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A DC Voltage Balancing Strategy Based on Active Vector Correction for Single-Phase Cascaded SST

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ABSTRACT
The disadvantages in power system with traditional industrial frequency transformer can be resolved by Solid State Transformer (SST). Cascaded SST can be transformerless connected to the high voltage grid. However, the output performance and reliability of cascaded SST are seriously influenced by DC voltage balancing problem which exists in cascaded configuration. In this paper, a DC voltage balancing strategy based on active vector correction is proposed. This strategy is characterized by on-demand active power and equal reactive power among modulars. Then, a quantitative analysis method is presented to validate active power adjusting ability of the traditional and the proposed strategies. Simulation and experimental results verify the feasibility and validity of these analysis and strategy.

KEY WORDS: solid state transformer, DC voltage balancing control, active vector correction, cascaded H-bridge.

1 INTRODUCTION

SOLID state transformer (SST), or is called electronic transformer (PET), intelligent universal transformer (IUT), is a kind of the power electronic device to realize isolated AC/AC conversion with high-frequency transformer. It not only can implement functions of conventional power transformer, including electrical isolation and voltage class translation, but also has stable output voltage, power quality control, harmonic control, reactive power compensation, fault isolation and other functions (Amaral et al., 2018). It will solve the problems of power transformer in modern power system, and further promote the development of smart grid and energy internet (Ahmed et al.,2018; Costa et al., 2017; Xu, 2013).

SST and its application in high-voltage and high-power is the hotspot in recent years. There have been reported cases of SST, including Future Renewable Electric Energy Delivery and Management (FREEDM) project of the State University of North Carolina (Xu, 2013; Zhao et al., 2013), Universal and Flexible Power Management (Uniflex-PM) project of the University of Nottingham (Iov et al., 2009), Power Electronic Traction Transformer (PETT) project of ABB (Besselmann et al., 2013) and IUT project of EPRI (Lai et al., 2005). These SST topologies of above cases adopt Cascaded H-Bridge (CHB) converter in the high-voltage input side, which can be connected to high-voltage power grid without transformer, easy implemented by modular structure, and has low switching loss and harmonic output characteristics. However, independent DC buses of H-bridge modules exist parallel or mixed loss difference and pulse delay difference, which cause unbalance problem of DC voltage (Geng et al., 2003; Hu et al., 2011; Tu et al., 2018). DC side voltage balancing is the premise for cascaded SST to operate safely and reliably. Otherwise, the overvoltage of DC side caused by imbalance will lead to the damage of the capacitor, the destruction of the Insulated Gate Bipolar Transistor (IGBT) and so on. And the safety and stability of the power grid will be seriously affected.

DC voltage balance of CHB can be resolved respectively by hardware and software. But the hardware method requires additional hardware circuit (Liu et al., 2004). Meanwhile, the control system

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complexity and costs will be increased. The software method is more practical, relatively speaking. The basic idea of these software methods is to increase the voltage balance of each H-bridge by adding a voltage balancing functional module (Rivera et al., 2012; Kouro et al., 2009). However, these control methods only take the DC side voltage as the control target, which will inevitably cause the uneven distribution of the reactive power of each H-bridge. It may not work normally when the load imbalance is large and the reactive power compensation task is heavy. In view of the power balance of cascaded H-bridge, the modulation method is mainly focused on the inverter, and the corresponding control algorithm is proposed for the power balance, but it cannot guarantee the voltage balance of the DC side of each H-bridge, and can only be used in a specific situation (Peng et al., 1996; Aquila et al., 2008). But the CHB of SST not only needs to run in the mode of active power transmission, but also plays as a reactive power compensation. Moreover, there can be equivalent to load or current source in the DC sides of SST, and the discrepancy of imbalance will be more obvious (Tao et al., 2011; Syed et al., 2018; Zhang et al., 2018).

In this paper, a DC voltage balancing strategy based on active vector correction is proposed for the single-phase cascaded SST. The strategy is achieved by adjusting active power according to loads and dividing reactive power equally among H-bridge modules. Compared with the traditional method, the proposed method brings stronger ability of active power adjustment and smaller DC voltage ripple.

This paper is organized as follows. In Section 2, a mathematical model of the single-phase cascaded SST is established. Section 3 proposes the DC voltages control strategy based on active vector correction for single-phase cascaded SST, and adjustment ability of active power was quantitative analyzed. Simulation and experiment are described respectively in Section 4 and 5 to validate the merits of the proposed method. Finally, Section 6 presents the conclusions.

