Research on Reactive Power Compensation Control of V2G Vehicle-Mounted Converter Suitable for Sharing Scenarios

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Abstract. The paper proposes an electric drive reconfigurable on-board converter for V2G energy management in a shared scenario. The proposed convert is obtained by adding an auxiliary circuit to the existing PEV driving hardware. In V2G mode, the converter uses drive motor as a power inductor to reduce the volume and increase power density. This paper proposes a method to adjustment active power and reactive power separately, which have able to be used for reactive power compensation on the load side. The feasibility of the system is verified by experiments.

Keywords: V2G; Electric Vehicles; Bidirectional Converters; Sharing Scenarios

1. Introduction

Electric Cars are the most promising alternative to vehicles with internal combustion engines, and sales of plug-in electric vehicles are growing year by year [1]. In shared scenarios, compared to other new energy vehicles (e.g., hybrids), plug-in electric vehicles are equipped with a larger capacity battery, enabling the plug-in electric vehicle to participate in the tidal wave dispatch of the grid, when the electric vehicle works in V2G mode. Since the energy storage system presents nonlinear external characteristics. Therefore, a converter is required to participate in the power regulation when the plug-in electric vehicle is operating in V2G mode.

V2G control technology is usually studied as part of a grid control strategy or microgrid control strategy, and the technology is used for peak shaving and energy saving [2,3]. For V2G systems containing a lost of electric vehicles, multi-stage systems are usually formed using energy aggregators [4-6]. The V2G control strategy for multi-stage systems is divided into three-level parts: the AC-grid-level control-strategy, the energy aggregator-level control-strategy., and the onboard-level control-strategy. The AC-grid-level control-strategy is usually based on the PEV parking model and grid demand to manage the system [7]. The energy aggregator level control strategy requires the allocation of energy based on the power grid demand and the policy demand of each EV. The onboard-level control strategy adjusts the V2G converter mainly based on the vehicle battery status and the operating parameters of the charging system [8-9]. Meanwhile, the various control strategies communicate with each other through an information exchange system [10]. In the V2G mode, the onboard-level control strategy should use the charging the active-power and the reactive-power separately [11]. Considering the direction of active currents, V2G is divided into two control modes of operation: the G2C mode and the C2G mode.

The EV charges the battery by grid in G2C control mode; in C2G control mode, the battery send
the active-power to the power grid through the converter. According to the requirements of the grid, in V2G control mode, the EV needs to provide reactive power to the grid and the converter should have the ability to adjust the power factor angle. In order to achieve the above goal, it is necessary to obtain the real-time phase of the grid-side-current and the grid-side-voltage through a phase-locked loop (PLL), instead of the usual case where only the grid-side voltage is phase-locked.

Electrically driven reconfigurable on-board converter (EDROC) operates at LEVEL 1 and LEVEL 2 power levels [12,13]. EDROC achieves size reduction and power density increase by using drive motor of drive system in V2G mode instead of charging inductor. EDROCs with rectifier bridges can achieve high power factor charging, but this type of converter cannot achieve bi-directional energy flow and this type of converter is not suitable for V2G mode. Because EDROCs without rectifier bridges usually use interleaved modulation, the switching frequency of the switching tubes in the converter varies, which makes the unipolar modulated EDROCs respond slowly to changes in power factor angle. Likewise, converters under unipolar modulation have current distortion at the cross-zero point, which can lead to additional harmonic pollution.

In the paper, the onboard system and its onboard system control strategy are proposed. The onboard system in the paper achieves the purpose of reducing the size to realize the vehicle by adding an auxiliary circuit to the drive hardware of the electric vehicle and using the inductor of the PMSM as an AC side inductor in V2G control mode. In this paper, a novel bipolar modulation method is proposed to make the performance of the proposed onboard system meet the requirements of V2G control mode for reactive power control. The proposed onboard level control strategy can respond quickly in the V2G control mode according to the active-power and reactive-power commands. Simulation and experimental results verify the performance of the proposed onboard system.

2. Topology and Modulation Methods

2.1. Electrically Driven Reconfiguration of On-board Converters

The proposed electric drive reconfigured vehicle converter (EDROC) in this paper combines a charging system and a drive system to achieve increased power density and reduced system size, as shown in figure 1. The EDROC uses the three-phase inductor of a motor as an AC-side power inductor with an auxiliary circuit. This topology is the basis of this study.

