

Research on DC Voltage Balancing Control for Single-Phase Cascaded Solid-State Transformers (Postprint)

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Abstract

Solid-state transformers can effectively address the shortcomings of conventional power transformers in power systems, among which cascaded SSTs can be well adapted to high-voltage grids. However, DC-side balance issues in cascaded structures severely affect device reliability. This paper first analyzes the circuit topology and operating principle of single-phase SSTs, establishes a mathematical model, further conducts a comparative study of existing DC voltage balance control methods, and determines a balance control method suitable for SSTs. The effectiveness and feasibility of this method in SSTs are verified through experiments, and the experimental results demonstrate that the method can ensure reliable device operation and maintain DC voltage balance even under complex operating conditions.

Full Text

Research on DC Voltage Balancing Strategy of Single-Phase Cascaded Solid State Transformer

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Abstract: Solid state transformers (SST) can effectively resolve the limitations of traditional line-frequency transformers in power systems, with cascaded SST being particularly suitable for high-voltage grid applications. However, the cascaded structure suffers from DC-side voltage imbalance issues that severely impact device reliability. This paper first analyzes the circuit topology and operating principles of single-phase cascaded SST, establishes its mathematical

model, and comparatively studies existing DC voltage balancing control methods to identify the most suitable approach for SST applications. Experimental results demonstrate the effectiveness and feasibility of the proposed method, showing that it maintains DC voltage balance and ensures reliable operation even under complex operating conditions.

Keywords: Solid state transformer, DC voltage balancing control, active vector correction method, cascaded H-bridge

2. Single-Phase SST Mathematical Model

The solid state transformer (SST), also known as power electronics transformer (PET) or intelligent universal transformer (IUT), is a power electronic device that achieves isolated AC/AC conversion through medium/high-frequency transformer coupling. Drawing upon domestic and international case studies, this paper adopts the single-phase SST topology shown in Figure 1 [Figure 1: see original paper]. The high-voltage stage employs a cascaded H-bridge (CHB) structure, the intermediate stage uses dual-active-bridge (DAB) converters connected to each DC side of the high-voltage stage with parallel outputs, and the final stage utilizes a three-phase four-leg converter to generate the AC output. The SST must not only perform conventional transformer functions such as voltage transformation, isolation, and energy conversion, but also provide voltage regulation, power control, harmonic mitigation, reactive power compensation, and fault isolation capabilities. By addressing the shortcomings of traditional transformers in modern power systems, SST technology will advance the development of smart grids [1-2].

High-voltage, high-power SST research and applications have become increasingly prominent in recent years. Notable international projects include: the FREEDM (Future Renewable Electric Energy Delivery and Management) project by Alex Q. Huang's team at North Carolina State University [2,15]; the UniFlex-PM (Universal and Flexible Power Management) project led by Areva and the University of Nottingham in Europe [3]; ABB's PETT (Power Electronic Traction Transformer) project [4]; and the IUT project by the Electric Power Research Institute [5]. All these SST topologies utilize CHB converters on the critical high-voltage side, enabling transformerless connection to high-voltage grids with modular implementation, low switching losses, and reduced harmonic output. However, the independent DC sides of each H-bridge exhibit parallel and hybrid loss differences, pulse delay variations, and grid voltage imbalances, leading to DC-side voltage imbalance issues [6-8].

DC-side voltage balancing control for CHB can be achieved through hardware or software approaches. Hardware methods require additional circuitry [9], increasing complexity and cost in both control and structure, making software approaches more practical. Software methods can resolve imbalance by adjusting the modulation index [10-11], phase-shift angle [12], or active power component

[13-16] of each H-bridge unit. However, the CHB in SST must operate not only in active power mode but also provide power quality improvement functions such as reactive compensation. Moreover, the DC-side connection of devices equivalent to large loads or current sources may generate greater imbalance, making the selection of an appropriate DC voltage balancing method crucial.

This paper first analyzes the circuit topology and operating principles of single-phase SST, establishes its mathematical model, compares existing DC voltage balancing control methods, identifies the suitable approach, and finally validates it through experiments.

The basic unit in the CHB structure is the H-bridge, as shown in Figure 2 [Figure 2: see original paper]. Under ideal conditions (ignoring dead time), the upper and lower switches in the same leg must maintain complementary states, allowing the upper switch state to represent the entire leg's status. Using the switching states s_1 and s_3 of the two upper switches in the H-bridge ("1" for on, "0" for off), the voltage-current relationships can be expressed as:

$$u_o = (s_1 - s_3)U_{dc} = Su_{dc}$$

$$i_o = (s_1 - s_3)i_s = Si_s$$

Further applying Kirchhoff's Current Law (KCL) and Voltage Law (KVL) to Figure 2 yields the simplified switching-function-based mathematical model for a single H-bridge rectifier:

$$L \frac{di_s(t)}{dt} = e_s(t) - Su_{dc}(t)$$

$$C \frac{du_{dc}(t)}{dt} = Si_s(t) - \frac{u_{dc}(t)}{R}$$

The duty cycle is defined through averaging operation over a switching period:

$$\bar{S}(t) = \frac{1}{T} \int S(t) dt$$

Averaging equation (3) and substituting equation (4) yields the continuous average mathematical model for the single-phase H-bridge rectifier:

$$L \frac{d\bar{i}_s}{dt} = \bar{e}_s - \bar{S}\bar{u}_{dc}$$

$$C \frac{d\bar{u}_{dc}}{dt} = \bar{S}\bar{i}_s - \frac{\bar{u}_{dc}}{R}$$

The average model of the H-bridge rectifier is shown in Figure 3 [Figure 3: see original paper].