2 MATHEMATICAL MODEL OF SINGLE-PHASE SST

AS shown in figure 1, the topology of single-phase SST is adopted in this paper on the basis of existing cases. The SST consists of CHB, dual active bridge (DAB), and three-phase four-leg inverter. The SST is modular and easy to implement, so the SST can be extended to different voltage levels by different cascaded numbers. The basic unit in the CHB structure is the H-bridge, as shown in figure 2. In the ideal case, the upper and lower switches of the same bridge arm need to maintain the complementary state, and then the upper state can be used to indicate the switching state of the bridge arm. Using the switching states S_1 and S_3 of the two upper switches in the H-bridge ('1' indicates the ON state, and '0' indicates the OFF state), the relationship among the voltage, the current, and the switching state is expressed as follows:

$$u_o = (s_1 - s_3) U_{dc} = S^{'} u_{dc} \tag{1}$$

$$i_o = (s_1 - s_3) i_s = S^{'} i_s \tag{2}$$

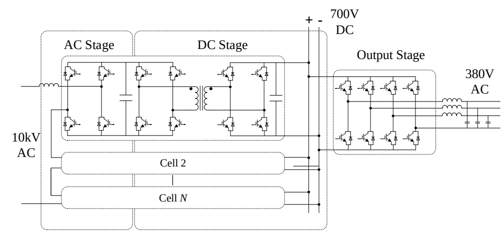


Figure 1. Circuit topology of single-phase SST

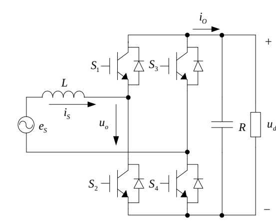


Figure 2. H-bridge module

The topology of the single-phase H-bridge is shown in figure 2, in which e_s and i_s are grid-connected voltage and current, L is the grid-connected filter inductance, R is the equivalent resistance of parallel loss, u_o is the output voltage of the H-bridge, u_{dc} is the DC side voltage value. Further according to figure 2, the simplified mathematical model of single H-bridge rectifier based on switching function can be obtained by using Kirchhoff's current law (KCL) and Kirchhoff's voltage law (KVL) without the internal resistance of reactor L.

$$\begin{cases} L\dfrac{di_s(t)}{dt} = e_s(t) - S^{'} u_{dc}(t) \\ C\dfrac{du_{dc}(t)}{dt} = S^{'} i_s(t) - \dfrac{u_{dc}(t)}{R} \end{cases} \tag{3}$$

With the utilization of average operation, the duty cycle in a switching period can be defined as:

$$d^{'} = \langle S' \rangle_{T_s} = \frac{1}{T} \int_{t}^{t+T_s} S'(t)\, dt \tag{4}$$

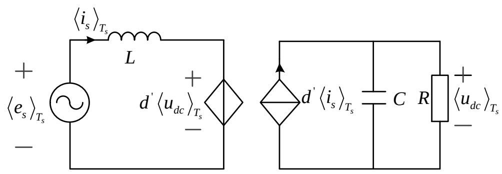


Figure 3. Average model of H-bridge module

From equations (3) and (4), the average mathematical model of single-phase H-bridge rectifier can be deduced as:

$$\begin{cases} L\dfrac{d\langle i_s\rangle_{T_s}}{dt}=\langle e_s\rangle_{T_s}-d'\langle u_{dc}\rangle_{T_s} \\ C\dfrac{d\langle u_{dc}\rangle_{T_s}}{dt}=d'\langle i_s\rangle_{T_s}-\dfrac{\langle u_{dc}\rangle_{T_s}}{R} \end{cases} \tag{5}$$

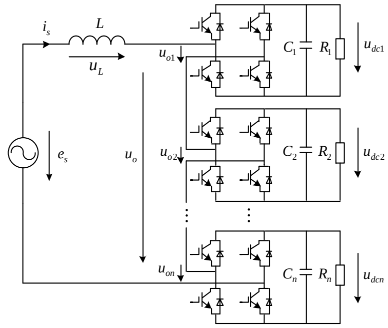


Figure 4. Equivalent Topology of SST

The single-phase cascaded SST is equivalent to CHB rectifier as shown in figure 4, so the average model of single-phase cascaded grid-connected converter can be extended as shown in figure 5. In figure 4 and figure 5, R_1, R_2 and R_n represent the equivalent load of the next stages. As each H-bridge has the same input current, the active power of each module can be adjusted by output voltage, and the overall DC voltage controller of cascaded SST can be designed as the H-bridge rectifier.