![Figure 1. Topology of the electric drive reconfiguration vehicle converter.](image)

2.2. Bipolar Modulation of EDROC in V2G Modules

In the V2G mode, switches S1 and S2 are disabled and switches S3-S8 are controlled via the proposed bipolar modulation, whose operating situation are shown in figure 2. The state switching is composed of two aspects, each with four states.
Figure 2. Switching state in V2G mode.

The states (a)-(d) are the states of mode I. States (a) and (b) operate in the half-cycle of positive-grid, with phase b of the PMSM acting as a rectifier and phase c of the PMSM acting as an inverter. In state (a), as shown in figure 2(a), switches S5 and S8 are turn on, switches S4, S6, and S7 are turn off, and current flows through the body diode of switch S3. The equation of state can be shown as

\[
\begin{align*}
\frac{di_a}{dt} &= \frac{2(V_{dc} - V_{ac})}{3L_x} \\
\frac{di_b}{dt} &= \frac{V_{ac} - V_{dc}}{3L_x} \\
\frac{di_c}{dt} &= \frac{V_{ac} - V_{dc}}{3L_x}
\end{align*}
\]  (1)

In state (b), as shown in figure 2(b), switches S4 and S7 are turn on, switches S3, S5 and S8 are turn off, and current flows through the body diode of switch S6. The equation of state can be expressed as

\[
\begin{align*}
\frac{di_a}{dt} &= \frac{2(-V_{dc} - V_{ac})}{3L_x} \\
\frac{di_b}{dt} &= \frac{V_{ac} + V_{dc}}{3L_x} \\
\frac{di_c}{dt} &= \frac{V_{ac} + V_{dc}}{3L_x}
\end{align*}
\]  (2)

States (c) and (d) operate in the half-cycle of the negative-grid, with phase b of the PMSM operating as an inverter, phase c of the PMSM is used as a rectifier. The state equations are the same as those in states (a) and (b). States (e)-(h) are method II. The methods I and II operate in the similar situations equations and they can operate with different needs.
3. Control Strategy in V2G Mode

In the V2G mode, the objective of the control strategy is to make the flow for the active-power and the reactive-power between the grid and the PEV storage system to meet the needs of the grid and the PEV. This control strategy includes (1) independent adjustment of the active-power, (2) independent adjustment of the reactive-power, (3) control of power factor angle, and (4) harmonic compensation. The control strategy includes power control loop, the DC-voltage control out-loop and the AC-current control in-loop, as shown in figure 3.

![Figure 3. Block diagram of the proposed control in V2G mode.](image)

The power control out-loop serves this purpose of regulating the active-power and reactive-power control separately. The control method obtains the $\alpha$ components of AC-current and AC-voltage and the $\beta$ component with quarter-cycle delay through a phase-locked loop (PLL), as shown in Equation 3. The active-power ($P$) and the reactive-power ($Q$) are shown with equation 4.

$$\begin{align*}
    v_\alpha &= v_{ac} \\
    i_\alpha &= i_{ac} \\
    v_\beta &= \frac{1}{\omega} \frac{dv_{ac}}{dt} \\
    i_\beta &= \frac{1}{\omega} \frac{di_{ac}}{dt} \\
    P &= \frac{1}{2} \left( v_\alpha * i_\alpha + v_\beta * i_\beta \right) \\
    Q &= -\frac{1}{2} \left( v_\alpha * i_\beta + v_\beta * i_\alpha \right)
\end{align*}$$

The power control out-loop meets the active-power demand by adjusting the setpoint voltage of the DC side, which is the given value of the DC voltage control loop. The output of the DC voltage control out-loop is the active power reference value. The power control in-loop and DC voltage control in-loop are controlled by PI module respectively. The setpoint of the AC current is obtained from the current calculation module. The input value of the current calculation module is the active-power reference value and the reactive-power reference value, and the calculation formula is as follows:
\[ \theta = \tan^{-1}\left( \frac{Q}{P} \right) \]
\[ I_m = \frac{P^*}{E_m \cos \theta} \]
\[ i_m^c = I_m \sin(\omega t - \theta) \]

