Research on MMC-SST Oriented AC/DC Distribution System

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Abstract. A modular multilevel converter-solid state transformer (MMC-SST) oriented AC/DC Distribution System is designed. Firstly, the topology structure is introduced, MMC is adopted in the input stage, multiple DC-DC converters are adopted in the isolation stage, and a Three-Phase Four-Leg inverter is adopted in the output stage. Then, the control strategy is analysed. Finally, simulation model and an experimental prototype of MMC-SST are built, simulation and experimental results show that topology and control strategy of MMC-SST are feasible.

1. Introduction

Distribution network is entering a sustainable post-carbon era characterized by "distributed energy + distribution network", energy internet is the strategic demand for the next energy revolution, The full use of solar energy and other renewable energy sources is an important way to achieve energy internet. Distribution transformer is the core equipment of energy internet, Traditional distribution transformers use transformer core to realize the basic functions such as varying voltage, electrical isolation and energy transfer. But it has many disadvantages, such as large size, large weight, much no-load loss and low efficiency, which greatly restrict its development in distribution network.

In this context, Solid State Transformer (SST) is proposed by domestic and foreign scholars, SST is called as Power Electronic Traction Transformer (PETT) that is a new type of transformer which achieves varying voltage and energy transfer in power system thought Power Electronic Traction Transformer technology. Compared with conventional transformer, SST has the advantages of small size and light weight. In addition, through advanced control technology, it can also flexibly control the primary side current, auxiliary side voltage and power flow. It can provide DC bus interface and integrate all kinds of distributed power supply, and realize the unified and coordinated distribution of power flow in distribution network, As a result, it meets the requirements of energy saving, environment protection and high efficiency of Micro-grid, and it is the future direction of distribution network.

In the past ten years, domestic and foreign scholars have begun to study SST [1-3]. Literature [4] proposed a unified reduced order modelling and single-level control strategy for the high-voltage power electronics transformer, a 10 k V power electronic transformer topology and its control feasibility of the strategy are verified in PSCAD simulation environment. Literature [5] analysed grid-connected mode and islanded mode of SST applied in a hybrid AC-DC micro-grid, the simulation model of AC-DC micro-grid and SST are built to analyses the power fluctuations of the distributed energy in micro-grid. Literature [6] proposed a new steady state control scheme of MMC-HVDC based on internal model controller under two-phase stationary coordinate, By analyzing features of internal model control method, the control structure and parameters of the current cycle are designed, and a double closed-loop control system based on IMC inner-cycle and PI outer-cycle is built. Literature [7] researched on

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restraining Circulating Currents of SST in Islanding, Simulations showed that the control strategy can restrain the circulating currents well, and can improve the output voltage stability of SST. Literature [8] proposed a novel energy router based on high frequency multi-winding transformer, which caters for the energy internet. Therefore, the research and application of SST are still in the stage of theoretical research.

Based on this, a modular multilevel converter Solid-State Transformer Oriented AC/DC Distribution System is proposed in this paper, SST topology consists of rectifier based on MMC, the isolated DC-DC converter and three-phase four-leg inverter. The different levels of control strategy are analysed, the rectifier module uses PWM to get a stable DC voltage and a rapid dynamic response, the isolated DC-DC converter uses active power balance strategy to solve the problem of DC voltage unbalance in rectifier and power unbalance among dual active bridge (DAB) modules. The inverter adopts the double closed-loop control strategy to realize static error free tracking control. Finally, a simulation model and an experimental prototype of SST are established, the simulation and experimental results verify the feasibility and effectiveness of the proposed topology and control strategy.

2. Topological Structure And Mathematical Model of MMC-SST

At present, SST technology has developed rapidly, and scholars have proposed various SST topologies. The SST topology shown in Figure 1 is one of the most widely studied topologies. MMC-SST topology consists of rectifier based on MMC, The isolated DC-DC converter and three-phase four-leg inverter. MMC is adopted as grid converter in the input stage, multiple DC-DC transform units in parallel are adopted in the isolation stage to achieve two-way flow of energy and electrical isolation, Three-Phase Four-Leg Inverter is adopted in the output stage.