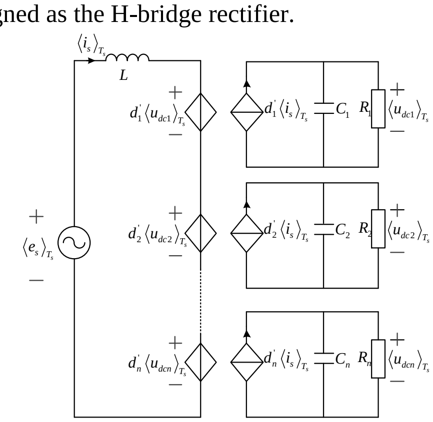


Figure 5. Equivalent Average Model of SST

3 DC VOLTAGE BALANCING CONTROL STRATEGY

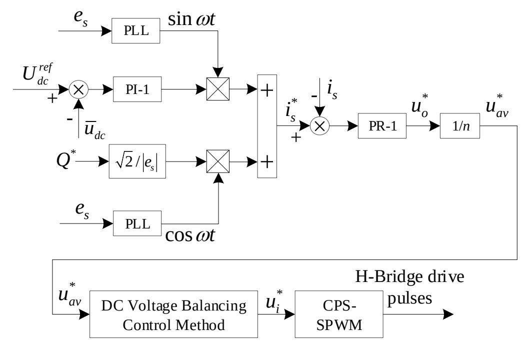
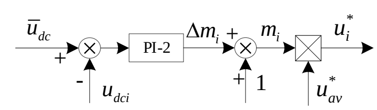
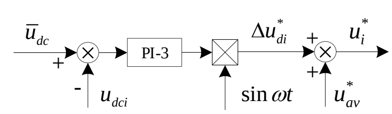


Figure 6. Overall Control diagram

AS shown in figure 6, the overall controller for single-phase cascaded SST regulates the whole DC voltage and the reactive power. In this classic double closed-loop control diagram, the reference current i_s^* consists of the active component produced by total DC voltage regulation and the reactive component formed by the reference reactive power Q^*. The total reference output voltage u_o^* of CHB is generated by proportional resonant (PR) controller for grid-connected current i_s. Then, the average reference output voltage u_{av}^* of each H-bridge can be produced. Finally, the referenced output voltage u_i for H-bridge is generated by the DC voltage balancing control method.



(a) The modulation ratio correction method

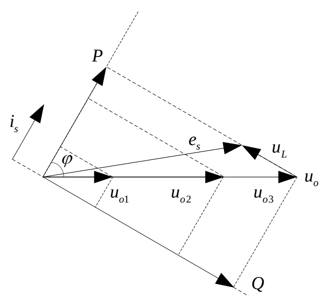


(b) The proposed active vector correction method

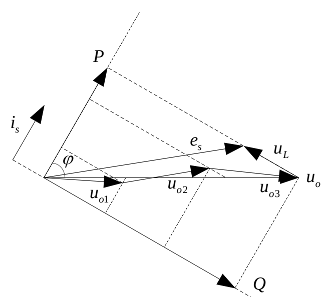
Figure 7. DC Voltage Balancing Control Methods

Figure 7(a) is the traditional modulation ratio correction controller for DC voltage balance. After comparing DC side voltage to DC side voltage of each H-bridge, the correction coefficient of modulation ratio Δm_i is formed by independent PI controller, and the difference between average DC voltage and each H-bridge voltage is eliminated by m_i. And figure 7(b) is the proposed DC voltage balancing method, the individual DC voltage of H-bridge u_{dci} is compared with the average DC voltage to generate the active voltage component Δu_{di}^* by PI controller and sinusoidal function. So the modulation ratio correction method adjusts the active and reactive power with the equal proportion. But the proposed method realizes the on-demand distribution of active power and equal distribution of reactive power.