The AC current inner loop contains a proportional resonance controller (PR), so that the AC current can reach a set value. The duty cycle \( D \) is the output of the AC current loop. The duty cycle controls the on/off of the switching tubes: when switches S5 and S8 are off, switches S4 and S7 are on. When switches S5 and S8 are on, switches S4 and S7 are off; when switches S5 and S8 are take on, switches S4 and S7 are take on. The relationship between the AC voltage and DC voltage can be obtained from Equation (6), where \( G \) is the voltage gain; \( V_{ac} \) is the amplitude of the voltage for AC grid. \( m \) is the modulation index of the converter.

\[ \begin{cases} 
G = \frac{2}{1 - D} \\
V_{dc} = mGV_{ac}
\end{cases} \]

### 4. Working State of Reactive Power Compensation

Electric vehicles have both load characteristics and energy storage characteristics, and have certain ability to participate in tidal current dispatch, making the electric vehicle tidal current characteristics different from the base load. The resulting transmission line model of load and EV is shown in figure 4.

**Figure 4.** Transmission line model with load and electric vehicle.

where \( U_a \) and \( U_b \) represent the first and last voltages of the line, \( P_a \) and \( Q_a \) represent the first active-power and reactive-power, \( P_b \) and \( Q_b \) represent the active-power and the reactive-power of the base load on the end, respectively. \( P_{ev} \) and \( Q_{ev} \) represent the active-power and the reactive-power of the electric vehicle.

When the reactive-power compensation characteristics of the electric vehicle are not considered, the voltage drop can be calculated by Equation (7)

\[ \Delta U_{ab} = \frac{R(P_a + jQ_a)}{U_a} \]

Since in the economic operation mode of the power system, the loss of energy transmission is much less than the transmitted power, the voltage drop at this time can be rewritten as

\[ \Delta U_{ab} = \frac{R(P_a + P_{ev}) + XQ_a}{U_a} \]

Similarly, the expression of line transmission loss can be obtained
The proposed converter can perform a bidirectional flow of energy and the converter has a power factor correction function. When the converter participates in the tidal current distribution for reactive power compensation, equations (8) and (9) can be rewritten as

\[
\Delta P = \frac{(P_b + P_{ev})^2 + Q_{ev}^2}{U_a^2} R \tag{9}
\]

The above formula shows that the voltage drop and line loss about the electric vehicle reactive power compensation value is not a monotonic function, thus two special states and three compensation regions can be obtained. The regions are divided as shown in figure 5.

**Figure 5. Working state of reactive power compensation.**

The zero-compensation state is the state in which the electric vehicle does not compensate reactive power, and its voltage drop and line loss are shown in equations (8) and (9).

When the electric vehicle reactive power is compensated, the electric vehicle is in the negative compensation state, when the electric vehicle absorbs reactive power. This state area mainly works in the case of light base load and the state is used to eliminate the excess reactive-power in the line.

When the electric vehicle reactive-power compensation power When, at this time, the electric vehicle happens to fully compensate this reactive-power required by the base load, the power factor angle at this time is the critical compensation power factor angle expressed by. The electric vehicle reactive power compensation value at this time is substituted into the formula (10) can get the electric vehicle involved in the compensation of the minimum voltage landing and line power loss.

\[
\begin{align*}
\Delta U_{ab, min} &= \frac{R(P_b + P_{ev})}{U_a} \\
\Delta P_{min} &= \frac{(P_b + P_{ev})^2}{U_a^2} R
\end{align*}
\tag{11}
\]

When the reactive power compensation state of EV is between zero compensation state and critical
compensation, the reactive power compensation state is in the undercompensation region. According to the formula (10) can be obtained, in this state with the angle for power factor increases, voltage loss and power loss gradually decreases, until the angle of power factor increases to the critical power factor angle, the voltage landing and line loss is reduced to the minimum value.

