Application of a Multi-Port Solid State Transformer for Volt-VAR Control in Distribution Systems

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***Abstract*—Distribution systems need significant voltage support with growing penetration of distributed generations especially intermittent renewable energy resources and smart loads. This paper introduces the application of the Multi-Port Solid State Transformer (MPSST) as an effective tool to support grid voltage at distribution level while integrating distributed energy resources. The solid state transformer replaces the conventional transformer between two voltage zones of distribution systems. Matlab/Simulink environment is used to simulate the IEEE 14 bus test system with an MPSST as a case study. The simulation results prove the effectiveness of the MPSST supporting the distribution system at local level in a fast and efficient manner in response to disturbances caused by load variations.**

Keywords— Distribution system, integrated power system, SST, solid state transformer, voltage compensation.

I. INTRODUCTION

As a major domain of Smart Grid focus area, power distribution holds a significant role to deliver the power from transmission system to the customers. With the wide area where the smart grid spreads; conceptually and physically, a trend of decentralization is being adopted in order to achieve locality in controls, and to minimize communication requirements [1]. This will result in a faster response and avoidance of undesired calculation overhead for the central control system. The Distribution system can also provide the network connection for Distributed Generations (DG), Distributed Energy Resources (DER) and Energy Storage (ES) to supply electricity to the customers.

With the increasing global interest in the application and utilization of alternative energy resources, the necessity of utilizing proper and efficient power electronics converters, operated and controlled with less complicity, became a topic of interest for power systems researchers at system and device levels. The main advantage of DER utilization in the distribution system is decreasing transmission losses by partially localizing power support, increasing the reliability and survivability of the critical loads, and providing distributed and local support for grid voltage and frequency [2]. Controllable power electronics converters allow faster response to the variations of power demand, using low bandwidth communications, in addition to regulating voltage and frequency of the local bus [3] [5].

In a distribution system, the feeder voltage level is a standard parameter for the power quality. The fact of being sensitive to load demand variations or faults at any node impacts the rest of the distribution system. Maintaining the voltage level within the standard range is a major concern. Volt-VAR schemes to control system voltage are based on controlling the reactive power fed to a feeder. The needed reactive power to be absorbed or fed in the system in the conventional power system is provided from the power plants as an ancillary service in the electricity market or by other means including switching load tap changer (LTC) transformer, voltage regulator (VR), and switched capacitor banks, or using static VAR compensator (SVC) or static synchronous compensator (STATCOM)[1]. Most of these methods use a central control and measurement method to track and regulate the voltage in the network feeders from top to bottom.

Many efforts have been proposed on VAR compensation and control strategy in power networks to improve voltage stability [4]. The advantage of integrating DERs in transmission systems [5] and distribution system have been investigated [4]. Volt-VAR control (VVC) method is proposed to overcome the intermittent behavior of DERs in [4]. Communication based centralized control strategy for the smart grid is discussed in [6]. This method has the advantage of tracking the most efficient point from the system perspective. Advanced converter technologies are also proposed to improve voltage regulation, which uses solid state converter (SST) as enabling converter for the grid control [7].

This paper uses MPSST as a compact isolated power electronic converter for hybrid DER applications. MPSST is introduced in Section II. MPSST is an effective solution to apply Volt-VAR compensation in the system in case of faults or load variations, as it provides connection node to integrate DERs supporting active and reactive power. Furthermore, having an active controllable converter (unlike traditional transformers) improves online measurement of the system parameters and the ability to control bidirectional power flow at each node to enable smart distribution.

II. MULTI-PORT SOLID STATE TRANSFORMER

Power electronic converters are the main components in the utilization of DER; where they play an essential role in connecting different voltage level zones and in integrating renewables and energy storage at the distribution level. It is highly preferred to have galvanic isolation between

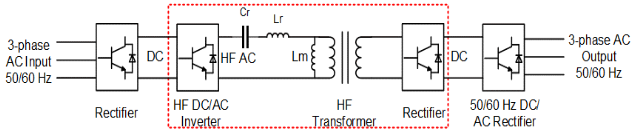


Figure 1. AC/AC five-stage SST

different voltage zones and main elements which are conventionally provided by 50/60 Hz transformers [11].

Solid State Transformers (SST) or Smart Transformers are combinations of high frequency transformer and power electronic stages with the advantage of providing smaller size, flexibility, and controllability, not offered by conventional transformers. SST can have several conversion levels based on the voltage type of the connected elements. Figure 1 shows an AC-AC SST configuration. The dashed zone in Figure 1 includes the high frequency conversion stages, which are the standard element for all SST designs. The presence of controllable converters in distribution system design improves the controllability and flexibility of the system [7].

