Research on seamless switching control strategy for T-type three-level energy storage inverter based on virtual synchronous generator

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Abstract: The topology of energy storage inverter is adopted with T-type three-level structure. The characteristics are analysed when the T-type three-level energy storage inverter is working on the grid-connected and isolated-island operation. In order to satisfy the stable switching operation from grid-connected to isolated-island, a seamless switching control strategy based on the virtual synchronous generator is proposed. A simulation model of seamless switching control for T-type three-level energy storage converter is built in MATLAB to verify the correctness of the proposed strategy.

1 Introduction

With the development of distributed energy, the mode of power generation has been changed by traditional distributed generation [1, 2]. As the hinge between distributed energy and distribution network, the important function of the grid-connected inverter has been affirmed [3]. However, the frequency and voltage of power system are unstable caused by lack of inertia with power electronic devices [4]. In order to change this situation, a new control strategy is proposed to make the inverter to own characteristic of synchronous generator [5]. In addition, a storage unit is added to the inertia simulation to keep the system frequency or voltage stability [6]. A control method called a virtual synchronous generator (VSG) is established based on the output characteristics of synchronous generator [7].

T-type three-level topology is adopted with fewer switching devices and lower loss [8, 9]. The T-type three-level topology is applied as the main circuit to the energy storage system. When the T-type three-level is working on the grid-connected and isolated-island operation, the characteristics are analysed. At the same time, a seamless switching control strategy based on the principle of VSG is proposed. Finally, a simulation model is built in MATLAB so that the effectiveness of the proposed method is verified by simulation results.

2 Characteristics of grid-connected operation and isolated island operation

The main circuit topology of T-type three-level energy storage inverter is shown in Fig. 1. When the switch K1 is closed and the switch K2 is open, the energy storage inverter is in a grid-connected operation state. When the switch K1 is opened and the switch K2 is closed, the energy storage inverter is in an isolated-island operation state.

Where \( E_{dc2} \), \( E_{dc1} \), \( E_{dc3} \) are the three-phase voltages; \( U_{dc} \) is the DC voltage; \( C1 \) and \( C2 \) are the DC side capacitors, and \( C1 = C2 = C \), \( U_{dc1} = U_{dc2} \); \( U_{ac1} \), \( U_{ac2} \), \( U_{ac3} \) are the bridge arm phase voltages; \( L1 \) is the output filtering inductor of inverter; \( L2 \) is the inductance of network side, and \( L_3 = L_1 + L_2 \); \( C_4 \) is the filter capacitor; \( R_4 \) is the damping resistance; \( R_s \) is the system resistance; \( R_p \) is the load resistance; \( L_{ph}, L_{sh}, L_o \) are the out phase currents of inverter; \( i_{a}, i_{b}, i_{o} \) are the phase currents while grid-connected operation.

When the energy inverter is working in the grid-connected operation state, the mathematical model of rotating coordinate system is described as follows:

\[
\begin{align*}
\frac{d}{dt}i_{d1} &= -u_{d1} - u_{ad} + \omega l_1 \omega i_{q1} \\
\frac{d}{dt}i_{q1} &= -u_{q1} - u_{aq} + \omega l_1 \omega i_{d1}
\end{align*}
\] (1)

When the energy inverter is working in an isolated-island operation state, the mathematical model of rotating coordinate system is described as follows:

\[
\begin{align*}
\frac{d}{dt}u_{ao} &= R_1 \frac{du_{ao}}{dr} - L_1 \frac{di_{ao}}{dr} \\
&+ \left[ u_{o} - u_{ao} - \omega L_{ph} i_{ao} \right]
\end{align*}
\] (2)

3 Operational principle of VSG

In order to make the output characteristic of the system to have inertia, a proper control algorithm is added between the energy storage unit and the inverter, which can be equivalent to a synchronous generator. Therefore, the control algorithm is called the VSG control algorithm [10]. The distributed generation system is called the VSG when this VSG control algorithm is used [11].

The power angle vector of VSG is shown in Fig. 2.

Where \( \phi \) is the power angle of VSG, \( \theta \) is the angular frequency of grid, \( \omega \) is the angular frequency of rotor, \( \beta \) is the angle of VSG.
The relationship of $\delta$, $\omega_g$, and $\omega$ is described as follows:

$$\frac{d\delta}{dt} = \omega - \omega_g = \Delta \omega \tag{3}$$

The equation of rotor motion is described as follows:

$$J \frac{d\Delta \omega}{dt} = T_m - T_e - D \Delta \omega \tag{4}$$

where $J$ is the moment of inertia, $T_m$ is the torque of VSG, $T_e$ is the electromagnetic torque created by electromagnetic power and $D$ is the damping coefficient.