Compared with other SST topologies, MMC-SST topology has the following advantages. (1) It can provide AC voltage as well as DC voltage. (2) three-phase current on the high-voltage side still remains stable after the low-voltage side connecting unbalanced loads.(3) According to the voltage and power demand of the distribution network, the voltage of micro-grid system based on MMC-SST can be controlled flexibly by increasing or decreasing the number of MMC sub modules. Compared with the cascaded structure of H Bridge, MMC structure has many advantages, such as improving the quality of output voltage, reducing the amount of high-frequency transformer and power electronic switching device.

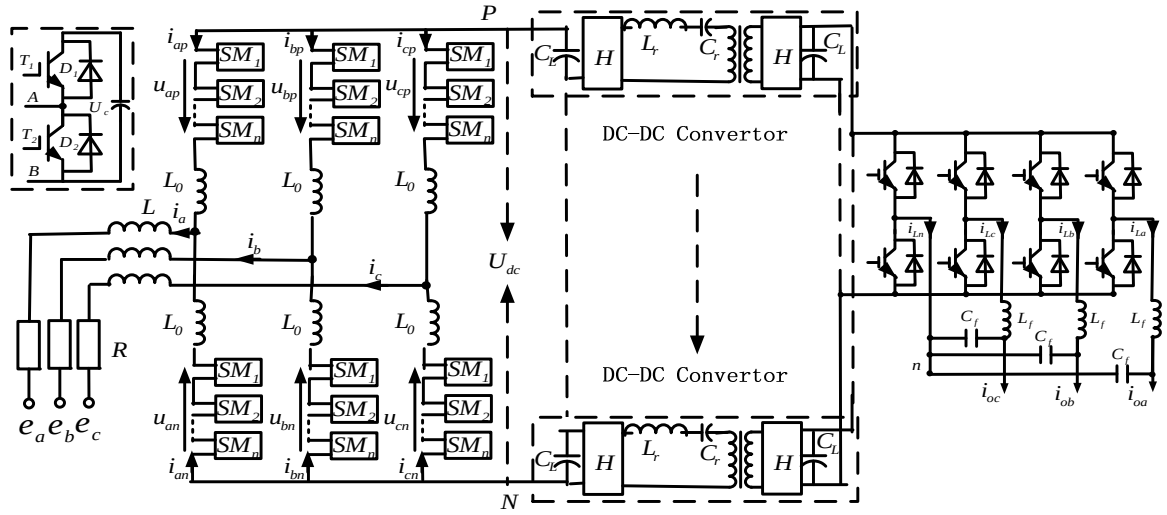


Figure 1. Topological structure of MMC-SST

2.1. The input stage

The input stage is the key part of the whole system, the performance of the input stage has a direct impact on the following two stages, MMC structure is adopted in the input stage, Each MMC Bridge consists of multiple sub-modules and a series reactor, each phase unit consists of upper and lower bridges.

The withstand voltage of the system is improved by module superposition, and higher equivalent switching frequency can be obtained by Carrier Phase Shift Algorithm, the harmonic injected into the network from the system and the switching loss of the system are effectively reduced. As a result, MMC-SST can be applied in the field of medium and high voltage. In addition, unit power factor operation can be achieved by proper control of the input stage, or it operates at a given power factor according to the reactive power demand of the power grid.

2.2. The isolation stage

The isolation stage is used to achieve DC-DC conversion and electrical isolation, The isolation stage is composed of multiple identical DC-DC conversion units, which are connected by input series output parallel(ISOP), Each DC-DC unit consists of a Single-Phase Full-Bridge inverter, a high frequency transformer and a Single-Phase Full-Bridge rectifier.

2.3. The output stage

The output stage is used to convert DC to AC, The output stage adopts three-phase four-leg inverter, but traditional three-phase four-leg inverter can only deal with three-phase symmetric linearity load, the asymmetry among three-phase voltages is arisen when it deals with nonlinear loads. Three-phase four-leg inverter is adopted to improve the capacity of unbalanced load, which adding the fourth bridge to directly control Neutral Point Voltage and three independent voltages are obtained. As a result, it can maintain symmetrical output voltages under unbalanced nonlinear load. In addition, the whole filter effect can be improved and THD value of output voltage can be reduced by adding inductors to Neutral line in Three-phase four-leg inverter circuit.