Figure 8 shows the vector diagrams with different methods in steady state, in which the cascaded number N is 3. e_s is the voltage vector of the power grid, i_s is the grid-connected current, u_L is the voltage drop on the grid-connected reactance, u_o is the output voltage vector of the cascaded H-bridge converter, and u_{o1}, u_{o2}, u_{o3} are the output voltage vectors of the three H-bridge modules respectively. u_o in figure 8(a) and figure 8(b) is equal. The output voltage vectors of three modules in figure 8(a) have the same direction, and their length are directly proportional to the active power distribution. Meanwhile, they have different directions in figure 8(b). The active components of the output voltage vectors are proportional, and the reactive power components are equally distributed. It can be seen that the modulation ratio with the proposed method is smaller to regulate the same active power among modules.



(a) The modulation ratio correction method



(b) The proposed active vector correction method

Figure 8. **Vector diagrams with different methods in steady state**

In order to further quantitatively compare the active power ability between the two methods, the modulation ratio of H-bridge output voltage m_i with the proposed method can be deduced as,

$$m_i = M\sqrt{\left(n\frac{P_i}{\sum_{i=1}^{n} P_i}\cos\varphi\right)^2 + \sin^2\varphi} \tag{6}$$

In which, the total modulation ratio of output voltage is defined as M. the phase angle of the output voltage and current is φ. P_i is the active power of unit i.

$P_i/\Sigma P_i$ represents the ratio of i unit active power to the total active power, and can be used to indicate the active power adjusting ability of the H-bridge unit. The following constraints must be satisfied,

$$P_i \Big/ \sum_{i=1}^{n} P_i \le 1 \tag{7}$$

The equation (6) shows that maximum value $P_i/\Sigma P_i$ can achieve by the maximum modulation ratio (m_i =1). According to the equations (6) and (7), the analysis diagram of active adjusting range with the proposed method can be drew when m_i=1and n=3. It can be seen from the figure 8 that each unit has wider adjusting range of the active power with smaller M and bigger $|\varphi|$.

With using the modulation ratio correction method, output voltage modulation ratio for i unit can be expressed as:

$$m_i' = n\frac{P_i}{\sum_{i=1}^{n} P_i}\mathrm{M} \tag{8}$$

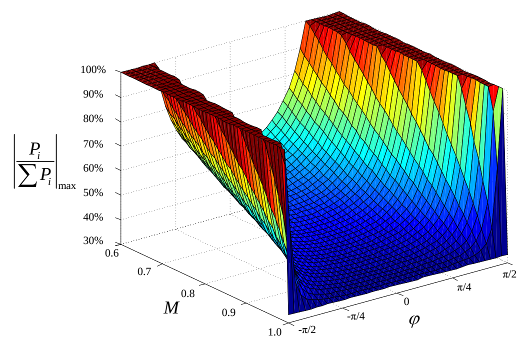


Figure 9. **Analysis diagram of Active Adjusting Range with Active Vector Correction Method**

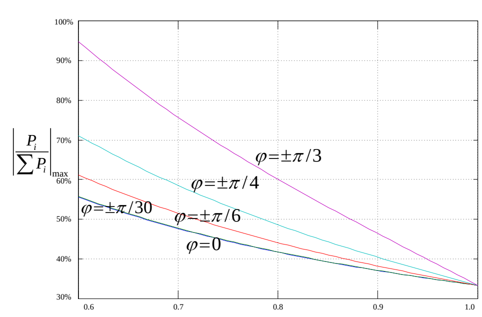


Figure 10. **Active Adjusting Range with Different Phase Angles**

From equations (6) and (8), it can be found that the expression of $m_i^{'}$ and m_i are consistent when φ=0. Therefore, the diagram of active adjusting range with different phase angles can be projected from figure 9 for comparison. The corresponding curve of the traditional method is φ=0 in figure 10. When the cascaded SST work in the state of rated power and without reactive power compensation (assuming that n=3, M=0.9, and φ= π/30), the regulation ratio of maximum active power with the traditional method is 37.04%, while the ratio with the proposed method is 37.24%. The effects of the two methods are almost the same, and the nearly identical curves of φ= π/30 and φ= 0 in figure 10 can also confirm that. As shown in figure 10, with the growth of reactive power component, the proposed method has stronger adjusting ability of active power than the traditional method obviously. In the same condition, the modulation ratio correction method will output bigger modulation ratio by comparing to the proposed method. Thus the more serious DC voltage ripple difference, voltage and current THD will be led.

As reactive power compensation is a necessary mode in SST, the DC voltage balancing strategy based on active vector correction has obvious advantages.

4 SIMULATION RESULTS

IN order to verify the effectiveness of the proposed voltage balance control strategy, a single-phase cascade SST were built in Matlab/Simulink. The main parameters of the simulation system are shown in Table 1.