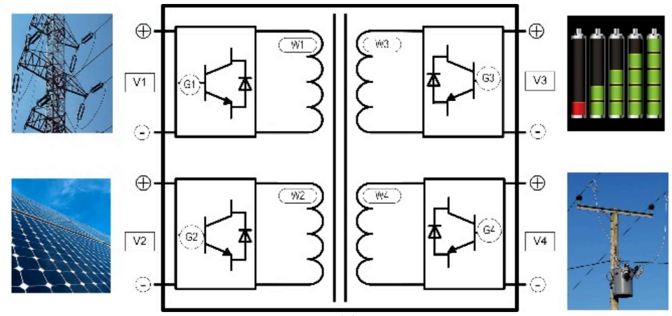
A high frequency transformer is used in the design of the SST to minimize the size and weight of the isolation transformer [11] leading to the decreased total size for the SST. The installation and maintenance process of the transformer is easier and this power electronics based transformer can actively controls the parameters such as voltage and power flow [5]. The most recent advancement in SST converters is the development of multi-port solid state transformers (MPSST), which provides multiple isolated connection legs for the elements within one configuration [10] to enable modular DERs and energy storage at different voltage levels. As an active element, system parameters in MPSST are monitored within the configuration. Measurements are inputs to the online and real time control for the system.

In [7], multi-port power electronic transformer is used for traction machine application. The converter works with divided parallel voltage source. For a system, which includes hybrid DG and energy storage units, a four-port SST is proposed to connect two voltage zones in microgrids [10]. The quad-active bridge configuration (Fig. 2.a) maximizes the power density of the converter, which decreases the size and cost of the system design.

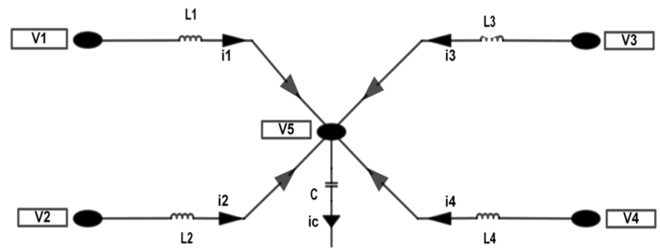
In this paper, the concept of MPPST is applied to distribution systems. Quad-active bridge (QAB) [10] is expanded by adding low frequency AC/DC 3-phase inverter at two legs. In MPSST control, the QAB acts as a DC-DC converter to regulate the DC voltage for the grid side legs (legs 1, 4 in Fig.2.a). A two level control method including DC voltage regulation and phase shift modulation (PSM) [12] for power flow control is implemented. The bidirectional active and reactive power at each leg are defined in (1) and (2), respectively.

$$P_i = \frac{1}{2}\left(v_d^i i_d^i + v_q^i i_q^i \right) \tag{1}$$

$$Q_i = \frac{1}{2}\left(v_d^i i_q^i - v_q^i i_d^i \right) \tag{2}$$



(a)



(b)

Figure 2. (a) Quad-Active Bridge General Structure (b) Quad-Active Bridge equivalent circuit.

Where P, Q are the active and reactive power at leg i, respectively. v_d^i, v_q^i and i_d^i, i_q^i are the d-q transformation of voltage and current at leg i. calculated from (3) and (4) [13]

$$v^i = v_d^i \sin(\omega t) + v_q^i \cos(\omega t) \tag{3}$$

$$i^i = i_d^i \sin(\omega t + \varphi) + i_q^i \cos(\omega t + \varphi) \tag{4}$$

Figure 3 shows the simplified equivalent circuit of a QAB. parameters L_1, L_2, L_3, L_4 and C in (5) are the quivalent internal inductances and capacitance of the ports from the transformer core. As an example, the current of leg 4 (Fig. 2.b) at the transformer side, the transfer function could be modeled as in (5).

$$\left.\begin{aligned} I_4 &= -\left(\frac{K_4 * K_1}{K_5}\right) v_1 - \left(\frac{K_4 * K_2}{K_5}\right) v_2 - \left(\frac{K_4 * K_3}{K_5}\right) v_3 - \left(K_4 - \frac{{K_4}^2}{K_5}\right) v_4 \\ &\text{Where } K_i = \frac{1}{sL_i} \qquad , i \in [1,4] \\ K_5 &= \frac{(L_1L_2L_3 + L_1L_2L_4 + L_2L_3L_4 + L_1L_3L_4) + s^2 L_1L_2L_3L_4C}{sL_1L_2L_3L_4} \end{aligned}\right\} \tag{5}$$

III. CASE STUDY

A. IEEE 14 Bus Test System

IEEE 14 bus test system is selected for the study purposes. A single line diagram of IEEE-14 bus test system is shown in Fig. 3. Although this test bus system is designed for transmission system, it can be used to demonstrate the fundamental benefits of MPSST for distribution and power system. It consists of five synchronous machines with IEEE Type-I exciters, three of which are synchronous compensators used only for reactive power support. There are eleven loads in the system totaling 259 MW and 81.3 MVAR. The IEEE 14 bus system is selected for testing purposes or the following reasons: 1) A starting point for

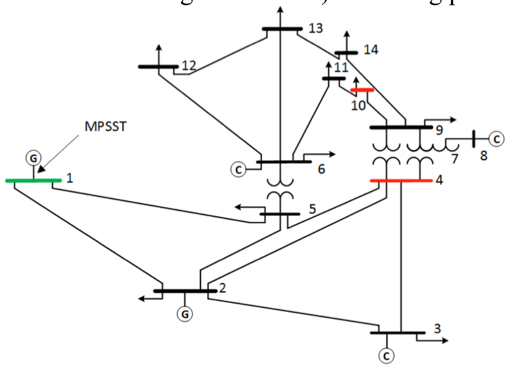


Figure 3 IEEE 14 Bust Test System.