The SST in Figure 1 can be equivalent to the CHB rectifier shown in Figure 4 [Figure 4: see original paper]; thus, the average mathematical model in equation (5) can be extended to obtain the average model of the single-phase cascaded grid-connected converter shown in Figure 5 [Figure 5: see original paper]. As indicated in reference [13], the overall DC-side voltage control for the single-phase cascaded grid-connected converter is consistent with that of a single H-bridge rectifier, allowing controller design to follow the same approach.

3. Comparative Study of DC-Side Voltage Balancing Control Methods

The total active and reactive power control for the single-phase cascaded grid-connected inverter is illustrated in Figure 6a [Figure 6: see original paper], employing a classic dual-loop control strategy. The control system consists of two parts: an active current component generated through proportional-integral (PI) regulation of the total DC-side voltage, and a reactive current component derived from the reactive power command. The difference between the commanded current i_s^* and actual current i_s is processed by a proportional-resonant (PR) controller to generate the total commanded output voltage u_o^* for the cascaded grid-connected inverter, which is then divided to obtain the average commanded output voltage u_{av}^* for each unit.

Two primary methods exist for intra-phase DC-side voltage balancing control: modulation index correction (Figure 6b) and active component correction (Figure 6c). The modulation index correction method adjusts only the modulation index, proportionally modifying both active and reactive power of each H-bridge unit simultaneously. In contrast, the active component correction method adjusts the active component of the commanded voltage, enabling independent active power distribution among units while maintaining balanced reactive power distribution.

Figure 7 [Figure 7: see original paper] shows the steady-state vector diagrams for both methods with a cascade number $n = 3$. The diagrams reveal that for the same active power adjustment, the active vector correction method achieves the maximum $P_i/\Sigma P_i$ value. When $m_i = 1$ and $n = 3$, equations (6) and (7) yield the active power adjustment range analysis shown in Figure 8 [Figure 8: see original paper].

To further quantify and compare the active power regulation capabilities of both methods, assume the cascaded grid-connected inverter has a total output voltage modulation index M , phase angle ϕ between output voltage and current, P_i as the active power of unit i , and n as the number of cascaded units. For

the active component correction method, the output voltage modulation index of unit i is:

$$m_i = \frac{M}{n} + \frac{P_i}{\Sigma P_i} \sin(2\phi)$$

where $P_i/\Sigma P_i$ represents the proportion of active power of unit i to total active power, indicating the active power regulation capability of the H-bridge unit. The following constraint must be satisfied:

$$\sum_{i=1}^n m_i = n$$

Comparing equations (6) and (8) reveals that the expression for m'_i is consistent with m_i when $\phi = 0$. Therefore, projecting the active power regulation range analysis diagrams for different ϕ values (Figure 8) yields Figure 9 [Figure 9: see original paper]. The curve corresponding to $\phi = 0$ also represents the active power regulation capability curve for the modulation index correction method. When the cascaded inverter operates at rated active power only, assuming $n = 3$, $M = 0.9$, and $\phi = \pi/30$, the maximum active power regulation ratio is 37.04% for the modulation index correction method and 37.24% for the active vector correction method. The difference is minimal in pure active operation, as confirmed by the nearly overlapping curves for $\phi = \pi/30$ and $\phi = 0$ in Figure 9. However, Figure 8 shows that as the reactive power component of the output voltage increases, the superior active power regulation capability of the active vector correction method becomes more pronounced. For the same active power adjustment, the modulation index correction method requires a larger output voltage modulation index for the H-bridge unit, leading to issues such as greater DC-side voltage ripple variation and higher voltage/current THD.

Since the SST must operate not only in active power mode but also provide power quality improvement functions such as reactive compensation, the intraphase DC-side voltage balancing method based on active vector correction offers clear advantages.

4. Experimental Verification

To validate the effectiveness of the active vector correction method in cascaded solid-state transformers, a three-module platform shown in Figure 10 [Figure 10: see original paper] was used to construct a single-phase SST system, with multiple resistor furnaces connected as loads at the DC output. Figure 11 [Figure 11: see original paper] shows experimental waveforms of the single-phase three-stage cascaded SST with DC-side reference set to 50V. Channel CH1 displays the grid voltage waveform (100V/div), CH2 the grid current waveform

(10A/div), CH3 the converter output voltage (100V/div), and CH4 the DC output voltage (50V/div).

Figure 11a shows operation at a grid voltage peak of 130V, where the three-stage H-bridge on the high-voltage side produces a seven-level output waveform. Figure 11b demonstrates operation at lower grid voltage, where the converter operates with a lower modulation index, producing only five output levels. Figures 11c and 11d illustrate waveforms during system voltage sag and swell conditions. Despite load power remaining constant, the high-voltage side current varies with grid voltage fluctuations, while the low-voltage DC output remains stable. This verifies that the single-phase cascaded SST provides fault isolation between primary and secondary sides—a capability lacking in traditional line-frequency transformers—and demonstrates the effectiveness of the DC balancing control method under various operating conditions.

5. Conclusion

Based on the established mathematical model of single-phase cascaded SST, this paper discusses the differences in active power regulation capability among various DC voltage balancing control methods, demonstrating that the active vector correction method offers superior regulation characteristics and is better suited for the complex operating conditions of single-phase cascaded SST. To validate the effectiveness of the DC voltage balancing method based on active vector correction, a three-stage experimental platform was built and tested. The results show that the method exhibits good steady-state and transient performance, holding significant value for future SST applications.

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