Photovoltaic Grid Connected Control Algorithm Based on Covariance Optimization Ant Colony Algorithm

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Abstract

There are oversized power pulsation, unfixed switching frequency and other defects while the conventional direct power control method is applied in photovoltaic, grid-connected inverter system. To overcome the above problems, this paper puts forward a kind of control method for predicting optimal switch sequence, namely, carrying out combinatorial output for a group of zero voltage vectors and nonzero voltage vectors in a control cycle. Take the prediction and control theory of photovoltaic, grid-connected inverter as the basis to constitute the mathematical function of system power tracing the errors in a single control cycle and regard the minimum error that power traces as the control object to deduce and obtain the optimal action time which is corresponding to each voltage vector. Results of prototype examination has shown that, this method can efficiently optimize the stability control precision of grid-connected inverter system to realize the operation of fixed switching frequency and it also maintains the high dynamic responsive characteristics of the conventional direct power control method.

Keywords: Grid-connected inverter; Power pulsation; Fixed switching frequency; Predictive power

1. Introduction

With the increasing worldwide energy crisis, development and utilization of renewable and clean energy whose representative is photovoltaic generation has gradually become the focus of attention [1]. As the core part of photovoltaic generation system, control performance quality of grid-connected inverter will directly influence the operation efficiency of whole system. Now, the major control strategies are the two following kinds: grid voltage orientation control [2] and direct power control [3]. Compared to the voltage orientation control, because it does not need inner rings of the current and its settings, direct torque control have simple structure, rapid dynamic response, good robustness and other advantages while steady-state power pulsation, changed switching frequency and other problems has restricted the actual application of this control methods all the time. Aiming at the above defects existed in conventional direct power control, this paper puts forward a kind of control method for predicting optimal switch sequence, namely, carrying out combinatorial output for a group of zero voltage vectors and nonzero voltage vectors in a control cycle. Take the prediction and control theory of photovoltaic, grid-connected inverter as the basis to constitute the mathematical function of system power tracing the errors in a single control cycle and regard the minimum error that power traces as the control object to deduce and obtain the optimal action time which is corresponding to each voltage vector. Results of prototype examination has shown that, this method can efficiently optimize the stability control precision of grid-connected inverter system to realize the operation of fixed switching frequency and it also maintains the high dynamic responsive characteristics of the conventional direct power control method [4-9].

2. Mathematic Model of Photovoltaic Grid-Connected Inverter

Voltage type of grid-connected inverter topology structure is as shown in Figure 1, in which, $L$ is filter inductance and $R$ is equivalent resistance.

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Assume that voltage of three-phase network is balance and, ignoring switching loss, drop voltage. According to Kirchhoff’s law, mathematics of the system under the two-phase static $\alpha\beta$ coordinate are established as:

$$L \frac{d}{dt} v_{\alpha\beta} = e_{\alpha\beta} - e_{\alpha\beta} - Ri_{\alpha\beta} \quad (1)$$

In formula, $i_{\alpha\beta}$ is the moment of network current $\alpha\beta$ coordinate; $v_{\alpha\beta}$ is the moment of output voltage $\alpha\beta$ coordinate of grid-connected inverter; $e_{\alpha\beta}$ is the moment of network voltage $\alpha\beta$ coordinate.

According to instantaneous relative power theory, we can know that instantaneous active power, relative power can be defined as:

$$\begin{align*}
P &= -1.5(e_{\alpha}i_{\alpha} + e_{\beta}i_{\beta}) \\
Q &= -1.5(e_{\beta}i_{\alpha} - e_{\alpha}i_{\beta})
\end{align*} \quad (2)$$

In order to get the change rate of instantaneous active, reactive power, the formula (2) can be processed as follow:

$$\begin{align*}
\frac{dP}{dt} &= -1.5 \left( e_{\alpha} \frac{di_{\alpha}}{dt} + i_{\alpha} \frac{de_{\alpha}}{dt} + e_{\beta} \frac{di_{\beta}}{dt} + i_{\beta} \frac{de_{\beta}}{dt} \right) \\
\frac{dQ}{dt} &= -1.5 \left( e_{\beta} \frac{di_{\alpha}}{dt} + i_{\alpha} \frac{de_{\beta}}{dt} - e_{\alpha} \frac{di_{\beta}}{dt} - i_{\beta} \frac{de_{\alpha}}{dt} \right)
\end{align*} \quad (3)$$

