Research on Virtual Synchronous Generator Control for Vehicle-to-Grid System

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Abstract. This paper investigates the concept of Virtual Synchronous Generator (VSG) and analyses the working principle of common VSG control technology. With the promotion of Vehicle-to-Grid (V2G) technology, large-scale power electronics devices will be connected to the grid. Consequently, the stability of the grid will be influenced by the lack of mechanical inertia and system damping within these power electronic devices. The extant normal control methods are difficult to cope with this issue. Accordingly, a VSG control technology is proposed by this study, which can be applied to V2G system. Moreover, the mathematical analysis of this control method is also suggested in this research. This control method provides mechanical inertia and system damping, which is similar to synchronous generators. It also can achieve the accurate control of power. The original P/Q-U-I three-loop control is simplified to P/Q-I dual-loop control in the condition of not losing the inertia of the converter. Ultimately, the simulation examines the accuracy and effectiveness of the control method.

1. Introduction
Many countries initiate a plan to reduce the utilization of fuel vehicles because of the continuous development of new energy vehicles in recent years. What follows is the huge energy storage potential of electric vehicle batteries. If it can be applied to the active distribution network of grid, it will greatly benefit the voltage and frequency stability of the power grid [1-2]. In addition, the popularity of V2G will lead to an increasing usage of converters which contain lots of power electronic devices [3]. In general, these converters give a response too rapidly without the similar synchronous generators’ rotational inertia and damping characteristics [4]. Because of that, the stability of the grid will be affected. This emerging problem cannot be solved by existing control methods. Therefore, it is essential to propose a converter control method, which can be applied to V2G system [5]. In conclusion, this paper gives a certain consideration to the aforementioned problems and discusses the relevant solution.

Compared with synchronous generators of traditional power systems, common P/Q control, U/f control, and droop control are difficult to provide rotational inertia and damping characteristics. These characteristics are crucial to the stability of grid [6-8]. The VSG technology improves the control strategy of the inverter by studying the mechanical structure and working characteristics of the synchronous generator [9]. Features that increase the virtual inertia of the system. This emerging technology originated from the research on DC micro-grid and has also been applied to DC transmission in recent years [10-11]. Although V2G technology is similar to DC micro-grid, there are some differences [12]. The most important point is that the converter in V2G technology is connected to the grid side all the time. There is no island situation, so it is not necessary to lock out the phase.
frequency through the active power control loop like the traditional VSG control technology. Phase-locked loop could give frequency support through the grid. Moreover, the traditional VSG control unable to achieve precise control of power, which can't well accomplish the function of V2G. This paper proposes a new VSG control method based on the technical requirements of V2G.

According to the investigation on the fundamental mechanism of VSG control and the existing VSG approach, this paper suggests a new VSG control method based on the actuality of V2G. The control strategy can be significantly simplified in light of this new method, which also retaining the inertia of the converter. To be specific, the original P/Q-U-I three-loop control [13] is simplified to P/Q-I dual-loop control. Finally, the verification of control method is supported by the simulation.

2. The Analysis of VSG Principle and Existing VSG Control Methods

2.1. VSG principle analysis

The basic structure of the V2G transmission system is shown in the Figure 1.

![Figure 1. The basic structure of the V2G transmission system.](image)

The V2G transmission system mainly involves electric vehicle batteries, DC side capacitors, inverters, and line impedance. In general, the inductance L of the line impedance is considerably larger than the resistance R. \( E \) denotes converter output voltage vector; \( U \) is the grid side voltage vector; \( X \) is specified as the line impedance; \( \delta \) is identified as phase difference between \( E \) and \( U \).

The active power \( P \) is mainly determined by \( \delta \), while the reactive power \( Q \) is basically depended on \( E \). In this context, the V2G system is considered as a synchronous generator. The active power is controlled by the varying \( \delta \). It can be simulated as the speed regulation. The varying \( E \) would influence the output of the reactive power. It is regarded as the excitation adjustment of the synchronous motor. The V2G system exhibits a certain degree of similarity with the output of the synchronous generator.

