A New Power Decoupling Control Strategy of Synchronverter Based on Current Feedback

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ABSTRACT

Synchronverter has the grid friendly features while simulating synchronous motor internal mechanism and external characteristics, but the coupling between active power and reactive power exacerbates synchronous frequency resonance simultaneously, which easy to cause power oscillation and may lead to system instability. To address this problem, a small signal model for synchronverter power-angle characteristics is established to analyze the mechanism of generating power coupling at first. On this basis, a new type of power decoupling control method is proposed in this paper, which adds a feedback current loop in the synchronverter to dynamically compensate of coupling power. This method converts the quantity of dynamic coupling power need to compensate into the value of the dynamic compensation current. Therefore, power decoupling is realized and the steady-state error of virtual synchronous control is improved. Finally, the effectiveness and feasibility of the proposed method is validated in a normal test system comparing with experiment results.

Keywords: Synchronverter; power angle characteristics; power coupling; feedback current loop; dynamic current.

INTRODUCTION

With the gradual depletion of fossil fuels, the distributed generation, such as wind energy, solar energy, have been widely connected to the grid through a grid-connected inverter [1-2]. But the grid-connected inverter has no moment of inertia and damping, which may easily lead to frequency instability [3-6]. Therefore, synchronverter is designed to address the above-mentioned problem [7]. The synchronverter can realize the independent regulation of active power and reactive power. However, this adjustment method of the synchronverter is only feasible under the condition of the power angle between the induced electromotive force and the generator terminal voltage is very small. Otherwise, the adjustment method is unfeasible due to the active and reactive power output of synchronverter is coupled [8-9].
Many methods have been developed to realize the decoupling between active and reactive power. The droop control was improved by using the method of adding droop parameter adaptation [10] and virtual impedance [11], but these methods will cause voltage drop. A method of power oscillation suppression for virtual synchronous motor was proposed in [12-13]. The basic idea is linearize the active power transfer equation. This method decouples the damping factor from the angle deviation by introducing the linear control theory, and realizes the active power oscillation suppression, ignoring the reactive power oscillation. The Nonlinear damping controller was designed for synchronverter in [14], the additional quantity of excitation control was introduced in the $Q-V$ control loop, which can suppress reactive power oscillation effectively, but ignored the active power oscillation.

In this context, this paper proposes a new power decoupling control strategy based on current feedback for synchronverter. The main contributions of this paper can be summarized as follows:

1) A small signal model for synchronous inverter power-angle characteristics is established and the mechanism of generating power coupling is analyzed.
2) A feedback current loop in the synchronverter is added to dynamically compensate of coupling power, meanwhile converting the quantity of dynamic coupling power need to compensate into the value of the dynamic compensation current, which making it easier to regulate and control.

The rest of the paper is organized as follows: Power Analysis of Synchronverter in Section 2, Power Decoupling Control Strategy is presented in Section 3, The Realization of Decoupling Control Strategy in Section 4, the effectiveness of the proposed method is verified by simulation in Section 5. Finally, the conclusions are given in Section 6.

**POWER ANALYSIS OF SYNCHRONVERTER**

Synchronverter is mainly composed of main circuit and control circuit. Figure 1 shows the main circuit part of the synchronverter. The basic idea of the synchronverter main circuit is that the midpoint voltage $e_{abc}$ and capacitance voltage $V_{abc}$ of the inverter leg in the figure are equivalent to synchronous generator induction electromotive force and terminal voltage respectively; the inductance $L_s$ and resistance $R_s$ can be chosen to represent the stator inductance of the synchronous generator and satisfy the electromagnetic equation (1), $L_g$ indicates the line impedance.

$$v_{abc} = -R_s i_{abc} - L_s \frac{d i_{abc}}{dt} + e_{abc} \quad (1)$$
The core algorithm of control part shown in Figure 2, $D_p$ is the damping coefficient, with the function of frequency droop and damping. $P_{\text{set}}$ is active power, it can be directly converted to the corresponding mechanical torque $T_m$. $M_f, i_f$ is excited, $J$ is the moment of inertia, $T_e$ is the electromagnetic torque, $V_m$ is the voltage amplitude.