When the compensated reactive power over the critical compensation state, reactive power compensation state into the over-compensation region. At this time, the voltage drop still decreases via the increase of angle of power factor, but the line loss increases instead. When the electric vehicle works in this area, the active power of charging or discharging is reduced due to the excessive power factor angle, and this state is not conducive to the normal use of electric vehicles, so reactive power compensation should be avoided to enter this state. Both electric vehicles for reactive power compensation when the angle of power factor should be less than the critical power factor angle.

5. The Simulation and Experimental Results

Try to verify the proposed V2G power compensation theory, a model containing base load and electric vehicle is simulated in this paper by means of tidal wave calculation, and the structure of this model is shown in figure 4. The simulation parameters are shown in table 1.

| Table 1. Simulation parameters for tidal current calculation. |
|---------------------------------------------------------------|
| Parameters                      | Value               |
| Unit line impedance            | 1.96(Ω/km)         |
| Unit line reactance            | 0.404(Ω/km)        |
| Line length                    | 10km                |
| Line power level               | 35kV                |
| Base load active power         | 365kw               |
| Base load reactive power       | 120kvar             |
| Apparent power of single electric vehicle | 2kw               |
| Critical power factor angle    | 36°                 |

In this paper, the tidal state in the undercompensated area is simulated as shown in table 2. According to the tidal simulation results can be seen, zero compensation state line loss of 5.433kw, when reactive power compensation in critical compensation, line loss minimum 4.486kw, compared with the zero compensation state reduced by 0.947kw. simulation results of the voltage drop reactive power factor angle increases and decreases, the voltage drop of critical compensation than the voltage drop of zero compensation lower 39.6V.

| Table 2. Simulation results of tidal current calculation. |
|----------------------------------------------------------|
| Operating condition | Power factor angle of reactive power | Line loss     | Voltage drop |
| Zero compensation  | 0°                                    | 5.433kw       | 336.0V       |
| Undercompensation  | 15°                                   | 5.153kw       | 336.0V       |
| Undercompensation  | 20°                                   | 5.001kw       | 318.5V       |
| Undercompensation  | 25°                                   | 4.862kw       | 312.3V       |
| Critical Compensation | 36°                                 | 4.486kw       | 296.4V       |

In this project, the experimental platform for Level 1 charging of the proposed electric drive reconfigurable vehicle-mounted converter system is built using a semi-physical simulation platform, which is used to verify the control capability of the system in paper the for active and the reactive-power in V2G mode. The parameters of this experimental platform are shown as table 3.
Table 3. Experimental parameters of electric vehicles in V2G mode.

| Parameter                               | Value   |
|-----------------------------------------|---------|
| Power rating of converter               | 2.0kw   |
| Grid-side voltage                       | 220V    |
| AC-side frequency                       | 50Hz    |
| Switching frequency                     | 10KHz   |
| Motor rated torque                      | 14.5Nm  |
| Stator inductance                       | 3.34mH  |
| DC side battery open circuit voltage    | 850V    |
| Time coordinates of the figure          | 0.01s/div|
| Voltage coordinates of the figure       | 100V/div|
| Current coordinates of the figure       | 20A/div |

The figures 6 and 7 show the current and voltage waveforms of the proposed vehicle-mounted converter system in paper during charging at a power factor angle of 36°, respectively. The apparent power for both operating modes is 2.0 KVA.

Figure 6. Current-voltage of the vehicle converter operating in the first quadrant.

Figure 7. Current-voltage of the vehicle converter operating in the fourth quadrant.

Figures 8 and 9 show the current waveforms and the voltage waveforms of the proposed on-board converter system at grid connection with a power factor angle of 36°, respectively. The apparent power for both operating modes is 2.0 KVA.

Figure 8. Current-voltage of the vehicle converter operating in the second quadrant.
Figure 9. Current-voltage of the vehicle converter operating in the third quadrant.

The above experiments show that the proposed converter system can achieve power factor angle control in both G2C mode and C2G mode, and realize the four-quadrant operation of the proposed converter system.

6. Conclusion
In this paper, a new electrically driven reconfiguration converter is proposed, which can realize the bidirectional flow of energy. A control method matching with the converter is proposed in this paper, which achieves arbitrary control of the converter power factor angle. Based on this, this paper analyzes the mode and state of compensating load-side reactive power using electric vehicles, and verifies the above analysis conclusions by building a tidal simulation and experimental platform.

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