Table 1. Main parameters of simulation system

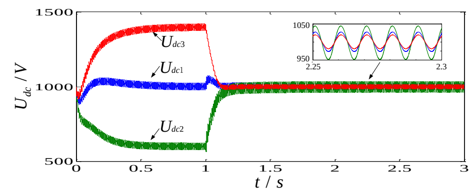
Parameter	Symbol	Value	Unit
Input peak voltage	U_{sm}	1500	V
DC voltage	U_{dci}	1000	V
Reference load	R	50	Ω
Reactive power	Q	-100	kVar
DC capacitor	C	3000	μF
Filter inductor	L	2	mH
Switching frequency	f	1	kHz

This paper adopts the carrier phase-shift sinusoidal pulse width modulation (CPS-PWM) strategy as the modulation method, and the lower switching frequency can be used to achieve a higher equivalent switching frequency. In order to eliminate the influence of DC voltage fluctuation on the PI voltage controller, the collected DC voltage is averaged. The following three parts will be used to verify the control strategy described above.

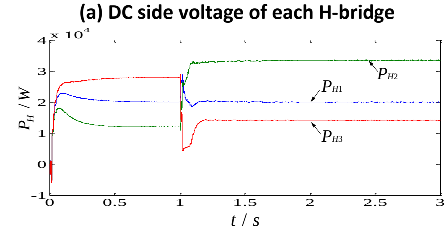
4.1 The traditional method

Based on figure 7(a), the voltage of the DC sides is balanced by directly modifying the modulation ratio of the H-bridges. The simulation time is 3 s, and the traditional balance control is added at 1 s. The simulation results are shown in figure 11.

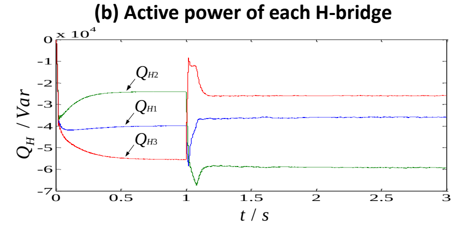
As shown in figure 11(a), the DC voltage fluctuations after balancing are different, and the larger ripple is determined by the heavier load. The active power transmission of each H-bridge is shown in figure 11(b) and 11(c). The active and reactive power have the equal proportion, which is corresponding to theoretical analysis results. It can be seen in figure 11(d) that the three H-bridge modulation waves are only different in amplitude.



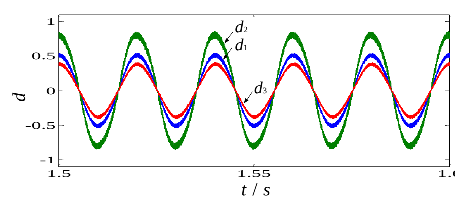
(a) DC side voltage of each H-bridge



(b) Active power of each H-bridge



(c) Reactive power of each H-bridge



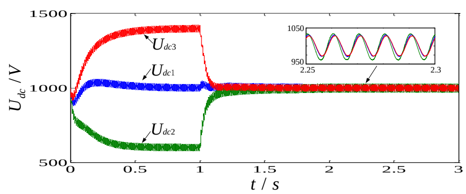
(d) Each H-bridge modulation wave

Figure 11. Waveforms under the traditional method

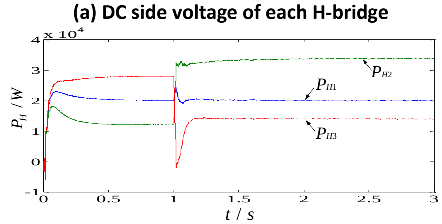
4.2 The proposed method

Based on the control algorithm presented in this paper, the simulation waveforms are shown in figure 12. The simulation time is 3s, and the proposed control is added at 1s. As can be seen from figure 12(a), the voltage ripple on the DC side of each H-bridge is basically the same, regardless of the load. The active power of each H-bridge is the same as in figure 12(b), and it is distributed on demand.

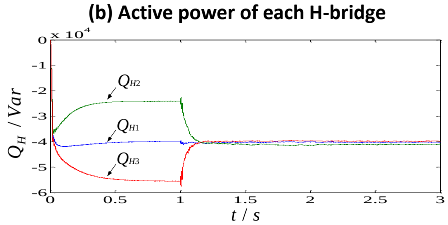
Meanwhile, the reactive power of each unit tends to be consistent. So, the reactive power required by the average distribution is independent of the load, as shown in figure 12(b) and 12(c). As shown in figure 11(d), the modulation amplitudes and phases of three H-bridge are different and it is consistent with theoretical analysis.