The simple model of VSG while in grid-connected operation state is shown in Fig. 3.

The active power and reactive power are calculated [12]

$$
\begin{align*}
P &= \frac{U_{\text{vsg}}}{R_s + L_s} [R_s (U_g \cos \delta - U_{\text{vsg}}) + L_s U_g \sin \delta] \\
Q &= -\frac{U_{\text{vsg}}}{R_s + L_s} [R_s U_g \sin \delta + L_s (U_{\text{vsg}} - U_g \cos \delta)]
\end{align*}
$$

where $R_s$ is the armature resistance of VSG, $L_s$ is the synchronous reactance, $U_g$ is the effective value of grid voltage, $U_{\text{vsg}}$ is the effective value of VSG voltage

$$U_{\text{vsg}} = U_0 + k_Q (Q^* - Q) \tag{6}$$

where $U_0$ is the output voltage of idler, $k_Q$ is the adjustment coefficient of reactive power, $Q^*$ is the reference value of reactive power.

4 Seamless switching control strategy

In order to realise seamless switching between grid-connected and islanding operation of energy storage inverter, VSG control strategy is adopted. The control strategy is shown in Fig. 4.

Not only the rotor motion equation of a synchronous generator is used as a control equation by VSG, but also the inertia characteristic of a synchronous generator is introduced into the control of inverter. The VSG control schematic diagram is shown in Fig. 5.

Decoupling control of the $dq$ axes is used to decouple the voltage and current loop, by which the stability problem caused by grid-connected and islanding operation switching can be avoided. The schematic diagram of decoupling control is shown in Fig. 6.
5 Simulation

A simulation model of T-type three-level energy storage inverter is built in MATLAB. The parameters of the simulation are listed in Table 1.

In order to realise the switch process, the instructions are given at both 0.08 and 0.16 s. \( K_1 \) is closed, and \( K_2 \) is open at 0.08 s. In addition, \( K_1 \) is open, and \( K_2 \) is closed at 0.16 s. The simulation waveform of \( u_{ab} \) is shown in Fig. 7. Between 0.0 and 0.08 s, the energy storage inverter is in grid-connected operation, and between 0.08 and 0.16 s, the energy storage inverter is in isolated-island operation, else after 0.16 s, the energy storage inverter is in grid-connected operation.

Only when the frequency, phase, and amplitude of VSG are same as a grid, can grid-connection operation state be achieved. The output voltage phase of VSG and the grid are same as shown in Fig. 8.

The frequency waveform of VSG is shown in Fig. 9. The frequency is kept near 50 Hz both in grid-connected operation and isolated-island operation.

The simulation waveform of open-loop output voltage \( u_{ab} \) is shown in Fig. 10 and three-phase voltage waveforms are shown in Fig. 11.

| Parameters                      | Value   |
|---------------------------------|---------|
| DC side voltage, V             | 540     |
| DC capacitor, \( \mu \)F         | 1100    |
| effective value of grid side phase voltage, V | 220     |
| inductance \( L_1 \), mH          | 0.44    |
| inductance \( L_2 \), mH          | 0.11    |
| filter capacitor, \( \mu \)F      | 65.8    |
| damping resistance, \( \Omega \)  | 0.4     |
| load resistance, \( \Omega \)     | 24      |
| \( \omega^* \), rad/s            | 314     |
| \( k_p \)                        | 20.3    |
| \( k_Q \)                        | 181.8   |
| \( J \), kg m\(^2\)              | 20.3    |
| \( J \), kg m\(^2\)              | 0.5     |

Fig. 7 Voltage of VSG and grid

Fig. 9 Frequency of VSG

Fig. 10 Open-loop output voltage \( u_{ab} \)

Fig. 11 Three-phase voltage of VSG

Fig. 12 Waveform of active power
At this simulation, $P^* = 10$ kW, $Q^* = 10$ kW, and the load is resistance. The energy storage inverter is kept running independently with a load before 0.08 s. And the active power is absorbed by the load after 0.16 s. The active power waveform is shown in Fig. 12.

6 Conclusion

A simulation model of grid-connected operation and isolated-island operation switching based on VSG is built in MATLAB, and the system simulation analysis is carried out. It is shown that the VSG control strategy can realise seamless switching between grid-connected operation and isolated-island operation.

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