To Resolve The Voltage Unbalance Of The Dc Links In Different H-Bridges Based Solid State Transformer (SST)

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Abstract:
As the expansion of the dc distribution system and the augment of the penetration of distributed generations an intelligent transformer with the capability to actively supervise the power and allowing for the easy connection of the distribution resources is becoming essential. The solid state transformer (SST) has the features of immediate voltage regulation, voltage sag compensation, fault isolation, power factor correction, harmonic isolation and dc output. Acting very much like an energy router, each SST has bidirectional energy flow control potential allowing it to control active and reactive power flow and to handle the fault currents on both low- and high-voltage sides. Its large control bandwidth offers the plug-and-play feature for distributed resources to speedily recognize and respond to changes in the system. This paper proposes a 20-kVA cascaded H-Bridge multilevel converter-based SST to directly interface with 7.2-kV single-phase distribution voltage level. The SST consists of a cascaded multilevel ac/dc rectifier, dual active bridge (DAB) converters with high-frequency transformers. The DAB converter regulates the 400-V-low-voltage dc bus and added dc/ac inverters can be added to present a 60 Hz 120/240-V ac residential voltage.

Keywords: Cascaded H-Bridge converter, dq vector control, solid-state transformer (SST), voltage and power balance.

Introduction:
The paper recommends a new voltage and power balance control for the cascaded H-Bridge converter-based SST. Based on the single-phase dq model a novel voltage and the power control strategy is proposed to stabilize the rectifier capacitor voltages and the real power through parallel DAB modules. In addition the intrinsic power constraints of the cascaded H-Bridge voltage balance control are derived and analyzed. With the proposed control methods the dc-link voltage and the real power through each module can be balanced. The SST switching model simulation and the prototype experiments are presented to validate the performance of the proposed voltage and power balance controller. Low-frequency PWM techniques for STATCOM are presented. The dc-link voltage is balanced by using different switching patterns to charge and discharge each H-Bridge capacitor but the reactive power is not controlled. Barrena et al. present an individual voltage-balancing scheme to balance the dc-link voltage with PWM. The method preserves delivered reactive power equally distributed among all H-Bridges. However the method is based on the STATCOM application and no power unbalance constraints are mentioned in this paper.

Related Work:
In the proposed electric configuration of the smart grid system low voltage (120 V), residential class distributed renewable energy resource (DRER), distributed energy storage device (DESD) and loads are connected to the 400-V dc distribution bus and then to distribution bus (12-kV three phase or 7.2-kV single phase) through a SST. The SST is used to facilitate active management of DRER, DESD, and loads, rather than a 60-Hz conventional transformer. The SST has a 400-V dc port that will make possible more professional connection of certain classes of DRERs and DESDs. The regulated 400-V dc bus is distributed for easier connection of battery and other distributed resources. The rectifier stage is a seven-level cascaded H-Bridge converter which controls the input power factor and regulates the 3.8-kV high-voltage dc link.

Existing Method:
Iman-Eini et al. present a method that makes sure the dc-link voltages congregate to the reference value when load power is different. The method results in different switching frequencies for the H-Bridges and a complicated controller implementation. Leon et al. and Barrena et al. presents different PWM methods to balance the dc-link voltages. However the balance range and power control are not included.

Disadvantages:
One of the main disadvantages of the cascaded H-bridge rectifier is the voltage unbalance of the dc-link voltages at different H-Bridges. Relevant
research mainly focuses on the unbalance issues in static synchronous compensator (STATCOM) or drive applications and no power control method. It necessitates a high frequency modulation and both real and reactive power control. Besides due to the intrinsic constraint of the cascaded rectifier topology the voltage balance control is limited and the power balance control is therefore required.

**Proposed Method:**
The modelling of the SST, including ac/dc rectifier, DAB converter are developed. A single-phased dq vector controller is designed for the rectifier stage; therefore the real power and reactive power can be controlled separately. Based on the single-phase dq control, a voltage balance control system is proposed to resolve the voltage unbalance that could appear on the dc links of different H-bridges. The projected voltage and power control are verified by the switching model simulation. Finally, a SST scale-down prototype is implemented by using 600-V insulated gate bipolar transistor (IGBT) devices.

**Advantages:**
It has balanced dc-bus voltage, balanced real power, evenly distributed reactive power between H-bridges and use simple phase-shift pulse width modulation (PWM).

**System Architecture:**
- The solid-state transformer (SST) is an interface device between ac distribution grids and dc distribution systems. The SST consists of a cascaded multilevel ac/dc rectifier stage, a dual active bridge (DAB) converter stage with high-frequency transformers to provide a regulated 400-V dc distribution, and an optional dc/ac stage that can be connected to the 400-V dc bus to provide residential 120/240 Vac. The SST is rated as single-phase input voltage 60 Hz, 7.2 kV, output voltage 400-V dc. The first stage of the SST is a high-voltage cascaded H-Bridge ac/dc rectifier that converts 60 Hz, 7.2-kV ac to three cascaded 3.8-kV dc links. The second stage consists of three high-voltage high-frequency dc/dc converters that convert 3.8 kV to 400-V dc bus and then additional inverter can be connected to 400-V dc bus to invert 400-V dc to 60-Hz, 240/120 V. The switching devices in high-voltage H-bridges and low-voltage H-bridges are 6.5-kV IGBT and 600-V IGBT, respectively. The switching frequency of the 6.5-kV IGBT devices is 1 kHz, because the device current is very low resulting in low switching losses. The 20-kVA SST unit is envisioned as a building block for construction of a larger rated SST. The controller of each stage in the SST is independent from each other.