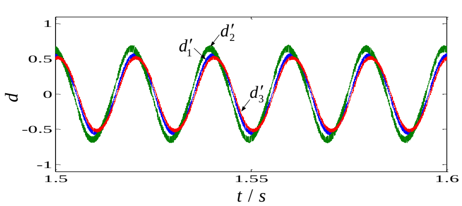
(a) DC side voltage of each H-bridge



(b) Active power of each H-bridge



(c) Reactive power of each H-bridge



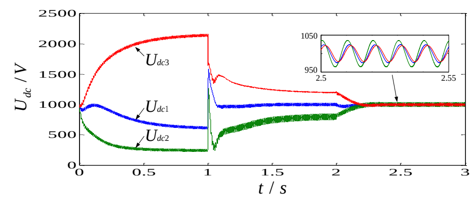
(d) Each H-bridge modulation wave

Figure 12. Waveforms under the proposed method

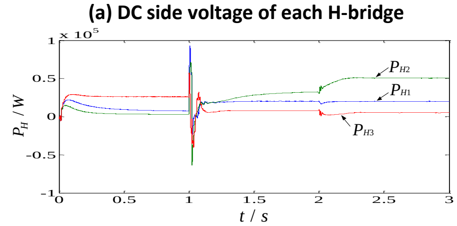
4.3 Comparison of regulation ability

On the assumption that the unbalanced loads satisfy R_2=20, R_3=180, the other simulation conditions are shown in Table 1. Then, the initial modulation ratio m=0.56, sinφ=0.85 can be calculated. According to figure 12, the load unbalance degree satisfies the constraint condition of the proposed method, and does not satisfy the conditional method. The whole simulation time is 3s, the traditional voltage balance control is added at 1s, and the proposed control is added at 2s.

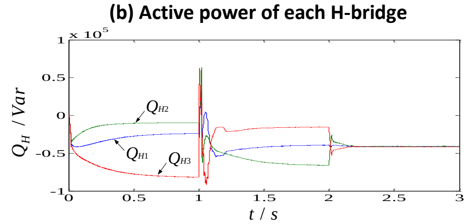
From figure 13(a), it can be seen that the load imbalance exceeds the constraint conditions of the traditional method, and this method cannot keep the DC-side voltage balanced with the different DC-side voltage fluctuations. Due to the expansion of the constraint range with the proposed method, the unbalanced load is returned to the constraint, so the voltage of the DC sides can still maintain balance after 2s.



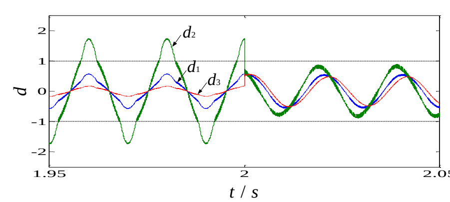
(a) DC side voltage of each H-bridge



(b) Active power of each H-bridge



(c) Reactive power of each H-bridge



(d) Each H-bridge modulation wave

Figure 13. Comparison of two control methods under large load imbalance

Figure 13(b) and figure 13(c) are active and reactive power change of three modules. Similarly, due to exceeding the constraint range, the active and reactive power of each H-bridge does not satisfy the linear relationship with the load. When the proposed method is added at 2s, the active power is re-assigned and the reactive power is distributed evenly.

Figure 13(d) shows the modulated wave waveforms of each H-bridge in the whole process. Before the proposed control is added, d_2 obviously exceeds the range of the linear modulation region, and each modulation wave has been distorted. And after t=2s, d_2 re-entering the constraints to ensure the effectiveness of the proposed control method.

5 EXPERIMENTAL RESULTS

A lab-scale prototype of single-phase cascaded SST is constructed to test the presented DC voltage balancing method. The experimental platform is shown in figure 14. It adopts master-slave control mode, the master controller applies DSP+FPGA architecture, in which DSP is used for main control algorithm and FPGA is for sending the control command and receiving information of power unit. All the FPGA slave controllers of power unit not only receive the control command from the master controller and then produces digital pulse signals, but also collect the information of power units and sends them to the master controller. The DC output is connected with multiple resistance furnace as the load.

