Research on characteristics of bidirectional CLLC DC–DC transformer used in DC microgrid

Wen Chunxue1, 2, Hu Mingming1, Hu Changbin1, Piao Zhengguo1, Zhou Jinghua1

1College of Electrical and Control Engineering, North China University of Technology, Beijing, People’s Republic of China
2E-mail: wcx@ncut.edu.cn

Abstract: In the DC microgrid system, the energy storage system must have both high power density and high energy density, and it is difficult for a single type of energy storage device to meet this requirement. The battery and the super capacitor are highly complementary in performance. Here, the battery and the super capacitor are, respectively, connected to the DC bus through a bidirectional DC–DC converter to form a hybrid energy storage system. For a 380V DC microgrid system, a new type of symmetrical circuit topology structure with two inductors and two capacitors (CLLC) resonant network is proposed. Since the symmetrical CLLC resonant network has the zero voltage switching capability of the main power switch and the soft commutation capability of the output rectifier, the converter can operate at high power conversion efficiency. Finally, the effectiveness of the system control strategy is verified through simulation and experiments.

1 Introduction

The massive use of renewable energy can not only ease the current energy crisis, but also greatly reduce the emission of pollutants, and can achieve relatively good energy-saving emission reduction benefits [1]. Renewable energy power generation units have some disadvantages such as unstable power generation. Therefore, energy storage systems have become an important part of distributed power generation systems that use solar energy, wind energy etc. as the main energy sources, and have important research significance [2, 3].

Batteries are widely used in energy storage devices, and their energy density is relatively large, which meets the requirements of distributed generation for energy density [4,5]. However, the power density of the battery is small. When the load power suddenly changes, the target power cannot be quickly absorbed or released, and it is difficult to meet the dynamic requirements of the system. Super capacitor charging can provide high power in a short period of time, providing buffer for other devices, but the energy density is relatively low, so the super capacitor and the battery have a strong complementarity in performance, often through the two kinds of energy storage elements [6–8]. The way to connect to form a hybrid energy storage system [9], in order to fully play the advantages of both to make the system get better performance, this is the starting point of this article.

2 Analysis of structure and working principle of hybrid energy storage system

The battery and the super capacitor are, respectively, connected to the DC bus through the DC converter to form a hybrid energy storage system [10,11]. The converter in the battery is the most widely used bidirectional converter in the photovoltaic power storage system – Buck/Boost converter. The super capacitor is connected to the bus through the CLLC DC converter. The simplified structure of the system is shown in Fig. 1.

The control principle diagram of the energy storage system is shown in Fig. 2. In order to maintain the stability of the bus voltage of the DC distribution network and ensure the stable operation of the DC distribution network, two controllers are designed in the control system of the energy storage system [12].

The controller 1 collects the DC bus voltage and the battery current, compares the collected bus voltage value with a given voltage value, and determines the working mode of the battery according to the difference between the two, thereby stabilising the bus voltage. The controller 2 collects the battery voltage and the super capacitor current, judges the working mode of the super capacitor through the voltage fluctuation of the battery, provides or absorbs the abrupt power, and realises the control of charging and discharging the super capacitor, thereby providing buffer for the battery.

The hybrid energy storage control block diagram is shown in Fig. 3, where the expression of the PI compensator is:

$$G_{Bat}(s) = \frac{K_{pBat}(s) + \theta_{Bat}}{s}$$  \hspace{1cm} (1)

The open-loop transfer function of the battery individually controlling the bus voltage is

$$G_{BatBus}(s) = \frac{0.5G_{Bat}G_{Bat}}{(1 + 0.5G_{Bat})C_{Bus}H_{Bus}(s)}$$  \hspace{1cm} (2)

The open-loop transfer function of the hybrid energy storage control bus voltage is

$$G_{Busoc}(s) = \frac{G_{dc}G_{Bat}(1 + 0.5G_{Bat}) + 0.5G_{Bat}G_{Bat}(1 + G_{dc})}{(1 + G_{dc})(1 + 0.5G_{Bat})} \times \frac{1}{C_{Bus}H_{Bus}(s)}$$  \hspace{1cm} (3)

The battery and hybrid energy storage control Bode diagram is shown in Fig. 4. Compared with the battery control bus voltage

![Fig. 1  Simplified structure of distributed power generation system](image-url)
alone, the hybrid energy storage control system increases the crossover frequency, the phase margin increases, and the adjustment speed increases. Therefore, the hybrid energy storage system performs better.

3 CLLC resonant converter operating mode

With the development of modern power electronics and the birth of high-frequency switching devices, switching power supplies are moving towards higher frequency, integration, and modularisation. Resonant converters have been widely studied and studied in the field of high-frequency power conversion because of their ability to achieve soft switching, which effectively reduces switching losses and enables the frequency to be further increased. The new CLLC bidirectional DC–DC transformer (CLLC-BDCT) has the advantages of simple control strategy and high conversion efficiency, and has become an optional topology for high-frequency isolation between low-voltage DC microgrid system and energy storage units. However, the complicated operation process has seriously hindered the research and application of CLLC resonant converters [13–15].

The CLLC resonant converter is based on the traditional second-order resonant converter based on the addition of a shunt inductance improved, so in comparison with the ordinary series, parallel resonant converter in the characteristics of a significant improvement. This converter can operate at high power, enabling the CLLC resonant network to implement soft-switching technology [16].

