Research on Compound Control Strategy of Dynamic Voltage Restorer

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Abstract. Dynamic voltage restorer (DVR) is an economical and effective device to suppress the voltage drop of the power grid. This paper establishes the equivalent circuit and mathematical model of the DVR. Aiming at the shortcomings of feedforward control and feedback control, a composite control strategy is adopted, feedforward control is introduced on the basis of feedback control, and the load adaptability and stability of composite control are analyzed. Finally, MATLAB is used for simulation verification, and the results show that the compound control can meet the requirements of the DVR control system.

1. Introduction

The power distribution network structure of the power system is becoming more and more complex, especially the investment of large-load electrical equipment, so that there are various dynamic power quality problems in the power grid such as power supply interruption, harmonics, flicker, and voltage sag. Dynamic voltage restorer (DVR) is currently one of the most economical and effective means to solve the dynamic power quality problem of voltage sag [1-2]. The DVR itself is equivalent to a controlled voltage source, which can insert a voltage of any amplitude and phase between the power supply and the sensitive load [3]. When the power supply voltage is distorted, the purpose of stabilizing the sensitive load voltage is achieved by changing the voltage of the DVR. In DVR, control strategy is a key factor, it is directly related to the DVR compensation effect.

At present, the linear control strategy of DVR mainly includes feedforward control, various feedback control and so on. Feedforward control has the characteristics of simple control and fast response, but there will be voltage amplitude attenuation and phase shift in the impedance of coupling transformer and filter. It is an open-loop control mode without feedback link, so the output cannot follow the input completely, so it is difficult to achieve complete compensation, and the adaptability to the load is not strong[4-5]. The feedback control has strong load adaptability, but the parameter design is difficult, and the limitation of control coefficient value will affect the compensation effect. Considering the advantages of the two, this paper adopts the compound control strategy of feedforward control on the basis of feedback.

2. DVR system structure

The DVR system structure is shown in Fig.1. The inverter adopts a three single-phase H-bridge structure, which is composed of three single-phase full bridges. The control system controls the inverter circuit and reverses the energy storage of the battery on the DC side. It becomes a three-phase AC output, and after filtering out higher harmonics through an LC filter, it is finally injected into the
grid through a series transformer. Through appropriate control strategy, the output voltage of DVR can track the change of command voltage in real time. Finally, the compensation voltage is generated to offset the voltage drop in the power supply side voltage, so as to improve the power quality of the system.

According to the working principle of DVR, the equivalent circuit diagram of DVR [6] is shown in Fig.2.

In the figure, $V_s$ is the system side voltage; $V_{DVR}$ is the compensation voltage output by the DVR; $V_l$ is the load voltage; $V_i$ is the output voltage of the DVR inverter; $V_C$ is the voltage across the filter capacitor; $I_o$ is the primary current of the transformer; $I_f$ is the filter inductance Current; $I_c$ is the current of the filter capacitor; $L_f$, $C_f$ and $R_f$ represent the inductance, capacitance and line resistance of the filter circuit, $L_t$ and $R_t$ represent the winding resistance and leakage inductance of the transformer, respectively; $Z_l$ is the load resistance, and the transformation ratio of the transformer is $1:n$.

According to Kirchhoff's law, the state equation of the equivalent circuit diagram can be obtained as:

$$ V_i = L_f \frac{dI_f}{dt} + I_f R_f + V_C $$

(1)

$$ V_C = L_i \frac{dI_o}{dt} + I_o R_o + \frac{V_{DVR}}{n} $$

(2)

$$ V_l = V_i + \frac{V_{DVR}}{n} $$

(3)

$$ I_c = C_f \frac{dV_C}{dt} $$

(4)
3. DVR control strategy

3.1. Feedforward control strategy
The feedforward control mode has the advantages of fast response speed, high stability, simple control method, etc., so this control method is used in quite a few occasions. In the feedforward control method of DVR, a linear link with a gain of $k_m$ is used instead of the inverter. According to equations (1) to (6), the block diagram of the feedforward control strategy is shown in Fig. 3. In the figure, $V'_L(s)$ is the reference value of the load voltage, and the load voltage $V_L(s)$ can be expressed as:

