Research on the Structure and Control Strategy of Energy Storage Grid Connected Inverter

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Abstract. This paper studied the structure of energy storage grid connected inverter which is composed of super capacitor, bi-directional DC/DC converter, and voltage type DC/AC converter. The working principle of bi-directional DC/DC converter and DC/AC converter was separately analyzed. Then a joint control strategy of DC/DC converter and DC/AC converter was proposed with the main control objective of maintaining DC bus voltage. According to the different states of DC bus voltage and super capacitor voltage, five control modes of energy storage inverter were set. Besides, the DC/AC converter was controlled to compensate the reactive power and harmonics, and provide certain active power for the power grid according to the actual situation. Finally, the effectiveness of the proposed energy storage inverter structure and control strategy were verified through simulation analysis.

1. Introduction

With the access of non-linear load, new energy generation system and distributed generation system, the power quality problems such as harmonic, three-phase imbalance, voltage fluctuation and voltage sag in distribution network become more prominent. At present, the power quality control devices used in distribution network mainly include distribution static compensator (D-STATCOM), active power filter (APF), dynamic voltage restorer (DVR), and so on. D-STATCOM and APF are mainly used to compensate reactive power and harmonic current, DVR is mainly used to compensate voltage sag.

However, D-STATCOM and other grid connected inverters can only compensate reactive power and partial harmonic and unbalanced current, but can not provide active power because of the limited capacity of DC side capacitance [1]-[2]. With the rapid development of energy storage technology, energy storage system is more and more widely used in the distribution network. The energy storage device and grid connected inverter are combined to form the energy storage inverter system [3], which can not only compensate the comprehensive power quality of the grid, but also provide the active power for the grid, further improving the power quality and reliability of the distribution network. At present, energy storage grid connected inverter has become a research hotspot [4]-[6].

This paper studied the structure of energy storage grid connected inverter mainly composed of energy storage device, DC/DC converter, and voltage type DC/AC inverter, and then proposed the joint control strategy of DC/DC converter and DC/AC inverter with the main control objective of maintaining DC bus voltage. Through simulation analysis, the effectiveness of the proposed energy storage inverter structure and control strategy were verified.
2. System structure of energy storage inverter

Super capacitor has high power output capacity and high energy conversion efficiency, but less energy storage. In the process of charging and discharging, the terminal voltage will change with the stored energy. If the super capacitor bank is directly connected to the DC bus of the DC/AC inverter, enough units are need to be connected in series to meet the requirement of the bus voltage, which will lead to a great waste of power capacity [7]-[8].

In this paper, based on the characteristics of super capacitor and the structural requirements of three-phase four-wire energy storage inverter, a bi-directional DC/DC converter is added between the super capacitor bank and the DC bus of the inverter to form the main circuit structure of the energy storage grid connected inverter. As shown in Figure 1. The energy storage inverter mainly consists of super capacitor, bi-directional DC/DC converter, DC bus and voltage type DC/AC inverter. The super capacitor is located on the low voltage side of the bi-directional DC/DC converter, improving the utility rate of super capacitor and the energy storage economy. Besides, the DC bus voltage of the inverter can be controlled by controlling the DC/DC bi-directional converter, and the control effect and output performance of the energy storage inverter can be improved.

![Figure 1. Structure diagram of energy storage grid connected inverter.](image)

3. Principle analysis

3.1. Bi-directional DC/DC converter

The bi-directional half bridge DC/DC converter realizes the boosting, charging and discharging of the energy storage device. In the super capacitor energy storage system, the non-isolated DC/DC converter is usually used. The non-isolated bi-directional DC/DC converter can realize two quadrant operation, that is, the voltage direction at both ends of the converter is unchanged while the current direction can be changed, that is, it has two working modes of boost converter and buck converter. The two operation modes of bi-directional half bridge DC/DC converter are shown in Figure 2.

![Figure 2. Operation modes of bi-directional DC/DC converter.](image)

In the figure, UC is the voltage of the super capacitor energy storage device, UDC is the voltage of the DC bus. UC is lower than UDC. The main control objective of bi-directional DC/DC converter is to maintain the DC bus voltage within a certain range by controlling the charge and discharge of the
super capacitor. When UDC is lower than a certain set value, the super capacitor releases energy to the DC bus; when UDC is higher than a certain set value, the super capacitor absorbs the excess energy of the DC bus.

