Utilization of Resonant Controller to Control the Power Converter in Vehicle-to-Grid Application

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Abstract

By using bidirectional AC-DC power converters to interface the grid with the plug-in electric vehicles (PEV) batteries, the vehicle-to-grid (V2G) approach is enabled. By this approach, the PEV batteries can work as distributed storage systems that deliver electric energy to the grid under peak power requests. In addition, the battery-converter set can be exploited to execute ancillary functionalities such as to stabilize the grid voltage by injecting reactive power and to improve the power grid quality by filtering current harmonics and by balancing the line currents. This paper presents at first some possible scenarios for the application of the V2G approach. Then the functionalities offered by the V2G approach are addressed. An improved controller is applied in order to achieve low input current harmonics. The Proportional resonant controller is utilized for the V2G mode. Compared with conventional PI controllers, the proposed controllers greatly enhance the grid connected converter's performance in the aspects of low harmonics output.

Key Words: Electric vehicle, Vehicle-to-Grid, Bi-directional converter, Proportional resonant controller.

1. Introduction

As the number of plug-in electric vehicles (PEVs) entering into the market increases, the load of the grid becomes more and more sizeable due to the need of charging the PEV batteries [1]. On the other hand, the availability of a lot of batteries interfaced to the grid could be exploited to strengthen, instead of weakening, the grid operation. PEV batteries, indeed, especially if grouped together in a large cluster, could be actively participating in the power transactions with the grid, behaving like a distributed electric energy resource [2], [3]. This approach, termed vehicle-to-grid (V2G) approach, adds new functionalities to the basic rectifying operation of a vehicle charger because of the capabilities offered by the batteries of bidirectional routing and storage of electric energy. Under this perspective, the PEV batteries can be considered as a grid resource that delivers electric energy to the grid under peak power requests. Moreover, ancillaries' functionalities can be executed such as grid voltage stabilization, power quality improvement, and current balancing. by injecting reactive power backup under peak demands, energy storage/generation to even out power fluctuations, and reactive power absorption for voltage regulation purposes [2]-[5].

To execute these functionalities, two basis points must be met. First, a bidirectional AC-DC converter must interface the batteries with the grid. The main requirements for the converter are as follows: i) easy control of the bidirectional power flow, ii) good regulation and shaping of the AC side voltage/current waveform, and iii) low ripple and good voltage regulation on the DC side [12]. Second, a V2G system must be aware of the states of grid and battery and the demands of grid operator and must be controlled accordingly. The main functionalities that a V2G system can be execute are as follows: i) when the utility is lost, it can immediately supply the loads, ii) when the utility recovers, it must be arranged to operate in the charging mode (the battery cluster is charged), in the discharging mode (the battery cluster delivers energy to the grid) and in the floating mode (the power out of the battery cluster is minimized), iii) it can stabilize the grid by injecting reactive power into it, and iv) it can improve the power quality by filtering the harmonics and/or by balancing the grid load.

Therefore, the research related to V2G systems includes the following subjects: the development of suitable AC-DC converter equipment and the development of control architecture and algorithms to execute the various functionalities [7]-[10].

In this paper, a bi-directional grid-connected converter was simulated and improved control methods is used for the converter to achieve better performance compared to a conventional PI controller.

2. Vehicle-to-grid configurations

Today's PEV can only charge its batteries using AC power typically provided by utility grid. PEV's can also be designed so that power can be sent back to the grid. A vehicle with this type of technology is defined as being V2G capable. All of the topologies, as discussed in [1], utilize a battery pack to store DC energy that must be converted to AC power to be exchanged with the utility for V2G applications. The unique aspect of power...
The electronics for V2G vehicles is that it must be bidirectional, that is capable of both taking power (during charging) and providing power (during discharge) from/to the grid. The V2G vehicles for distributed energy applications can provide voltage and frequency regulation, spinning reserves and electrical demand side management. If used in large numbers, V2G vehicles have the potential to absorb excess electricity produced by renewable sources, such as wind power, when the grid is operated at low load conditions. Studies show that V2G vehicles could be a significant enabling factor for increased penetration of wind energy. Controls can be developed that would allow an operator to dispatch these renewable resources through the use of the battery of the vehicles when they are needed by the utility. During periods of low demand, excess generation can be used to charge the onboard batteries. A set of fleet vehicles that are parked at a company's facility could potentially be used to provide electricity during periods of high demand to offset the facility's electrical demand charges.