**Rectifier Controller:**
The function of the rectifier controller is to control the reactive power (or power factor) and regulate the dc-link voltages. With the chosen phase-locked loop, the voltage vector is aligned with the direction of the d-axis during steady state. The grid-voltage component in the d-direction is equal to its peak value and the q-component of the grid voltage is equal to zero. Thus, the d-component of the current vector (in steady state parallel to the grid-voltage vector) becomes the active current component (d-current) and the q-component of the current vector becomes the reactive current component (q-current) [15]. The decoupled dq vector controller for each H-bridge is shown in Fig. 3. The three sinusoidal pulse width modulation (SPWM) carriers for the cascaded H-bridge are phase shifted so that the rectifier has seven voltage levels to reduce the voltage stress and harmonics.

**Dual Active Bridge (Dab):**
The DAB topology offers zero voltage switching, relatively low-voltage stress for the switches, low passive component ratings and complete symmetry of configuration that allows seamless control for bidirectional power flow. Real power flows from the bridge with leading phase angle to the bridge with lagging phase angle, the amount of transferred power is controlled by the phase angle difference and the magnitudes of the dc voltages at the two ends.

$$P_o = \frac{V_{dcH} V_{del}}{2L f_H} d_{dc} (1 - d_{dc})$$
where, $V_{dcH}$ is input side high dc-link voltage, $fH$ is switching frequency, $L$ is leakage inductance, $V$ dc$L$ is output side low dc bus voltage referred to input side, and $d$dc is the ratio of time delay between the two bridges to one-half of switching period. For the DAB converter, the phase-shift control is applied to regulate the low-voltage dc voltage to the reference 400 V under different load conditions. First, the difference between the low dc voltage $V_{dc}$ and the reference voltage is compared. Then, the phase-shift angle is adjusted by the proportional-integral (PI) controller to regulate $V_{dcL}$ according to this voltage error.

**Voltage And Power Balance Control:**
The three H-Bridge dc-link voltages become unbalanced after the power change. The H-bridge that transfers more power has the highest dc-link Voltage. Fig. 8 shows the three dc-link voltages with voltage balance control. With the voltage balance controller, the three dc-link voltages are equally regulated in the steady state. The different resistors simulate a 20% power difference, which is caused by no power balance control in the DAB modules. So when the power balancing control is implemented in DAB, the power difference is dominated by converter power losses, the power unbalance is much smaller than 20%. The switching model simulation is implemented to verify the proposed power balance control. The DAB module with smaller leakage inductance has large current and transfers more power. Figs. 13 and 15 illustrate the DAB primary currents and power with power balance control. The transformer current and the power transferring through each DAB module is balanced. So the power balance control guarantees the power unbalance of the parallel DAB modules meet the (21), so that the dc-link voltages can always be balanced with the proposed voltage balance control.

**Voltage Balance Constraints:**
Due to the intrinsic constraints of the cascaded H-Bridge structure, in order to maintain the dc-link balanced, the real power unbalance range of the H-Bridges is limited. This limitation is determined by the input ac voltage, dc-link voltage reference, input inductance, and the number of H-bridges.

$$V_1 + V_2 + V_3 = V_{line} - j\omega L \text{jline}$$
$$V_1 = (d_1 + j q_1) E, \quad V_2 = (d_2 + j q_2) E, \quad V_3 = (d_3 + j q_3) E$$

where, $V_n$ is the $n$th H-Bridge voltage vector, $V_{line}$ is the single phase input ac voltage, $f_{line}$ is the input ac current, $d_n$ and $q_n$ are the $d$-axis and $q$-axis duty cycle generated by the controller, and $E$ is the dc-link reference voltage of each H-Bridge.

**Experimental Results:**
The dc-link voltage is regulated to the reference 400 V total (133 V each H-Bridge) and the input current is in phase with the input voltage, which indicates a unity power factor. The SST rectifier stage not only converts the input ac to regulated dc voltages, but also has reactive power compensation capabilities. Depending on the reactive power reference in the SST controller, the SST can generate or absorb reactive power to the power grid.

**Conclusion:**
A new voltage balance control method is proposed to resolve the voltage unbalance of the different H-bridges. The power intrinsic unbalance constraints of the voltage balance control for the cascaded H-Bridge rectifier is derived and verified by simulations and experiments. Meanwhile, a power balance control method is proposed to regulate the real power transferring through the parallel modules. Finally, the switching model simulation and SST scale-down prototype are implemented with the proposed controller. The single-phase $dq$ vector modeling and control of the SST, including ac/dc rectifier, DAB converter is developed.

**REFERENCES:**