Supposing the pole pairs $P$ of the non-salient-ole SG equal 1, the main control equations of the synchronverter are shown in (2) ~ (5).

$$P_m$$

$$\omega$$

$$\theta$$

$$D_p$$

$$\theta_{\text{set}}$$

$$Q_{\text{set}}$$

$$v_e$$

$$\theta_{\text{PWM}}$$

$$e$$

$$i$$

$$P_{\text{PWM}}$$

$$Q_{\text{PWM}}$$

$$\varphi$$

$$\varphi_{\text{PWM}}$$

$$\alpha$$

$$\alpha_{\text{PWM}}$$

$$\beta$$

$$\beta_{\text{PWM}}$$

$$\gamma$$

$$\gamma_{\text{PWM}}$$

$$\delta$$

$$\delta_{\text{PWM}}$$

Figure 2. Synchronverter Control Section.

The expression of the induced electromotive force when the excitation current is constant:

$$e = M_f i_f \dot{\theta} \sin \theta$$  \hspace{1cm} (2)

where $M_f$ is the mutual inductance, $I_f$ is the excitation current, $\dot{\theta} = w$.

Rotor mechanical equation:

$$J \frac{d\omega}{dt} = T_m - T_e - D_p \dot{\theta}$$  \hspace{1cm} (3)

Electromagnetic torque equation:

$$T_e = -M_f i_f <i, \frac{\partial}{\partial \theta} \cos \theta > + M_f i_f <i, \sin \theta >$$  \hspace{1cm} (4)

The active and reactive power of the synchronverter output is respectively:
\[
P = \theta M_j i_j <i, \sin \theta > \\
Q = -\theta M_j i_j <i, \cos \theta > \\
\hat{\sin \theta} = [\sin \theta, \sin(\theta - \frac{2\pi}{3}), \sin(\theta + \frac{2\pi}{3})]^T \\
\hat{\cos \theta} = [\cos \theta, \cos(\theta - \frac{2\pi}{3}), \cos(\theta + \frac{2\pi}{3})]^T \\
\] 

(5)

where \(<, >\) represents the inner product.

The synchronverter is operated to mimic the behavior of SG, therefore, the power-angle characteristics of the SG is still appropriate for synchronverter. After the synchronverter is connected to the network, output active and reactive power can be expressed as equation (6) [15-16].

\[
\begin{align*}
P &= \frac{3EV}{X_s} \sin \delta \\
Q &= \frac{3(E \cos \delta - V)V}{X_s} \\
\end{align*}
\]

(6)

where \(E\) is the effective value of the midpoint voltage of the synchronverter leg, \(V\) is the terminal voltage of the synchronverter, \(X_s = wL\), \(\delta\) is the power angle. According to the power-angle characteristics of the SG, there is a corresponding regulatory relationship between \(P-\delta\) and \(Q-V\) [17].

In order to analyze the relationship between \(P-\delta\) and \(Q-V\) in detail, the equation (6) is expanded according to the small signal model:

\[
\begin{align*}
\Delta P &= \frac{\partial P}{\partial \delta} \Delta \delta + \frac{\partial P}{\partial V} \Delta V \\
&= \frac{3EV_0}{X_s} \cos \delta_0 \Delta \delta + \frac{3E}{X_s} \sin \delta_0 \Delta V \\
&= P_0 + P_1 \\
\Delta Q &= \frac{\partial Q}{\partial V} \Delta V + \frac{\partial Q}{\partial \delta} \Delta \delta \\
&= 3\left(\frac{E}{X_s} \cos \delta_0 - \frac{2V}{X_s}\right) \Delta V - \frac{3EV_0}{X_s} \sin \delta_0 \Delta \delta \\
&= Q_0 + Q_1 \\
\end{align*}
\]