2.2. Analysis of existing VSG control methods

Among the existing common VSG control methods, the second-order model of synchronous generators considering rotor inertia and damping characteristics is widely used:

\[
J \frac{d\omega}{dt} = T_m - T_e - D(\omega - \omega^*)
\]

(1)

\[
\frac{d\theta}{dt} = \omega
\]

(2)

In the formula: \( T_m \) and \( T_e \) are the mechanical and electromagnetic torques of the synchronous generator; \( J \) and \( D \) are the moment of inertia and damping coefficient of the synchronous generator, respectively; \( \omega \) and \( \omega^* \) are the mechanical angular frequency of the synchronous generator and the grid angular frequency, respectively; \( \theta \) is rotor electrical angle.
Based on formula (1) (2), the common VSG control strategy is shown as Figure 2.
The method of Common VSG control strategy is: Considering formula (1), simulate $T_m$ with $P/\omega$ and $T_e$ with $P_{eq}/\omega$. Combined with the synchronous machine rotor equation, the active power control would be completed. Then, the obtained $\omega$ is integrated to obtain $\theta$. The reactive power control part mainly draws on the droop control. The system obtains the simulated $E$ from the reactive power control part. Combined with $\theta$ and $E$, it synthesizes the output voltage reference of the converter. Then it draws the current reference. Finally, compared with it and actual value, it will obtain the PWM control signal.

![Figure 2. Common VSG control strategy.](image)

In the existing VSG control strategy, it combines $\theta$ and $E$ to synthesize the output voltage reference. It’s more to explain the similarity between the VSG and the actual synchronous machine. However, the complexity of the control is greatly increased. Considering the island situation, d-q transform cannot be performed because the grid cannot provide phase angle support. As shown in Figure 3, in practice, the solution of most control schemes is replace d-q transform angle $\alpha$ by $\delta$. According to formula (1), The angle $\delta$ obtained by the integral is the phase difference between $E$ and $U$. In the actual control, the d-q transformation takes $U$ as the d-axis. Its d-q transformation angle $\alpha$ should be the phase angle difference between $U$ and the reference axis. $\alpha$ and $\delta$ are not the same meaning. In addition, these control methods cannot achieve precise control of active power.

3. Analysis of VSG control methods used in this paper

3.1. Mathematical Derivation of Control Principle
The voltage-current vector relationship of the AC side of the converter is shown in Figure 4. The meaning of each variable in the figure is the same as section 2. Because the inductance $L$ is much larger than the resistance $R$, so $X = \omega L$ when $R$ is ignored. When the system is running in steady state, $\omega = \omega^*$. Suppose that the direction of $\bar{U}$ is the d-axis. q-axis is 90 degrees ahead of the d-axis. According to the vector relationship in Figure 4, use the similar triangle properties (Usually, the voltage drop across the inductor $L$ is small. $E \approx U$, $\delta \rightarrow 0$, then $\cos \delta \approx 1$, $\sin \delta \approx \delta$):
The angle $\delta$ can be expressed as: $\delta = \int (\omega - \omega') \, dt$. Substituting it into formula (3). In order to improve the stability, a PI link is used instead of the integral link. The d-axis current command of the current loop can be expressed as:

$$I_d' = K(1 + \frac{1}{T_s})(\omega - \omega')$$  \hspace{1cm} (4)$$

$\omega$ can be obtained from formula (1), and $\omega'$ can be obtained from the grid side. The reference of $I_d$ can be associated with the active power reference through $\omega$ and $\omega'$.

According to formula (3), it can be seen that $I_q$ is related to the amplitude of the voltage output. The reference of the $I_q$ can be associated with reactive-voltage amplitude droop control. The droop control can be used to determine the voltage output. Through the PI regulator, it will get the reference of the $I_q$. In order to have a certain inertia of the reactive power output, an integral link is added.