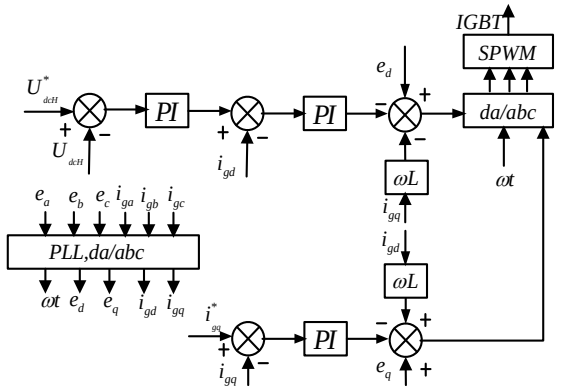


Figure 2. Control strategy of the input stage

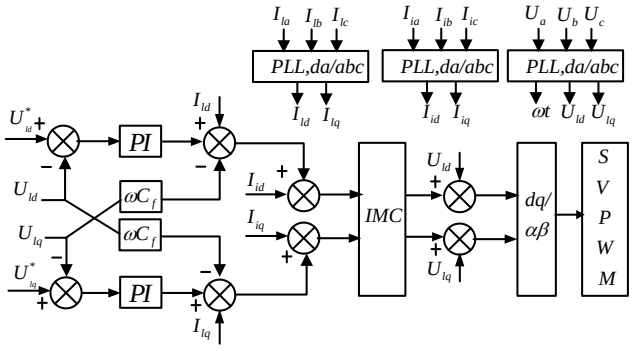


Figure 3. Control structure of output stage

3. Control Strategy

3.1. Control strategy of the input stage

Control strategy of the input stage is shown in Figure 2, the vector control strategy based on grid voltage orientation is adopted, and the control strategy is implemented under the synchronization reference frame. The outer-cycle is the voltage loop, which stabilizes DC side voltage, a certain DC voltage is

maintained by regulating the storage capacitor of MMC sub-module. The inner-cycle is the current loop, the fast current control is realized according to the current command from the outer-cycle, and the input stage is operated according to the given power factor, static error free tracking control of AC current is realized. In addition, in order to reduce mutual interference of d-axis current and q-axis current in the dynamic process, decoupling link is added to the current loop.

Control structure of MMC-SST output stage is shown in Figure 3, ω is the angular frequency of the grid voltage, L is the equivalent inductance of the bridge inductance and the filter inductance, $L=L_g+L_{arm}/2$; U^*_{dcH} is the reference value of U_{dcH} , i^*_{gq} is the reference value of i_{gq} , e_d is the d axis voltage component, e_q is the q axis voltage component, i_{gd} is the d axis current component, i_{gq} is the q axis current component, In order to operate under the input unit power factor, i^*_{gq} is set to 0.

PID is adopted in the outer-cycle and inner-cycle regulator. The parameters of the selected voltage loop regulator are as follows:

$$H_u(s)=0.055+0.5/s \quad ,$$

The parameters of the selected current loop regulator are as follows:

$$H_i(s)=50+6000/s$$

In order to improve the utilization rate of dc voltage, sinusoidal pulse width modulation (SPWM) is adopted to stabilize the capacitor voltage of the sub-modules.

3.2. Control strategy of the isolation stage

The isolation stage is composed of multiple identical isolated DC-DC converter, which are connected by input series output parallel (ISOP).The DC voltage is modulated into high-frequency square wave through multiple single-phase full bridge inverters with the same structure, The high-frequency square wave is coupled to the secondary side via a high-frequency transformer, Finally, the high -frequency square wave is converted to DC voltage through multiple single-phase full bridge rectifiers with the same structure.

DC-DC converter adopts open-loop control, the voltages on the high voltage side and the low voltage side are square wave voltage with duty cycle of 50%, and the phase is exactly the same.

Due to the use of ISOP in the DC-DC converter, the parameter mismatch may occur in each conversion unit, and the DC output voltage of the rectifier stage may occur unbalanced, which may cause uneven distribution of voltage stress in the switching device and produce circulating currents, the whole system will break down in severe cases. In order to solve this problem, Power balance control strategy is adopted, the duty factor of each module is adjusted by using the active component of duty cycle as feedback, and the switching device is in zero current state (ZCS) by setting RCL series-resonant circuit. As a result, the purpose of DC output voltage balance and power balance of each DAB module is achieved.

3.3. Control strategy of the output stage

DC/AC inverter is adopted in the output stage, the outer-cycle adopts PI controller to obtain stable AC frequency voltage, the inner-cycle adopts internal model controller to control the feedback current of filter inductance and feed-forward compensation current, and realizes static error free tracking control. Thus it has the very strong current limiting capacity, good dynamic response performance and strong disturbances ability. In addition, in order to improve DC voltage utilization ratio of inverter and decrease switching loss, space vector pulse width modulation (SVPWM) is adopted.