3.2. Voltage type DC/AC inverter

The main circuit structure of the three-phase bridge voltage type DC/AC inverter is the same as that of D-STATCOM, which has the ability of bi-directional four-quadrant operation. It can compensate the reactive power and harmonic currents of the AC power grid, and realize the power exchange between the DC bus and the AC power grid.

Through appropriate control strategy, the energy storage grid connected inverter system can exchange active and reactive power with the AC grid, so as to improve the power quality and reliability of the grid. The power flow between the inverter and the grid is shown in Figure 1.

4. Control method of energy storage grid connected inverter

4.1. Overall control strategy

In this paper, the proposed overall control strategy of energy storage inverter is that DC/DC converter and DC/AC inverter cooperates with each other to maintain the voltage stability of DC bus. At the same time, control the inverter to compensate the reactive power and harmonics, and provide the active power to the grid according to the actual situation.

Assume that the allowable fluctuation range of DC bus voltage is UDC1 < UDC < UDC2, and the normal working voltage range of super capacitor energy storage device is UC1 < UC < UC2. According to the different states of the two voltages, select the corresponding control mode for the energy storage inverter, as shown in Figure 3.

![Figure 3. Different control modes of energy storage inverter.](image)

Mode 1: Control the output current of the DC/AC inverter to stabilize UDC near its rated value. Jointly control the DC/DC converter and DC/AC inverter to realize the power exchange between the super capacitor bank and the AC power grid, and ensure that the voltage of the super capacitor is within the normal working range.

Mode 2: Control the DC/DC converter to work in the boost mode, and the super capacitor energy storage device releases energy to the DC bus.

Mode 3: Control the DC/AC inverter to work in the rectifier state, absorb the active power of the AC power grid, and charge the DC bus.

Mode 4: Control the DC/DC converter to work in the buck mode, and the super capacitor energy storage device absorbs the excess energy of the DC bus.

Mode 5: Control the DC/AC inverter to work in the inverter state, provide active power to the AC power grid, and consume the energy of the DC bus.
In addition, under any non-fault conditions, the DC/AC converter can be controlled to work in STATCOM mode to achieve reactive power and harmonic current compensation of the AC distribution network.

4.2. Control method of DC/DC converter
In this paper, the voltage and current double closed-loop control strategy [9] is used to control the DC/DC converter, and the control schematic diagram is shown in Figure 4.

![Figure 4. Control schematic diagram of DC/DC converter.](image)

In the figure, $u_{DC}$ is the instantaneous value of DC bus voltage, $i_L$ is the instantaneous value of output current of super capacitor bank, $u_{PWM}$ is the voltage on DC/DC converter bridge arm, $G_i(s)$ is the transfer function from $u_{PWM}$ to $i_L$.

The outer loop is DC bus voltage control and the inner loop is super capacitor bank output current control. Both the outer voltage loop and the inner current loop adopt PI control method.

It should be noted that the value of $u_{DC\_ref}$ is different under the conditions of super capacitor charging and discharging. When the DC bus voltage $u_{DC}$ drops below $U_{DC1}$ and super capacitor discharging is required, set $u_{DC\_ref}$ equal to $U_{DC1}$, when $u_{DC}$ rises above $U_{DC2}$ and super capacitor charging is required, set $u_{DC\_ref}$ equal to $U_{DC2}$. In addition, the direction of $i_L$ is the opposite in the case of super capacitor charging and discharging.

4.3. Control method of DC/AC converter
In this paper, double closed-loop control strategy [10] is used to control the three-phase output current $i_a$, $i_b$, $i_c$ of DC/AC inverter. The active and reactive power decoupling control method is adopted, and $i_a$, $i_b$, $i_c$ are transformed into $i_d$, $i_q$ in synchronous rotation coordinate system to track and control these two variables respectively.

The control objective of reactive current is to compensate the reactive current of AC power grid. The control objectives of active current include: to control the DC bus voltage to be constant and to output certain active power to the AC power grid.

4.3.1. Control the DC bus voltage to a constant value: The control schematic diagram is shown in Figure 5.

![Figure 5. Control the DC bus voltage to a constant value.](image)

4.3.2. Control to output certain active power: The control schematic diagram is shown in Figure 6.
5. Simulation analysis

A simulation model of the grid connected energy storage inverter system was established using Matlab/Simulink simulation software. See Figure 1 for the system structure. The main parameters of the simulation system are shown in Table 1.