### 3.2. Control Strategy

This control has made some improvements based on the analysis of the previous section. The most outstanding feature of this control strategy is that the simulation of the phase angle of the common virtual synchronous control is abandoned. But the simulation of $J$ and $D$ is retained. Collect the output of current and voltage, and transform them into d-q axis. Calculate $P$ and divide it by $\omega$, use $P/\omega$ to simulate $T_s$, and use $P_q/\omega$ to simulate $T_q$. And then, the rotor equation (1) can be simulated. However, the resulting $\omega$ will not be integrated. It is subjected to PI control as the reference of $I_d$. The active power control block is shown in Figure 5. In the reactive power control, inertial regulation of reactive power is not performed in traditional VSG control. This control scheme adds inertia links to the traditional droop control. And its output value is no longer used as the voltage amplitude of the converter output. Instead, the output value is adjusted by PI and is given as the reference of $I_q$. Ultimately, precise control of reactive power will be achieved through changing of $I_q$. It is shown in Figure 5. Since V2G does not need to consider the island mode, the grid can provide the real time phase support.

![Figure 5](image_url)
reduces the control difficulty. It also realizes the precise power control in V2G mode. Through the mature phase-locked loop technology, d-q transformation can be easily carried out.

4. Simulation results and analysis

In order to verify the effectiveness of the control strategy provided in this paper, the software Psim was used to build the simulation platform of this system. The basic parameters of the grid-connected converter designed in this paper are shown in Table 1.

Table 1. Parameters of the grid-connected converter

| Parameter                  | Value | Parameter                  | Value |
|----------------------------|-------|----------------------------|-------|
| Lithium battery voltage    | 600   | Three-phase line voltage   | 380   |
| $U_{dc}$/V                 |       | RMS u/V                    |       |
| DC capacitor $C$/mF        | 2     | AC inductance $L$/mH       | 3     |
| AC resistance $R$/Ω        | 0.01  | Switching frequency $f$/kHz| 10    |

To verify this control has the output characteristics of synchronous generator, compared PQ control with the VSG control strategy adopted in this paper. At the initial time, $P_{ref}$ is 5 kW, and $Q_{ref}$ is 1 kvar. When t=0.3s, $P_{ref}$ is increased by 1Kw, and $Q_{ref}$ is also increased by 1kvar. At t=0.4s, $P_{ref}$ and $Q_{ref}$ are simultaneously reduced by 1k, returning to the initial reference. Figure 6. shows the comparison of active and reactive power output under two different control methods.

![Figure 6. Comparison of two control strategies](image)

It can be clearly seen that at 0.2s, output of $P$ and $Q$ under the PQ control enters the new steady state in a very short time. At 0.3s, it changes back to the initial setting so quickly. The oscillation shock is very serious, and the output glitch is serious. The system using the control method of this paper can make a smoother transition when the reference changes at 0.2s and 0.3s. The simulation results show that when the power demand on the grid side fluctuates, compared with the traditional PQ control, the control method provided in this paper can achieve a more gradual transition. This control could provide a virtual inertia similar to that of a synchronous generator.

In order to verify the working condition of the system when taking different values of $J$ and $D$, the simulation duration is increased to 2.5s. $P_{ref}$ is changed at 0.8s and 1.5s.
Figure 7. Power curve when J and D take different values

Figure 7 shows the active power curve for different values of J and D when the reference is changed. It can be seen that the system has different dynamic responses when the J and D of the system change. Moreover, the larger the J and the D, the smoother the dynamic response. It shows the same output characteristics as the synchronous generator. It indicates that when the system is disturbed or the power demand of the grid fluctuates, this control method can effectively mitigate the impact on the system and enhance the safety and stability of the V2G system.

5. Conclusion

This paper illustrates a grid-connected inverter control strategy that can be applied to V2G systems based on VSG technology. This control method abandons the simulation of the inverter output voltage in the traditional VSG control. Nevertheless, it retains the most crucial rotor rotational equation in virtual synchronization control. This outcome improves the stability of the control system, because it not only retains the inertia and damping within the virtual synchronization, but also simplifies the control loop from the P/Q-U-I three-loop control to the P/Q-I double-loop control. The analysis of this research and the verification of simulation indicates that the control method can enhance the inertia and damping of the system. This method also can undertake the rigid control on active and reactive power. It is a relatively appropriate approach for grid to accommodate the demand of the peak-load and voltage regulation in V2G system.

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