Control structure of MMC-SST output stage is shown in Figure 3, I_{id} and I_{iq} are d-axis current and q-axis current of three-phase DC/AC inverter in the DQ rotating coordinate system, U_{ld} and U_{lq} are d-axis component and q-axis component of load voltage in the DQ rotating coordinate system, I_{ld} and I_{lq} are d-axis component and q-axis component of load current in the DQ rotating coordinate system, U^*_{ld}

is the reference value of U_{ld} , U_{lq}^{*} is the reference value of U_{lq} , ω_1 is AC voltage angular frequency, R_0 is equivalent resistor of DC/AC inverter and output line, L_f is equivalent inductance of DC/AC inverter and output line, C_f is equivalent capacitance of DC/AC inverter and output line.

The parameters of the selected outer-cycle regulator are as follows:

$$H_u(s)=2+1600s/(s^2+\omega^2) \quad (1)$$

The parameters of the selected inner-cycle regulator are as follows:

$$H_i(s)=1.5 \quad (2)$$

4. Simulation and experiment analysis

4.1. Simulation analysis

In order to verify the feasibility of the control strategy, the simulation model for test is set up based on MATLAB/SIMULINK. In the simulation model, the amount of bridge sub-modules is 10, power is 1.5MVA, frequency is 50Hz, voltage of high-voltage side is 10kV, DC voltage of fore-end side is 2100V, DC voltage of back-end side is 700V, and voltage of low-voltage side is 380V.