$$V_L = G_{LO} V'_L + G_{SO} V_S$$

(7)

$$G_{LO}(s) = \frac{nk_m (L_s + R_i)}{a_1 s^3 + a_2 s^2 + a_3 s + a_4}$$

(8)

$$G_{SO}(s) = \frac{L_i L_f C_f s^3 + (L_f R_i + L_i R_f) C_f s^2 + (R_f R_i C_f + (1-n) L_i) s + (1-n) R_i}{a_1 s^3 + a_2 s^2 + a_3 s + a_4}$$

(9)

Among them $a_1 = (L_i + n^2 L_f) L_f C_f$; $a_2 = (L_i + n^2 L_f) R_f C_f + (R_f + n^2 R_i) L_f C_f$; $a_3 = R_f R_i C_f (R_i + n^2 R_f) + n^2 L_f + n^2 L_i + L_i$; $a_4 = n^2 R_f + n^2 R_i + R_i$.

$G_{LO}$ represents the transfer function from the reference voltage $V'_L(s)$ to the load voltage $V_L(S)$, and $G_{SO}$ represents the transfer function from the system voltage $V_S$ to the load voltage $V_L(S)$. It can be seen from the formula (7) that in an ideal situation, only $V_L$ can track $V'_L$ well, and it is not affected by the disturbance of $V_S$ in a certain frequency range to ensure the correct output of $V_L$.

![Fig.3 Block diagram of DVR feedforward control system](image)

In order to verify the load adaptability of the feedforward control system, the transfer function of load current to load voltage can be expressed as:

$$G_i(s) = -\frac{n^2 L_i C_f s^3 + n^2 (L_f R_i + L_i R_f) C_f s^2 + n^2 (L_f + L_i + R_f C_f) s + n^2 R_i}{L_i C_f s^2 + R_f C_f s + 1}$$

(10)

From the transfer function, the Bode diagrams of $G_{LO}$, $G_{SO}$, and $G_i$ can be obtained, as shown in Fig.4.
It can be seen from Fig.4(a) that although the system is stable, the phase margin is relatively small, and the damping is small, which is prone to oscillation. From Fig.4(b), it can be seen that the system's disturbance to the grid voltage is inhibited in the low frequency band, while it will cause interference to the system in the high frequency band. It can be seen from Fig.4(c) that the feedforward control has a weak attenuation effect on the load current interference, so the load adaptability of the feedforward control is relatively poor.

From the above analysis, it can be seen that a simple feedforward control strategy cannot meet the requirements of DVR performance, and it is difficult to obtain good compensation effects and good load adaptability.
3.2. Compound control strategy
The compound control strategy is to introduce feedforward control on the basis of feedback control. Feedforward control can significantly improve the dynamic response speed of the system and shorten the time for the compensation voltage to be issued; the feedback control adopts double closed-loop feedback control, the inner loop is the feedback link of the instantaneous value of the filter capacitor current, and the outer loop is the instantaneous value feedback link of the load voltage. Closed-loop feedback control can not only improve the stability of the system, but also improve the dynamic performance and adaptability of the system to the load. In particular, the integral part of the PI controller can effectively reduce the stability error of the system. Compound control combines their advantages, and its system control block diagram is shown in Fig.5.

\[
\begin{align*}
V_L &= G_{LO}V^*_L + G_{SO}V_s \\

G_{LO} &= nR_i k_m \left[ R_L C_f \left( 1 + k_f \right) s^2 + (k_f + \tau + R_f C_f) s + 1 \right] \\

G_{SO} &= \frac{R_i \tau s [L_f C_f s^2 + (\alpha k_m + R_f - R_L - nk_m R_f) C_f s + (1 - nk_m)]}{b_1 s^2 + b_2 s^3 + b_3 s^2 + b_4 s + b_5}
\end{align*}
\]