(7)

where \(V_0\) is the steady-state terminal voltage and \(\delta_0\) is the steady-state power angle. From the formula (7), it can be seen that the active power is not only related \(\Delta \delta\) but also related \(\Delta V\), so the coupling effect of \(P-V\) exists; similarly, there is coupling \(\delta - \delta\) effect of reactive power regulation. To achieve the purpose of eliminating power coupling, the coupling amount \(Q_1\) between \(\delta - \delta\) and the coupling amounts \(P_1\) between \(P-V\) are eliminated.
POWER DECOUPLING CONTROL STRATEGY PROPOSED

The coupling ideas proposed by this paper based on the above analysis describes as follows. According to the mutual influence between the coupling amount $P_1$ and $Q_1$, the coupling is eliminated by compensating the opposite of $-P_1$ and $-Q_1$ dynamically. In order to compensate the coupling power easily, the compensating dynamic power quantity is converted into the form of compensating dynamic current in this paper.

**P-V Decoupling Strategy**

From equation (7), the necessary dynamic active power coupling quantity to eliminate the couple between the $P$ and $V$ is $-P_1$. The expression for $-P_1$ is:

$$-P_1 = -\frac{3E_0}{X_s} \sin \delta_0 \Delta V = -\frac{P_0}{V_0} \Delta V$$

where $P_0$ is steady-state active power, $V_0$ is the value of the terminal voltage at steady state, $\Delta V$ is the amount of terminal voltage interference, it is converted into a dynamic compensation current to achieve:

$$-P_1 = V_d \Delta I_d + V_q \Delta I_q = -\frac{P_0}{V_0} \Delta V$$

$$= -\frac{V_d I_d + V_q I_q}{V_0} \Delta V$$

$$= V_d \left( -\frac{I_d}{V_0} \Delta V \right) + V_q \left( -\frac{I_q}{V_0} \Delta V \right)$$

So it can be drawn that the current increment to be compensated is:

$$\Delta I_d = -\frac{I_d}{V_0} \Delta V$$

$$\Delta I_q = -\frac{I_q}{V_0} \Delta V$$

**Q-δ Decoupling Control Strategy**

From equation (7), the necessary dynamic reactive power coupling quantity to eliminate the couple between the $Q$ and $\delta$ is $-Q_1$. The expression for $-Q_1$ is:

$$-Q_1 = \frac{3E V_0}{X_s} \sin \delta_0 \Delta \delta = P_1 \Delta \delta$$

where $\Delta \delta$ is the power angle disturbance, it is converted into compensation current to achieve.

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\[ -Q_i = V_d \Delta I_q - V_q \Delta I_d = P_i \delta \]
\[ = (V_d I_d + V_q I_q) \Delta \delta \]  \hspace{1cm} (13)

Therefore, the current increment needs to be compensated:

\[ \Delta I_{d1} = I_q \Delta \delta \]  \hspace{1cm} (14)
\[ \Delta I_{q2} = -I_d \Delta \delta \]  \hspace{1cm} (15)

**THE REALIZATION OF DECOUPLING CONTROLLER**

As the increase of current loop can improve the dynamic response of the system, and can limit the current, and played the role of over-current protection. Therefore, this paper adds a feedback current loop based on the principle control algorithm to compensate for the elimination of the dynamic current required by the amount of coupling power.