In formula, voltage change ration of network in ideal condition can be defined as:

$$\begin{align*}
\frac{de_{\alpha}}{dt} &= \omega e_{\alpha} \sin(\omega t) = -\omega e_{\beta} \\
\frac{de_{\beta}}{dt} &= \omega e_{\alpha} \cos(\omega t) = \omega e_{\alpha}
\end{align*} \quad (4)$$

At this point, change rate of instantaneous power of grid-connected inverter system can be given as follow by substituting the formula (1), (4) into formula (3)

$$\begin{align*}
\frac{dP}{dt} &= -\frac{3}{2L} \left[ |e|^2 - (e_{\alpha}v_{\alpha} + e_{\beta}v_{\beta}) \right] - \frac{R}{L}P - \omega Q \\
\frac{dQ}{dt} &= -\frac{3}{2L} \left[ -(e_{\beta}v_{\alpha} - e_{\alpha}v_{\beta}) \right] - \frac{R}{L}Q + \omega P
\end{align*} \quad (5)$$
3. Impact Analysis of Voltage Vector

Effective voltage vectors can be provided by three-phase two level VSI, which include: 6 nonzero voltage space vectors \( \mathbf{v}_1 \sim \mathbf{v}_6 \), two zero voltage vectors \( \mathbf{v}_0, \mathbf{v}_7 \), the voltage vectors of two level VSI is shown as Figure 2. In classical direct power control method, \( \alpha \beta \) coordinate is divided into 6 different sectors as shown in Figure 2; according to the number of voltage vector \( i \) located section of network, select a optimal voltage vector, so that the actual value of power \( P, Q \) can track the expected value \( P^*, Q^* \). It is shown that only the number of voltage vector is defined as \( i \) in single voltage vector acts on grid-connected inverter in each control period, corresponding change rate of active, reactive power are defined as by this time:

\[
\begin{align*}
    s_P^i &= \frac{dP}{dt} | v = v_i \\
    s_Q^i &= \frac{dQ}{dt} | v = v_i
\end{align*}
\]  

(6)

![Figure 2. The voltage vectors of two level VSI](image)

When control period \( T_s \) of digital processing system is enough small, power change rate in certain control period can be thought as remaining unchanged, that is to say that power presents linear change rule, it is shown as follow:

\[
\begin{align*}
    P^{k+1} &= P^k + s_P^k T_s \\
    Q^{k+1} &= Q^k + s_Q^k T_s
\end{align*}
\]  

(7)

In formula, \( P_k, Q_k \) is initial value of \( k \)th control period of active, reactive power; \( P_{k+1}, Q_{k+1} \) is final value of \( k \)th control period of active, reactive power.

Power ripple of conventional direct power control is shown in Figure 3, and we can know that only acting on the single voltage vector of each control period is the main cause for the power ripple problem. When above model is used to control system, in order to get satisfactory stability control precision, the system needs to operate under the higher control frequency, its frequency is more than 10kHZ in general. At present, the higher requirement is proposed for computing capability of digital processing system; at the same time, when power device operates under overhigh switching frequency, the switching loss problem of system will be more serious.
4. Predict the Sequence Control of Optimal Switching

The method is to predict the optimal switching sequence proposed in this paper; two nonzero voltage space vectors and one zero voltage vector are combined to output in one control period to achieve the minimum control objective of power ripple in each control period, which specifically includes: selection of voltage vector, obtainment of operation time.

4.1. Selection of Voltage Vector

Basic principle for the selected voltage vector is: to not only choose voltage vector that will decrease active and reactive power within each sector, but also choose voltage vector that will increase active and reactive power, therefore, operation time of each vector can be calculated accurately according to tolerance of active and reactive power and power can be controlled accurately.