Among them: 
\[b_1 = n^2 \tau L_f L_f C_f; \quad b_2 = n^2 \tau (\alpha k_m + R_f - R_L) L_f C_f + \tau (n^2 L_f + R_f) L_f C_f;\]
\[b_3 = n^2 \tau (L_f + L_f) + \tau (n^2 R_f + R_f) (\alpha k_m + R_f - R_L) C_f + n\tau R_f C_f (k_m k_m R_f + nR_f)\]
\[b_4 = \tau (n^2 R_f + R_f) + nk_m R_f (R_f C_f + \tau k_f) + n^2 \tau R_f\]
\[b_5 = nk_m R_f\]

In order to verify the load adaptability of the system, the transfer function of load current to load voltage is:
\[
G_o(s) = \frac{L_f C_f s^2 + (R_f C_f + k_m n C_f) s^2 + (1 + k_m n R_f) s + k_m n}{L_f C_f s^2 + (L_f C_f R_f + R_f C_f L_f + k_m n C_f) s^2 + (L_f + R_f C_f + k_m n C_f + R_f) s^2 + (R_f + R_f) s}
\]

From the transfer function, the Bode diagrams of \(G_{LO}, G_{SO},\) and \(G_o\) can be obtained, as shown in Fig.6.
It can be seen from Fig.6(a) that the load voltage $V_L$ has a large stability margin to the reference voltage.* $V_{ref}$, and the load voltage can track the reference voltage well in the low frequency band, and has a better suppression of high-frequency signals. From Fig.6(b), it can be seen that the $G_{SO}$ gain is small in all frequency bands, indicating that the system has a good suppression effect on the
disturbance of the grid voltage. Comparing Fig.6(c) with Fig.4(c), the gain of $G_{oi}$ is relatively small in all frequency ranges, indicating that the system has better load adaptability.

It can be seen from the above analysis that the composite control combines the advantages of feedforward control and feedback control, and can improve the dynamic performance, followability and stability of the DVR system.

4. Simulation verification and analysis

Use Matlab/Simulink to simulate and verify the compound control strategy adopted in this paper. According to the DVR system structure shown in Fig.1, a simulation model is established for simulation verification.

1) Voltage sag tracking compensation experiment

In the experiment, a pure resistive load is selected to verify the following compensation performance of the control system when the voltage drops. As shown in Fig.7, at $t=0.045s$, a voltage drop occurs. After a short dynamic process, the output of the DVR is that the load voltage returns to the level before the drop, and the steady-state error is small.

2) Suppress system voltage interference experiment

The control system must have a certain suppression effect on the disturbance of the grid voltage and ensure the stable accuracy of the DVR output voltage.

As shown in Fig.8, the grid voltage contains a certain amplitude of the 3rd, 5th, and 7th harmonics, and a voltage drop occurs at $t=0.045s$. After a short dynamic process, the load voltage returns to the level before the drop. And the control system has a strong inhibitory effect on the harmonic disturbance of the grid voltage. Therefore, DVR can effectively compensate for voltage drops and harmonic disturbances.

(3) Load adaptability experiment

In the experiment, a resistive and inductive load is selected to compare the compensation effects of the compound control and the double closed-loop feedback control when the voltage drops. Fig.9(a) is
the compensation effect when double closed-loop feedback is used, and Fig.9(b) is the compensation effect when the compound control is used. It can be seen from the figure that compound control method is superior to double closed loop feedback control in overshoot, dynamic response time, compensation effect, etc.

5. Conclusion
Based on the brief introduction of the working principle of DVR, this paper proposes a compound control strategy composed of feedforward control, voltage instantaneous value feedback control and filter capacitor current instantaneous value feedback control, deduces the transfer function of the system, analyzes the Bode diagram, and finally verifies the rationality and effectiveness of the compound control strategy through matlab simulation.

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