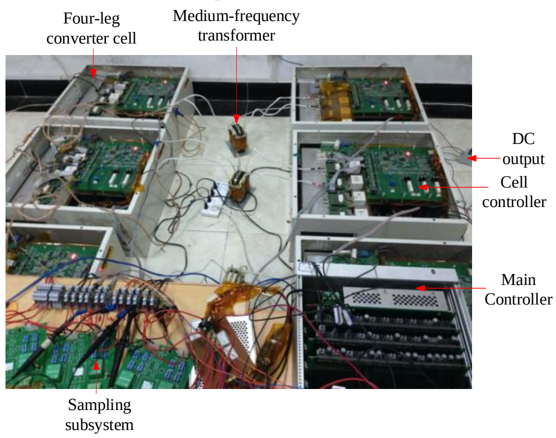
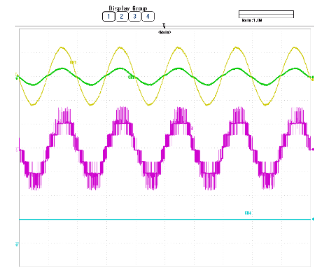


Figure 14. Experimental platform

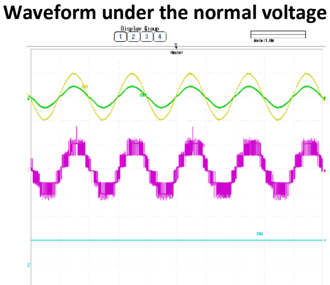
Due to the limitation of test conditions, a n=3 cascade H-bridge inverter is connected to grid though auto-transformer. The specific parameters are: the grid-connected reactor is 2mH, the DC capacitance value is 2000μF, the switching frequency of IGBT is 3.2 kHz, and the DC side reference voltage is 50V.

Figure 15 is the waveforms of single cascaded SST experimental, in which the CH1 channel is the voltage waveform of grid-connected side (100V/div), CH2 is the current waveform of grid-connected side (10A/div), CH3 is the output voltage of the cascaded H-bridge (100V/div), and CH4 is the DC output voltage (50V/div).

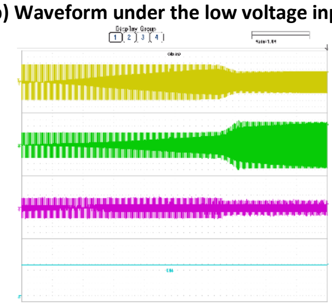
As the DC side reference value is set to 50V, figure 15 (a) shows the steady-state waveform under the normal voltage input, and the output voltage is seven level. The steady-state waveform under the low voltage input is shown in figure 15(b), and the output voltage is only five level with relatively low modulation ratio under the low voltage grid. Figure 15 (c) and 15(d) show waveform under the condition of voltage sag and jump, and it can be seen that the currents of AC side follow with the grid-connected voltage due to the constant power load and the DC output voltage remains constant. Therefore, the fault isolation function is verified in SST platform, and the effectiveness of the proposed DC balancing control method under various working conditions is also validated.



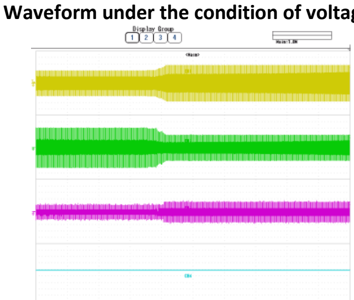
(a) Waveform under the normal voltage input



(b) Waveform under the low voltage input



(c) Waveform under the condition of voltage sag



(d) Waveform under the condition of voltage jump

Figure 15. Experimental Waveforms of Single-phase Cascaded SST

6 CONCLUSION

BASED on the established mathematical model of single-phase cascaded SST, a DC voltage balancing strategy is proposed in this paper. The new method makes full use of active vector correction in order to realize power exchange among modules. Compared to the traditional control method, it allocates equal reactive power among modules, has stronger regulation ability of active power especially in reactive compensation mode, and reduces the DC voltage ripple of each H-bridge. To compare and validate active power adjusting ability of the traditional and the proposed strategies, a quantitative analysis method is presented. Simulation and experimental results obtained from a downscaled model have verified the effect of the DC voltage control and dynamic performance of seriously unbalancing condition.

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9 DISCLOSURE STATEMENT

No potential conflict of interest was reported by the authors.

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