According to [18], the dynamic equation of formula (1) in the \(d-q\) coordinates can be written as follows:

\[
\begin{cases}
L_d i_d = -R_s i_d + wL_s i_q + e_d - v_d \\
L_q i_q = -R_s i_q - wL_s i_d + e_q - v_q
\end{cases}
\]  \hspace{1cm} (16)

From equation (16), the current loop control block diagram shown in Figure 3 can be informed. Combining equations (11), (12), (14), (15), the corrected current can be got:

\[ I'_{d, \text{mod}} = I^*_{d} + \Delta I_{d1} + \Delta I_{d2} \]  \hspace{1cm} (17)
\[ I'_{q, \text{mod}} = I^*_{q} + \Delta I_{q1} + \Delta I_{q2} \]  \hspace{1cm} (18)

where \(I^*_{d}\), \(I^*_{q}\) is the given current of the original current loop, the component can be got by the \(d-q\) coordinates change in reference current \(i_{ref}\), \(i_{ref}\) can be generated by equation (19):

\[ i_{ref} = \frac{e_{abc} - v_{abc}}{Ls + Rs} \]  \hspace{1cm} (19)

Combining the above analysis, the decoupling control method in this paper is shown in Figure 3.
Figure 3. Decoupling Control Block Diagram.

SIMULATION RESULTS

The proposed decoupling control strategy was verified with simulations carried out in MATLAB15b. Comparing with the literature [12] in the same condition, which used in the simulations was ode23tb with a relative tolerance of $10^{-3}$ and a maximum step size of 0.2ms.

The simulation result shows the feasibility and superiority of the method proposed. The simulation parameters are shown in Table I.

The initial setting for $P_{set}$ and $Q_{set}$ were 0, there break was turn on at $t=1s$; the real power $P_{set}=140w$ was applied at $t=1s$, and the reactive power $Q_{set}=80var$ was applied at $t=2s$. The voltage regulator were enable at $t=3s$. The simulation results of the synchronverter power during the whole adjustment process are shown in Figure. 4.

<table>
<thead>
<tr>
<th>TABLE I. SIMULATION PARAMETER DESIGN.</th>
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<tbody>
<tr>
<td>Parameter</td>
</tr>
<tr>
<td>$L_s$, $R_s$</td>
</tr>
<tr>
<td>$C$</td>
</tr>
<tr>
<td>$L_g$</td>
</tr>
<tr>
<td>DC side voltage $V_{dc}$</td>
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<tr>
<td>Grid voltage $U_g$</td>
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<tr>
<td>$D_p$</td>
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<td>$D_q$</td>
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<td>$K$</td>
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<td>$J$</td>
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From the above figure, when adding active power after $t=1s$, the proposed method in this paper can eliminate the impact of active power on reactive power comparing with the control method proposed in literature [8]. Meanwhile when the reactive power is added at $t=2s$, the decoupling method of this paper can make the active power unaffected. The voltage regulator will make an impact on reactive power according to the output power relational expression of the synchronverter when it is added at $t=3s$. From Figure 4(a), the impact of reactive power effect active power can be eliminated by using the control strategy proposed in this paper when the reactive power changes.

Figure 5 shows the dynamic response process of the synchronverter amplitude $V$ and frequency. After the active power is added at $t=1s$, it can be seen that the frequency has a dynamic adjustment process from Figure 5(b), which conforms to the previous analysis. The proposed method can eliminate the coupling between $P$ and $E$ from the Figure 5(a), so that the amplitude $E$ remains unchanged. When the reactive power is added at $t=2s$. It is proved that the coupling between $Q$ and $\delta$ can be eliminated form Figure 5(a). Similarly, the decoupling control method used in this paper can keep the frequency unchanged in Figure 5(b).
when the voltage regulator is added at $t=3s$. Therefore, the simulation result demonstrates that the proposed method can eliminate the coupling between active and reactive power, and make the system run stably.

![Graph](image)

Figure 5. Synchronverter Voltage Amplitude and Frequency.

**CONCLUSION**

In this paper, the power coupling control problem of synchronverter is analyzed in detail. A power feedback decoupling control strategy based on current feedback has been proposed, which is achieved by compensating the dynamic current. Comparing with the traditional synchronverter, the method proposed in this paper can achieve the decoupling of active power and reactive power and make the system stable operation. At the same time, this method can also improve the power sharing performance of parallel synchronverter.
REFERENCES