![Diagram](image)

**Figure 3. Power ripple of conventional direct power control**

4.2. Obtainment of Operation Time

As in shown in Figure 4, there is a pulsation analysis Figure of predictive switch order control of kth control period. After this control period finishes, $P$, $Q$ tracking tolerance can be described as:

$$
\begin{align*}
E_p &= P^* - P^{k+1} = P^* - P^k - S^p_aT_a - S^p_bT_b - S^p_cT_c \\
E_q &= Q^* - Q^{k+1} = Q^* - Q^k - S^q_aT_a - S^q_bT_b - S^q_cT_c
\end{align*}
$$

(8)

**Table 1. Selection of vectors in different sectors**

<table>
<thead>
<tr>
<th>Operation order</th>
<th>Operation time</th>
<th>Voltage vector choice of different sectors</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>$T_a$</td>
<td>$v_1$, $v_2$, $v_3$, $v_4$, $v_5$, $v_6$</td>
</tr>
<tr>
<td>2</td>
<td>$T_b$</td>
<td>$v_2$, $v_3$, $v_4$, $v_5$, $v_6$, $v_1$</td>
</tr>
<tr>
<td>3</td>
<td>$T_c$</td>
<td>$v_7$, $v_0$, $v_7$, $v_0$, $v_7$, $v_0$</td>
</tr>
</tbody>
</table>
In order to suppress power pulsation phenomenon to the maximum degree, establish a value function of power tracking tolerance by least square method as follows:

$$g = E_p^2 + E_q^2$$  \hspace{1cm} (9)

**Derivative of solving formula (9) to $T_a$, $T_b$ is**

$$\frac{\partial g}{\partial T_a} = 0$$

$$\frac{\partial g}{\partial T_b} = 0$$  \hspace{1cm} (10)

**Optimal switching operation time can be obtained by union vertical formula (8) ~ (10):**

$$T_a = P_{err}(s_a^0 - s_a^P) + Q_{err}(s_a^q - s_a^q) + T_s(s_a^P s_b^P - s_a^q s_b^q)$$

$$T_b = P_{err}(s_b^0 - s_b^P) + Q_{err}(s_b^q - s_b^q) + T_s(s_b^P s_c^P - s_b^q s_c^q)$$

$$T_c = T_s - T_a - T_b$$  \hspace{1cm} (11)

In the formula: $T_a$, $T_b$, and $T_c$ respectively are operation times of three voltage vectors; $P_{err} = P^* - P_k$, $Q_{err} = Q^* - Q_k$; $S_aP$, $S_bP$, and $S_cP$ respectively are variation rate of active power corresponding with three voltage vectors; $S_aQ$, $S_bQ$, and $S_cQ$ respectively are variation rate of reactive power corresponding with three voltage vectors.

**5. Results and Discussion**

In order to verify the feasibility and effectiveness of the proposed control method, experimental prototype of grid-connected photovoltaic inverter system is established; therein: main controller is TMS320F28335 in TI company; IGBT is 75GB124D in Semikron Company. Figure 5 is schematic Figure for sequences control method of predictive optimal control switch,
in which: network voltage 380V, DC bus voltage \( u_{dc} = 600V \), filter reactor \( L = 1.2mH \) and equivalent resistance \( R = 0.8\Omega \).

![Diagram of predictive optimal switching sequence control method](image)

Figure 5. Diagram of predictive optimal switching sequence control method

Comparative analysis results of steady-state performance of two control methods as shown in Figure 6. It can be seen that pulsation of active and reactive power of traditional direct torque control is relatively large and more burrs of high frequency harmonic on the current waveform. After reviewing switching sequence control of optimal forecast, it can be seen that its power pulsation as well as smoothing degree of current are improved obviously. From further analysis result of spectrum, it can be seen that total aberration rate of both currents are respectively 8.2\% and 4.3\%. The steady-state control performance of grid-connected inverter system has been improved obviously.
Comparative analysis results of steady-state performance of two control methods are as shown in Figure 7. It can be seen that when the set point of active power $P^*$ has mutation, two methods all can respond rapidly to the change of power and only three minutes are needed to realize the tracking of power. No overshoot phenomenon in system in the dynamic process and dynamic decoupling performances of active and reactive power are all excellent. Significant coupling changes will not be produced for reactive power with the drastic change of active power.
6. Conclusion
In order to overcome the problems of high power fluctuation during the process of traditional direct power control method applying to photovoltaic grid connected inverter system, the unfixed switching frequency and others, this paper presents a method for predicting the optimal switching sequence. The experimental result proves the feasibility and effectiveness of the method, and conclusions as follows can be made: 1) the essential reason of the high power pulse and the high sampling frequency demand of the traditional DPC is that two level VSI grid connected inverter can only provide 8 effective voltage vectors; 2) the predictive optimal switching sequence control optimizes the steady state control accuracy effectively through the reasonable combination of several voltage vectors, and it retains the excellent characteristics of the traditional DPC high dynamic response at the same time.

References