converter (C class chopper) in which the power used for both modes is restricted, as discussed below. The features of converters meet the desired bi-directionality, where the chopper operates as buck and boost for G2V and V2G operation modes, respectively. Some passive elements for filtering and energy storage purposes are also designed and implemented, which are relevant for achieving proper system dynamics, stability and power quality.

3. CONTROLLERS DESIGN

The controllers are PI-based and they aim at properly controlling the IGBT switching following voltage and current references.

For the chopper controller design, some assumptions were made to facilitate circuit analysis: capacities in both sides of the chopper are high enough for considering constant voltage, low L capacity (when compared to the C_{bus} capacity), and negligible switching losses.

For establishing the control laws, it was necessary to determine the differential equations describing the energy demand of the converter (see (21)–(24)), according to Kirchhoff laws. Typically, the state variables in the converters are associated with the energy stored in capacitors and inductors, leading to V_{Cbus} in the DC bus, VBAT in the batteries, and IL in the chopper inductor as displayed in Figure 4.

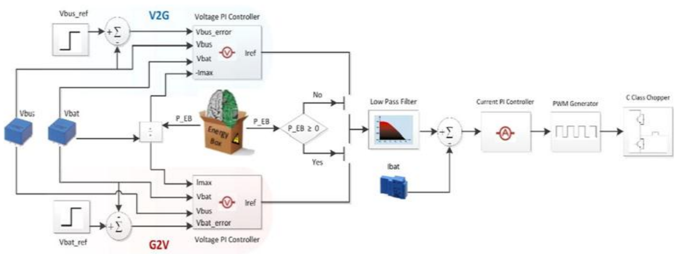

Fig -4: DC/DC converter controller architecture for V2G and G2V operation modes

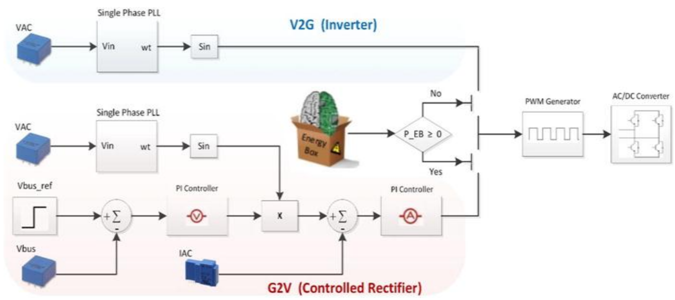

Fig -5: AC/DC converter controller architecture for V2G and G2V operation modes.

The controller for the rectifier is also PI based. A daisy chain of two PI controllers for DC bus voltage and AC current regulation is used. For AC current regulation, a phase-locked loop (PLL) is also used providing AC current control reference as stated in [30]. This controller was firstly tuned using a pole placement approach and then refined through experimental tests, being the final IGBT PWM signal provided by the unipolar PWM generator. The controller used for the AC/DC converter when this works as inverter is based only on the unipolar switching method. A unit sinusoid reference provided by a PLL is used, which is synchronized with the voltage grid. In this operation mode, the DC bus available power was already restricted by the chopper, being at this point only mandatory inverting the DC bus voltage in a proper way. Both AC/DC converter controllers are presented in Figure 5.

4. EXPERIMENTAL RESULTS

The experimental results have been obtained using a reduced scale setup (with power levels 5 times lower than the full scale). It is important to note that in this reduced scale setup the D_{CBUS} voltage was stabilized around 108 V and P_{max} was ±460W, being the "Advisable Energy Levels" used for sizing, simulation and further full-scale implementation. This setup uses the LEM HY25-P and LV 25-P transducers for current and voltage acquisition, respectively, as presented in Figs. 3 and 4. A DSP from NI for control and data logging purpose is also used, jointly with other laboratory equipment and several electronic components, as presented in Fig. 6.