A wireless configuration for independent system operator (ISO) to control charging and discharge of a V2G battery is shown in Fig. 1. This can be done in the view of keeping the utilities Area Control Error (ACE) low. ACE is a measure that indicates the deviation of the generation in a power system area from the load.

Each V2G capable vehicle must have three required elements: a power connection to the grid for electrical energy flow, control or logical connection necessary for communication with grid operators, and on-board or off-board (in the infrastructure) precision metering. The configuration depicted in Fig. 1 shows that the power electronics being controlled use a wireless cell connection to communicate with the V2G capable vehicles. While these vehicles could provide peak power demand-response resource, their economic values do not generally justify the expense. These services are needed for just a few hours each year, thus the potential revenue from providing these services is limited. It is suggested by the researchers that the most promising markets for V2G are for those services that the electric industry refers to as ancillary services such as voltage and frequency regulation [1].

State-of-charge regulation, battery life, power capacity, energy capacity, and available power connection will be critical factors in the design of these vehicles. The number of battery discharges, charges and state-of-charge control directly effects battery life. Typical V2G vehicles utilize either a Nickel Metal Hydride or Lithium-Ion battery pack.

A promising V2G architecture for supplying battery energy to the grid is the integrated motor controller/inverter shown in Fig. 2. This architecture utilizes for the connection to the grid the same power electronics used for the motor supply, thus eliminating the need for a separate battery charger. To this end, the power electronics is reconfigured according to the operation carried out.

### 3. Comparing Vehicle-to-Grid with Vehicle-to-Home

Vehicle-to-home (V2H) avoids the infrastructure and tariff problems associated with vehicle-to-grid. V2H would be used to level the house electricity demand profile; sharp power increases associated with running high power appliances for short periods would be controlled. The resulting smoother demand from the grid would give electric suppliers a more manageable load. With energy storage in place the peak demands could be shifted such that electric load remains more constant throughout the day. This would allow more efficient and cost effective electricity generation to be used. Vehicle-to-home would improve the effectiveness of renewable energy sources; excess generation can be stored and used when generation is low. Vehicle-to-grid (V2G) is parallel i.e. within a grid any car can be used to power any house by feeding its power back to the grid. In contrast, vehicle-to-home is more limited; a single vehicle is used to supply a single house. The trade-off is simplicity versus flexibility; more vehicles working together offer flexible storage but will be more difficult to control. A further
discussion point is locality. V2G and V2H are a form of distributed generation; the electrical load is geographically close to the electrical source. Transmission is therefore minimal compared to centralized generation so costs of transmission infrastructure and transmission losses are reduced. V2H represents the simplest case with regards to infrastructure and transmission. A single house operating V2H will have simple infrastructure requirements and negligible transmission losses. V2G can vary in infrastructure complexity and transmission distance depending on the number of vehicles involved and the geographical area serviced. A group of vehicles acting in a group as an electrical source is a more technically challenging situation than V2H and opens up the possibility of larger transmission distances [14].

4. Improved Control Method by Using Proportional Resonant controller

The bi-directional charger is the interface between the grid and PEV. This converter will control the power factor to unity and regulate the DC bus voltage and control the input current harmonics to be low. It can operate in three modes; the first is a battery charger. The second mode is V2G mode, that converter operates as the DG inverter to control its output current to be in phase with the grid voltage to feed real power back to the grid. The third mode is “Vehicle to Home” (V2H): the converter serves as a UPS to supply critical loads at a home when the grid has failure. Moreover, because vehicles are inherently easily moved, PEVs can be a movable power source for use in other applications.

As shown in Fig. 3 the conventional control uses the PI controller. In Fig. 4, the proposed control method is to use Proportional Resonant (PR) and integral controller in dq reference frame (PR+I).

The main goal of a Proportional Resonant (PR) controller is to obtain zero steady-state error for sinusoidal inputs with a specified frequency. In the continuous-time domain, the transfer function of a PR is given by [17], a block diagram of the PR is shown in.

\[
PR = kp + \frac{2k_s}{s + \omega_0}
\]

(1)

\[
PR + 1 kp + \sum_{n=6,12} \frac{2k_s}{s + (n\omega_0)^2} + \frac{k_i}{S}
\]

(2)

Where \( kp \) is the proportional gain, \( kn \) is the gain of resonant controller, \( \omega_0 \) is the resonance frequency of the PR that is fundamental frequency of the grid, and \( ki \) is the integral gain. The employment of PR controller, compared with other solutions, gives the following advantages.