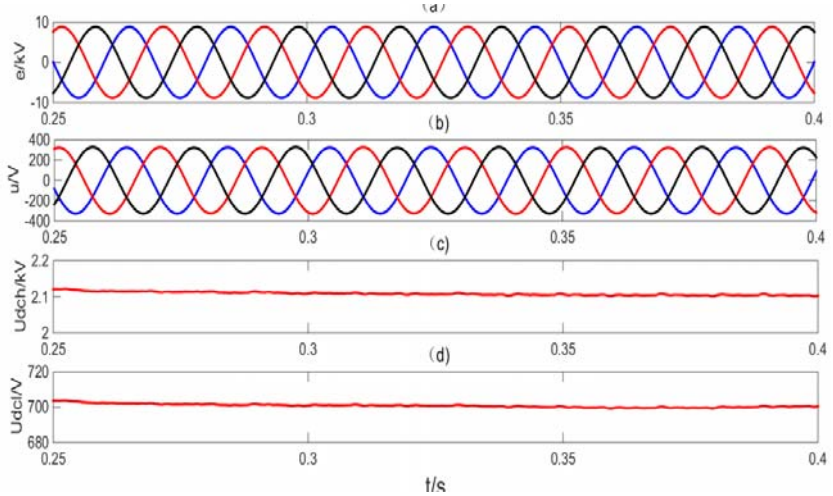


Figure 4. The steady-state simulation result

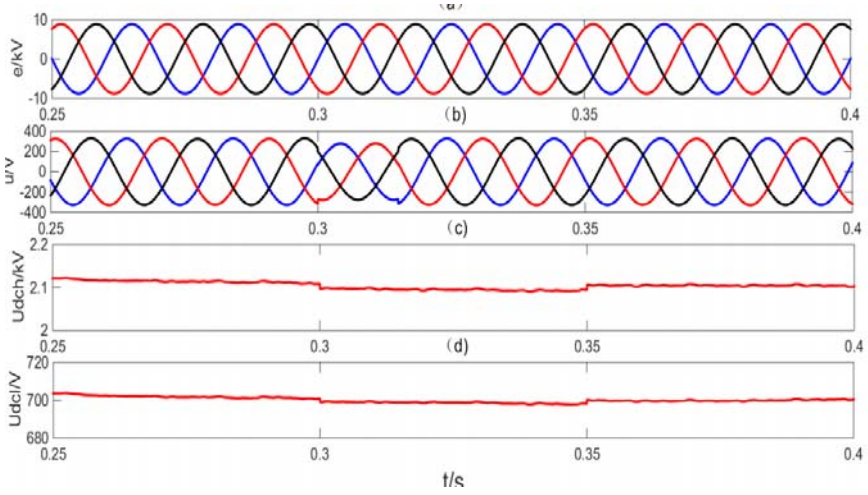


Figure 5. The dynamic simulation result

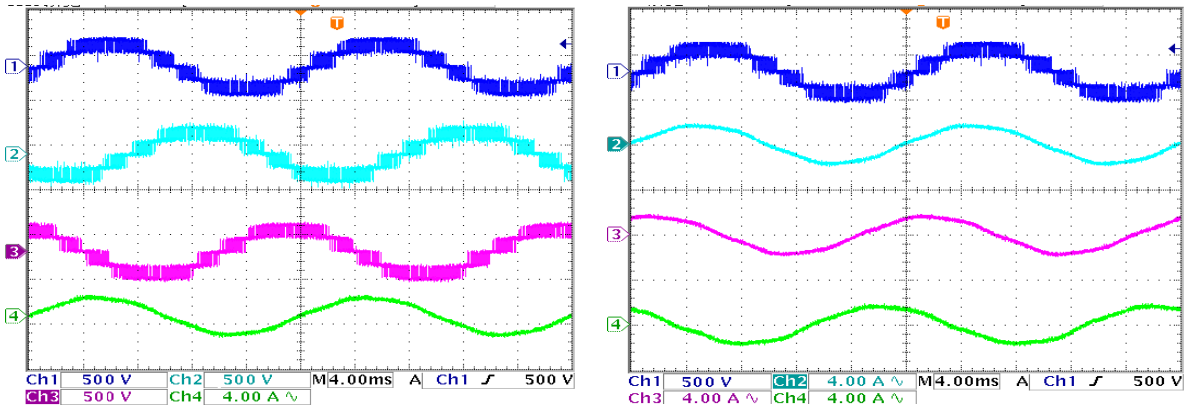
The steady-state simulation result of SST with three-phase load is shown in Figure 4, The three-phase grid voltages on the 10kV AC side is shown in Figure (a), the three-phase voltages on the low-voltage AC side is shown in Figure (b), the high DC voltage and the low DC voltage in steady state are shown in Figure (c) and Figure (d).As shown in Figure 4, voltage waveform of the low-voltage AC side is good and THD is small, The DC voltage of the high-voltage side and the low-voltage side is stable and the ripple factor is small. In addition, the average value of the low DC voltage is close to the design value 700V, It is proved that the impedance of the DC-DC converter in series resonant state is very small, the voltage drop can be neglected, and control strategy is feasible.

The dynamic simulation result of SST with three-phase load is shown in Figure 5, The three-phase grid voltages on the 10 k V AC side is shown in Figure (a), the three-phase voltages on the low-voltage AC side is shown in Figure (b), the high DC voltage and the low DC voltage in dynamic state are shown in Figure (c) and Figure (d). Low-voltage AC side is in no-load when time is less than 0.3s, low-voltage AC side is in load when time is greater than 0.3s.As shown in figure 5, voltage on the low-voltage AC side drops under abrupt change of load, but then it quickly returns. Voltages on the low-voltage AC side and the high DC voltage also recovers at about 50 ms under abrupt change of load, and the trend is almost the same.

4.2. Experimental verification

In order to verify the performance of SST, a experimental prototype is built. The main parameters of the system are as follows: (1)In the Input stage: the line voltage is 300 V, frequency is 50 Hz, the filter inductance is 2.5mH, the capacitor on high-voltage DC side is 1560 F, and the voltage on high-voltage DC side is 360V, The switching frequency is 4.8 KHz. (2) In the isolation stage:the operating frequency is 2 KHz, the transformer ratio is 3:1:1:1, the capacitor on low-voltage DC side is 3000 F, and the voltage on low-voltage DC side is 120V. (3) In the output stage:the filter inductance is 0.4mH, the filter capacitance is 22 F, and the switching frequency is 10 KHz, the load resistance on the low voltage side is 15.6Ω.