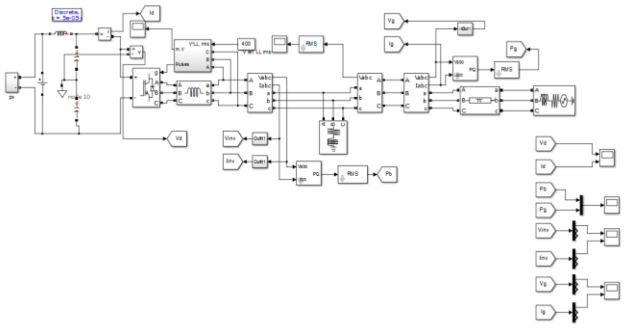

Fig -6: Simulation Diagram for PV based V2G System

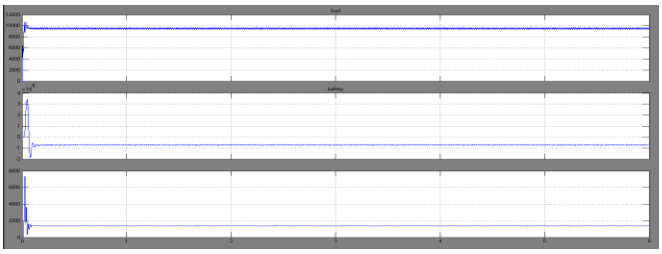

Fig -7: Simulation Result for PV, Grid and Battery Powers

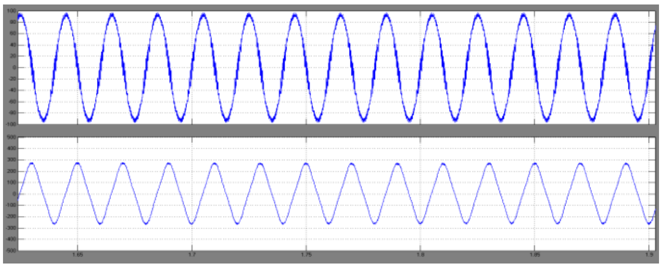

Fig -8: Simulation Result for DC Voltage and Current

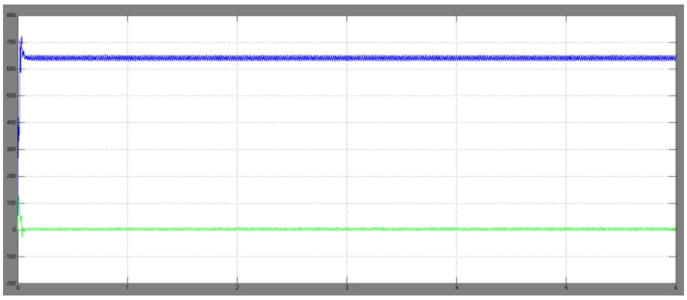

Fig -9: Simulation Result for Inverter Voltage and Current

5. CONCLUSION

Use of power electronics can convert electric and hybrid vehicles into plug-in or even V2G capable. With adequate power conversion, a plug-in vehicle can be charged from utility or a V2G capable vehicle can send power back to the utility. With ever rising gas prices and with energy policy thrust towards distributed resources, electric and hybrid vehicle with plug-in and V2G capability will surely get increased consumer and commercial attention in near future. Currently, the National Renewable Energy Laboratory (NREL) is reviewing various plug-in and V2G capable vehicles and performing tests to verify utility connection standards for these vehicles. The test results will be published in future papers as soon as the testing is complete.

6. REFERENCES

[1] Pacific Gas and Electric Company (PG&E) News Release, "Pacific Gas and Electric Company energizes silicon valley with vehicle-to-grid technology," April 2007.

[2] Electric Power Research Institute (EPRI) Report, "Technology primer: the plug-in hybrid electric vehicle," pp. 1-2, 2007.

[3] T. Jahns and V. Blasko, "Recent advances in power electronics technology for industrial and traction machine drives," Proc. of the IEEE, vol. 89, no. 6, pp. 963 – 975, June 2001.

[4] K. Wipke, S. Sprik, J. Kurtz, and H. Thomas, "Learning demonstration progress report – September 2007," National Renewable Energy Laboratory Report, NREL TP-560-42264, pp. 41, September 2007.

[5] K. Parks, P. Denholm, and T. Markel, "Costs and emissions associated with plug-in hybrid electric vehicle charging in the Xcel Energy Colorado service territory," National Renewable Energy Laboratory Report, NREL TP-640-41410, pp. 29, May 2007.

[6] T. Markel, A. Brooker, J. Gonder, M. O'Keefe, A. Simpson, and M. Thornton, "Plug-in hybrid vehicle analysis," DOE Milestone Report, NREL MP-540-40609, pp. 189, November 2006.

[7] W. Short and P. Denholm, "Preliminary assessment of plug-in hybrid electric vehicles on wind energy markets," National Renewable Energy Laboratory Report, NREL TP-620-39729, pp. 41, April 2006.

[8] J. Tomic and W. Kempton, "Using fleets of electric-drive vehicles for grid support," Elsevier J. of Power Sources, vol. 168, no. 2, pp. 459– 468, June 2007.

[9] E. Hirst and B. Kirby, "What is system control," Proc. of American Power Conference, Chicago, IL, April 1999.

[10] B. Kirby, "Frequency regulation basics and trends," Oak Ridge National Laboratory Report, ORNL TM-2004-29, pp. 32, December 2004.