- There is zero steady-state error for sinusoidal waveforms having the same frequency as \( \omega_0 \), this feature can be exploited for Active Power Filters (APF), where the signal frequencies are well defined and practically constant (mains’ frequency and its multiples).
- The PR acts as a resonant filter, tuned on \( \omega_0 \); in this way, multiple PRs with different resonance
frequencies can operate in parallel without interfering with each other.

- The PR can operate with both positive and negative sequence signals [17]-[20].

If V2G converter is utilized as APF the current control must deal with non-sinusoidal reference currents whose harmonic spectrum consists of a fundamental component and of the harmonics drawn by the nonlinear load. For diode or thyristor front-end rectifiers (as a load), these harmonics are of order \((6k \pm 1)(k = 1, 2, ..., )\) of the fundamental frequency \(\omega_c\). For balance reference waveforms, as explained above, harmonics of order \((6k-1)\) are negative sequence and harmonics of order \((6k + 1)\) are positive sequence that are shown in Table 1. If we consider the fundamental frequency component as a positive-type sequence, current harmonics and sequences, that correspond to balanced waveform, in synchronous reference frame SRF are illustrated in Table 1. The SRF uses a Phase Lock Loop (PLL) to catch the phase information of the grid voltage. To better show the advantages of the proposed control method, simulations of both control methods were carried out. The simulation uses the data from the measurement to emulate the grid voltage with the low order harmonics components. Here 5th and 7th harmonics are considered and percentage is shown in Table 2.

Fig. 6 and Fig. 7 show the comparison of the output current and reference current waveform between the improved control method and the conventional control method clearly demonstrating the improved control method's immunity to grid background harmonics. There is no much bigger difference between the two current harmonics, even the current generated by the conventional method may be allowed. However, this current will be a potential issue to the power quality of the whole power system with a large penetration of the PEVs in the coming future.

Fig. 8 and Fig. 9 are shown the error in one of the axis (\(\alpha-\)axis). Here both simulation results are extracted from \(\alpha\beta\) frame in order to compare two methods together; however it is possible to apply the proposed configuration just in \(dq\) frame.

![Diagram](image1)

**Fig. 6**: Simulation result using conventional PI controller; grid voltage, reference and output current of converter, (a) \(\alpha\)-component (b) \(\beta\)-component

| Harmonic order in (d,q) frames | Harmonic in (\(\alpha,\beta\)) Frame | Sequences |
|--------------------------------|---------------------------------|-----------|
| \(0\)                           | 1st                             | Positive, fundamental |
| \(-6\)                          | 5th                             | Negative  |
| \(+6\)                          | 7th                             | Positive  |
| \(-12\)                         | 11th                            | Negative  |
| \(+12\)                         | 13th                            | Positive  |

**Table 1**: Harmonics components of the grid voltage

| Harmonic In (\(\alpha,\beta\)) Stationary Reference Frame | Percentage |
|----------------------------------------------------------|------------|
| \(5th\)                                                  | 18%        |
| \(7th\)                                                  | 14%        |

| Harmonic order in (d,q) frames | Harmonic in (\(\alpha,\beta\)) Frame | Sequences |
|--------------------------------|---------------------------------|-----------|
| \(0\)                           | 1st                             | Positive, fundamental |
| \(-6\)                          | 5th                             | Negative  |
| \(+6\)                          | 7th                             | Positive  |
| \(-12\)                         | 11th                            | Negative  |
| \(+12\)                         | 13th                            | Positive  |

**Table 2**: Harmonics components of the grid voltage
Fig. 7: Simulation result using proposed PR+I controller; grid voltage, reference and output current of converter, (a) $\alpha$-component (b) $\beta$-component

5. Conclusion

The basis of this paper is to introduce the technical understanding of the V2G. 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. A grid-connected bi-directional converter for the V2G application with PR+I controller is utilized to achieve better performance compared to conventional PI controllers by use of simulation in this paper. The PR and selective harmonics compensation method achieves good rejection of dominant harmonics in V2G mode. Finally PR+I controller guarantees low THD of output voltage for different types of loads in V2G mode. The proposed controller can greatly improve the performance of PEV's integration with power grid.

Fig. 8: Simulation result using conventional PI controller; one period of reference and output current of converter, (a) $\alpha$-component, (b) error in $\alpha$-axis (c) $\beta$-component
Fig. 9: Simulation result using proposed PR+I controller; one period of reference and output current of converter, (a) $\alpha$-component, (b) error in $\alpha$-axis (c) $\beta$-component

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