(1) Experiments of the three-phase PWM rectifier

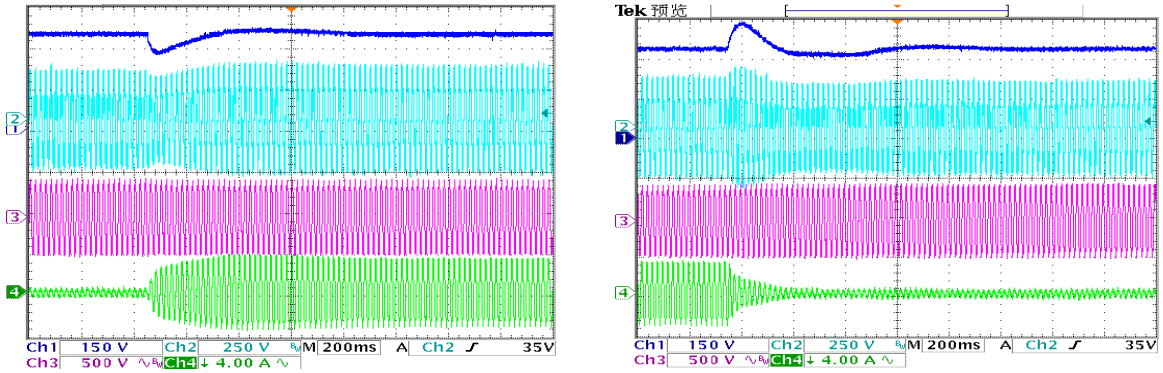


(1)Port voltage waveforms (2) current waveforms

Figure 6. waveforms of three-phase AC voltage and current

waveforms of three-phase AC voltage and current are shown in Figure 6, Port voltage waveforms are shown in Figure.6(1), Channel 1 is port voltage U_{an} ,Channel 2 is port voltage U_{bn} ,Channel 3 is port voltage U_{cn} ,Channel 4 is AC current i_{as} . AC current waveforms are shown in Figure 6(2), Channel 1 is port voltage U_{an} , Channel 2 is AC current i_{as} , Channel 3 is AC current i_{bs} , Channel 4 is AC current i_{cs} .

As shown in Figure 6(1), Port voltage waveform is five level, and the phase difference is 120°, and AC current waveform is sine wave. As shown in Figure 6(2), when three-phase rectifier transmits the active power, three-phase AC currents are sinusoidal and its phase difference is 120°, and the phase of voltage and current are almost identical.

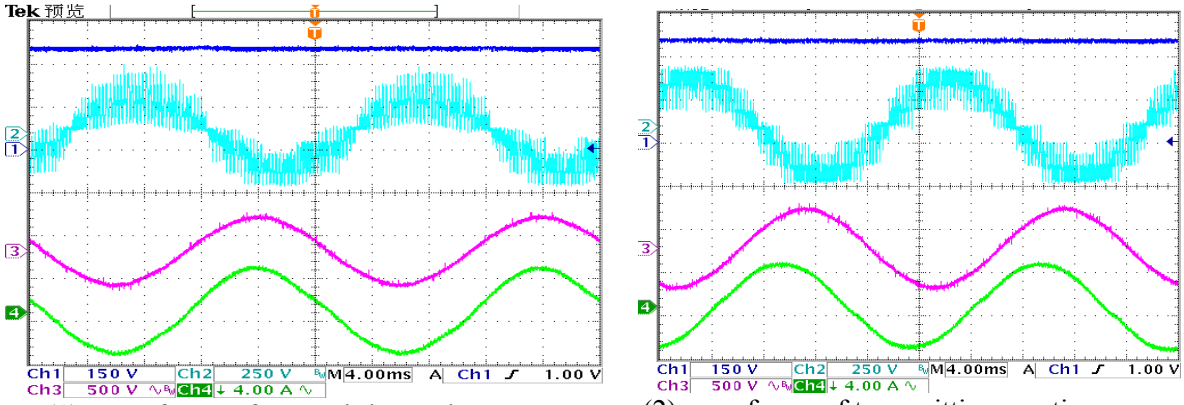


(1) waveforms varying from no-load to load (2) waveforms varying from load to no-load

Figure 7. dynamic waveforms of three-phase PWM rectifier

Dynamic waveforms of three-phase PWM rectifier are shown in Figure 7, waveforms varying from no-load to load are shown in Figure 7(1), waveforms varying from load to no-load are shown in Figure 7(2),Channel 1 is fore-end DC voltage U_{dc} , Channel 2 is Port voltage U_{an} , Channel 3 is supply voltage U_{sa} , Channel 4 is Supply current i_{sa} . As shown in Figure 7, Whether the load is input or the load is removed, U_{dc} is quickly adjusted to the steady value at about 400 ms, U_{an} is also adjusted to a stable value after a short adjustment, and five-level waveform is output, i_{sa} is adjusted to a new steady value, and the waveform is still sine wave.