Table 1. Main parameter setting.

| Element            | Project                  | Parameter                  |
|--------------------|--------------------------|----------------------------|
| Super capacitor    | Equivalent capacitance   | $C = 108 \text{ F}$       |
| bank               | Rated voltage            | $U_{CN} = 300 \text{ V}$  |
|                    | Maximum / minimum working voltage | $U_{C2} = 400 \text{ V}, U_{C1} = 200 \text{ V}$ |
| DC bus             | Equivalent capacitance   | $C_{DC} = 20 \text{ mF}$  |
|                    | Rated voltage            | $U_{DCN} = 750 \text{ V}$ |
|                    | Maximum / minimum working voltage | $U_{DC2} = 800 \text{ V}, U_{DC1} = 700 \text{ V}$ |

5.1. Case 1: DC bus voltage too high, $U_{DC} > U_{DC2}$

In the simulation model, the initial values of DC bus voltage is 1100 V, super capacitor bank voltage is 300 V. The super capacitor energy storage device starts to work at 0.06 sec, the three-phase DC/AC inverter starts to work at 0.20 sec, the reactive power compensation function is put into operation after 0.26 sec, and the active power output function is realized after 0.32 sec. The simulation results are shown in Figure 7.

![Figure 6. Control to output certain active power.](image)

(a) DC bus voltage.

(b) Super capacitor bank voltage.
6. It can be seen from Figure 7 that after the 0.06 sec energy storage system is put into operation, the DC bus releases energy to the super capacitor bank, the voltage of the super capacitor increases, and the voltage of the DC bus decreases from 1100 V to 800 V. After the 0.20 sec DC/AC converter is put into operation, the DC/AC converter works in the inverter state, outputs active power to the power grid, and consumes the energy of the DC bus, controlling its voltage to 750 V. After the 0.26 sec, the DC/AC converter outputs about 60 kVar of reactive power to the power grid, realizing the function of STATCOM. After the 0.32 sec, DC/AC converter outputs about 45 kW of active power to the power grid. When DC bus voltage drops below 700 V, super capacitor bank releases energy to DC bus to control its voltage at 700 V.

5.2. Case 2: DC bus voltage too low, $U_{DC} < U_{DC1}$

The initial value of the DC bus voltage is set to 300 V, and other parameters are the same as in the previous section. The simulation results are shown in Figure 8.

(c) Output active and reactive power of DC/AC inverter.

Figure 7. Simulation results when the starting value of DC bus voltage is 1100 V.

Figure 8. Simulation results when the starting value of DC bus voltage is 300 V.
It can be seen from Figure 8 that after the 0.06 sec energy storage system is put into operation, the super capacitor bank releases energy to the DC bus, the voltage of the super capacitor decreases, and the voltage of the DC bus increases from 300 V to 700 V. After the 0.20 sec DC/AC converter is put into operation, the DC/AC converter works in the rectifier state, absorbs active power from the power grid, and charges the DC bus, controlling its voltage to 750 V. After the 0.26 sec, the DC/AC converter outputs about 60 kVar of reactive power to the power grid, realizing the function of STATCOM. After the 0.32 sec, the DC/AC converter outputs about 45 kW of active power to the power grid. Then, the super capacitor bank releases energy to the DC bus to control its voltage at 700 V.

The simulation results of the above two cases verify the correctness of the proposed joint control strategy of the energy storage grid connected inverter.

6. Conclusion
In this paper, the system structure of energy storage grid connected inverter based on super capacitor was studied, and then the joint control strategy of DC/DC converter and DC/AC inverter based on the change of DC bus voltage was proposed. The DC/DC converter and DC/AC converter cooperate with each other to maintain the stability of DC bus voltage, meanwhile, DC/AC converter can also compensate the reactive power and harmonic of the power grid, and provide a certain amount of active power for the power grid according to the actual situation. Finally, the correctness of the proposed control strategy was verified by simulation analysis.

Energy storage grid connected inverter has the ability of flexible output of active power and reactive power, and can significantly improve the power quality and reliability of the distribution network. It has broad application prospects in distributed generation, micro-grid, urban rail transportation and other fields.

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