In Fig. 5, the power devices S1–S4 and S5–S8 form two full-bridge converters, respectively. When working in the forward direction, S1, S4 and S2, S3 plus complementary drive signals, to achieve the inverter function, S5–S8 does not add the drive signal, using the anti-parallel diode switch to rectify. In reverse operation, the corresponding S5–S8 plus drive signal is used to invert. At this time, the magnetising inductance can be equivalent to the secondary side of the transformer. The structure on both sides of the converter is completely symmetrical. \( L_m \) is the magnetising inductance of the high-frequency transformer. \( L_{r1} \) and \( L_{r2} \) are resonant inductances (see Table 1). They contain the leakage inductances of the primary and secondary sides of the transformer, respectively. \( C_{r1} \) and \( C_{r2} \) are resonant capacitors, and they have a blocking effect. DS1–DS8 are anti-parallel diodes S1–S8, respectively [17,18].

Fig. 6 shows the typical operating modes of the proposed converter. In Mode 1, there is a dead time duration. At this moment, the inductor current \( i_p \) is equal to the excitation current \( i_m \), and the secondary current is reduced to zero. DS6 and DS7 naturally turn off due to zero current. There is no reverse recovery process and ZCS soft switching is implemented. In mode 2, S1 and S4 are turned on and the primary current \( i_p \) is freewheeling through DS1 and DS4, and S1 and S4 are turned on at zero voltage. Power is transmitted through the transformer \( T_r \) to the secondary rectification stage. When the primary current \( i_p \) is equal to the magnetising current \( i_m \), Mode 2 will end. This operation will be repeated in modes 4 and 5 in the same way [19,20].

Fig. 7 shows the theoretical waveforms of all the converters in a single switching cycle. In Fig. 7, only the forward waveform (power supply) is turned on. However, in the case of reverse conduction (power generation), since the power levels and components of the main inversion and secondary rectification stages are symmetrical, the waveforms are exactly the same as those of the mutually inverted stages. During the forward conduction, only the switches in the main inversion stage are switched with (S1, S4) and (S2, S3) pairs. At this point, all switches in the secondary rectification stage are off and the secondary current is rectified by the anti-parallel diode of the switch. In contrast, during the power generation mode, only the secondary switches are switched with (S5, S8) and (S6, S7) pairs, and all the main inverting stage switches are turned off.

4 Simulation verification

In order to verify the correctness of the theoretical analysis and the rationality of the parameter design, the photovoltaic power generation system was simulated and analysed. The system mainly includes three parts: control circuit, functional circuit, and DC/DC conversion circuit. Among them, the functional circuit is divided into DC-side photovoltaic boost circuit, battery with Buck/Boost circuit, super capacitor with bi-directional CLLC resonant converter circuit. Energy units include: PV arrays, super capacitors, battery, and DC loads.

In Fig. 8, the load power is 3.2 kW before 0.3 s. At the initial stage, the super capacitor and the photovoltaic power supply to the
load. When the photovoltaic works in the MPPT mode, the photovoltaic power reaches 3 kW, the photovoltaic power supply to the load, and the super capacitor works stably. When the super capacitor voltage is unchanged, the battery does not work. At 0.3 s, the load power increases to 4.6 kW, the super capacitor discharges quickly, and the photovoltaic and super capacitors supply power to the load, and the battery does not work.

In Fig. 9, the DC load power is 0 kW before 0.15 s, and the super capacitor supplies the battery with photovoltaic power. At 0.15 s, the DC load power increases to 3.2 kW. At this time, the super capacitor power is insufficient, the bus voltage drops, and the battery stops charging and supplies power to the load. At 0.3 s, the load power is increased to 4.6 kW, and the battery and photovoltaic continue to supply power to the load, maintaining the bus voltage stability.

In the CLLC DC converter boost mode experiment, the super capacitor acts as a power source and discharges the load together with the photovoltaic unit. It can be seen from Fig. 10 that the initial load side current is 0.65 A, then the load power increases, the load measurement current rises, and the super capacitor discharge current increases. When the load current increases to 1.1

| Parameter name | Parameter value |
|---------------|-----------------|
| $L_m$         | 556 $\mu$H     |
| $L_1$         | 61.78 $\mu$H   |
| $C_{r1}$      | 0.46 $\mu$F    |
| $L_2$         | 10.99 $\mu$H   |
| $C_{r2}$      | 2.56 $\mu$F    |
In the CLLC DC converter buck mode experiment, the super capacitor acts as a load, and the photovoltaic unit supplies power to the super capacitor and the load. As shown in Fig. 11, the CLLC DC converter operates in the buck mode, and the super capacitor operates in a constant current charging state with a charging current of 2 A. The load side current is 0.25 A, and when the super capacitor is charged to the rated voltage of 150 V, the charging current is rapidly reduced. It can be seen from the experimental results that during the charging of the super capacitor, the bus voltage can be guaranteed to be maintained at about 380 V.

5 Conclusion

This article verifies a bidirectional full-bridge CLLC resonant converter for high-frequency galvanic isolation of a 380 V DC microgrid system and controls bidirectional power flow. The converter can operate in ZVS under soft switching of the main switch and output rectifier. In addition, the converter does not need any clamp and buffer circuit to reduce the voltage stress of the power switch. The hybrid energy storage system established in this paper uses the operating mode of the battery to stabilise the DC bus voltage and the super capacitor provides the high-frequency component of the abrupt-load power, and can fully utilise the advantages of the two types of energy storage components; so that the entire energy storage system has high energy density and high power density characteristics.

6 References

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