(2) Power Transfer experiment

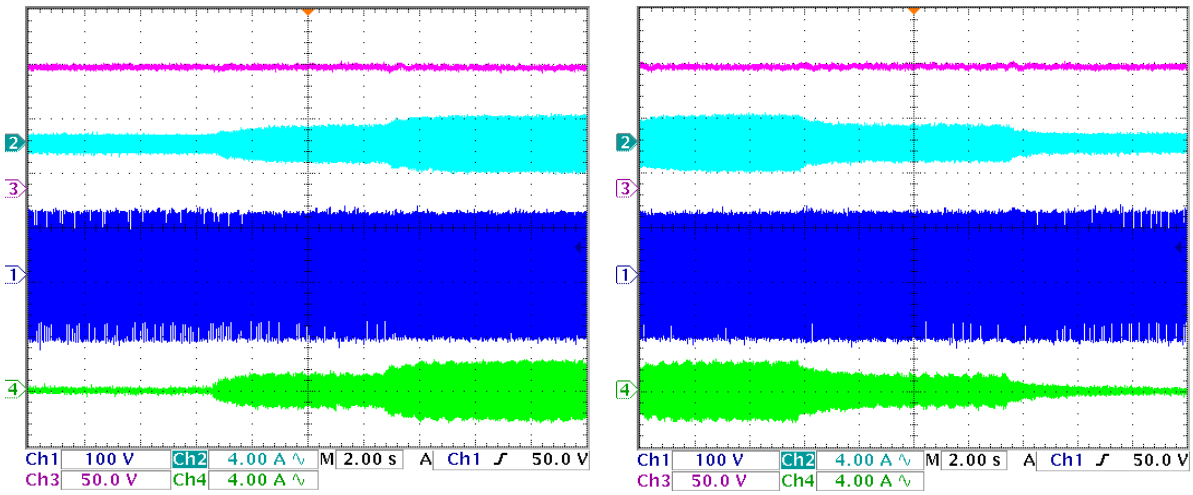


(1) Waveforms of transmitting active power (2) waveforms of transmitting reactive power

Figure 8. Waveforms of transmitting power

Waveforms of transmitting power are shown in Figure 8, Waveforms of transmitting active power are shown in Figure 8(1), Waveforms of transmitting reactive power are shown in Figure 8(2). Channel 1 is fore-end DC voltage U_{dc} , Channel 2 is Port voltage U_{an} , Channel 3 is line voltage U_{sa} , and Channel 4 is phase current i_{sa} . As shown in Figure 8(1), when the active power is transmitted to the low-voltage side, three-phase converter absorbs the active current from the grid and the phase current is in phase with the phase voltage, the active current on the low-voltage side is in phase with the low-voltage power

supply. As shown in Figure 8(2), the current leads the voltage through it by 90°, and U_{dc2} on the back-end side is stable at 120V. Therefore, the reactive power can be reliably transmitted to the power supply.



(1) waveforms varying from no-load to load (2) waveforms varying from load to no-load

Figure 9. Dynamic waveforms of transmitting active power

Dynamic waveforms of transmitting active power are shown in Figure 9, waveforms varying from no-load to load are shown in Figure 9(1), waveforms varying from load to no-load are shown in Figure 9(2), Channel 1 is Port voltage U_{an}, Channel 2 is Port current i_{an}, Channel 3 is back-end DC voltage U_{dc2}, Channel 4 is Supply current i_s. As shown in Figure 9, When the active power is mutated, U_{dc2} is stable at a given value (120V), and five-level waveform of Port voltage is stable.

5. Conclusion

Energy Internet has become the hotspot of the next generation of smart grid, and the distribution transformer with AC / DC interface is the key to the construction of energy internet. A MMC-SST for AC / DC micro-grid is proposed. Its topology and working principle are introduced, and its control strategies are analyzed. The MMC topology is adopted in the input stage. According to the voltage and power demand of the distribution network in the future, voltage of MMC-SST can be flexibly controlled by increasing or decreasing the number of sub modules of each bridge. The isolation stage is composed of multiple DC-DC converter units with identical structure, which are connected by input series output parallel (ISOP), which realizes DC transformer and electrical isolation. Three-phase four-leg inverter is adopted in the output stage, which achieves higher DC voltage utilization, improves the overall filtering effect and reduces the THD value of three-phase output voltage.

Acknowledgments

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