MPSST validity testing in larger distribution systems (IEEE 34, 123). 2) widely used for voltage stability as well as low frequency oscillatory stability analysis [6]. 3) The advancements of power electronics switch in high frequency and voltage levels enables MPSST design to be applied to various voltage levels. In this case study, the transformer at node 1 is replaced with an MPSST connecting the HV port to the higher voltage level zone, following the connection shown in PV source and energy storage are plugged into the remaining two ports.

B. Control Strategy

Figure 4 shows the flow chart control strategy which is applied on the described distribution system. The main outcome is to regulate the voltages of the system within the standard limits. The system voltages are monitored online and verified to be within the acceptable limits (±5% p.u.). However, if any bus voltage happens to change due to the possible fault or load change, the reactive power is calculated based on the lowest voltage detected in the grid and commands the MPPST to inject the calculated Q^* based on (2).

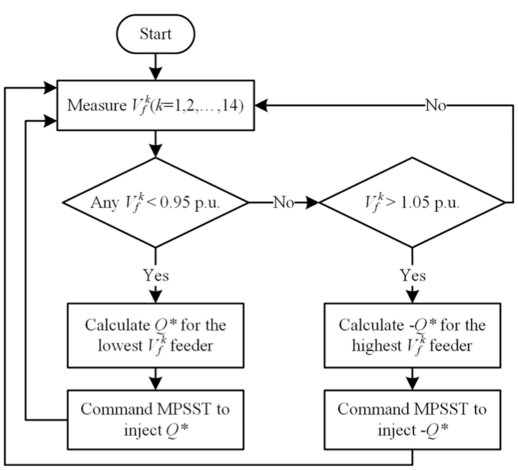


Figure 4 Control strategy flow chart.

In order to compensate for the voltage limit violation. This infinite loop ensures that the voltage is always in the expected range. Some minor voltage spikes may occur during the transition period.

IV. SIMULATION RESULTS

In order to test the capabilities of the MPSST and the applied control strategy, the system is simulated using Matlab/Simulink tool. have been investigated. The scenario is intended to test the control strategy shown in Fig. 5, where the voltage levels at all nodes are being monitored continuously. At certain time, a high load demand occurs on one of the buses. The local MPSST with the control strategy inject ramp reactive power values until the voltage is retrieved within the limits.

Table 1 Bus voltages during transition period.

Node	Normal load V(p.u.)	High load V(p.u.)	After Q* command
V_f^1	1.011	0.9695	1.008
V_f^2	1.004	0.961	1.003
V_f^3	0.9779	0.9371	0.9642
V_f^4	0.9901	0.9266	0.9584
V_f^5	0.995	0.9396	0.9732
V_f^6	0.9972	0.9621	0.9786
V_f^7	0.9934	0.9482	0.9685
V_f^8	0.9836	0.9555	0.9657
V_f^9	0.9811	0.9358	0.9564
V_f^{10}	0.9778	0.9345	0.9542
V_f^{11}	0.9781	0.9392	0.9571
V_f^{12}	0.9813	0.9461	0.9626
V_f^{13}	0.9752	0.9394	0.9561
V_f^{14}	0.9859	0.9444	0.9634

Figures 5-7 show the 3-phase RMS voltage at the bus nodes 1, 4, and 10 respectively. At 0.2s, an overload occurs on bus 4 which affects the rest of the system buses and the lowest voltage level happens at node 10. MPSST and the control strategy applied respond to this change by calculating the reactive power to be injected in a ramp manner to retrieve the voltages to their acceptable levels, the MPSST response begins at 0.3s (within 0.1s of the overload).

As Table 1. Shows, at normal load conditions, all voltages are within ±5% of the nominal voltage. At the load side, power demand increases which causes voltage limit violations where the control strategy takes part to retrieve voltages to acceptable levels.

MPSST at node 1 feeds the system with the calculated amount and ramp of reactive power, while monitoring the system voltages in order to avoid overvoltage at any other node. Fig. 8 shows the reactive power curves of the three feeders under testing during the transition period. Reactive power injected by the MPSST at node 1 increases and reaches a steady state at 0.6 p.u., while node 4 absorbs approximately 0.4 p.u. of the reactive power, 0.2 p.u. is absorbed by the rest of the nodes as their voltage where affected by the overload at node 4 (Table 1).

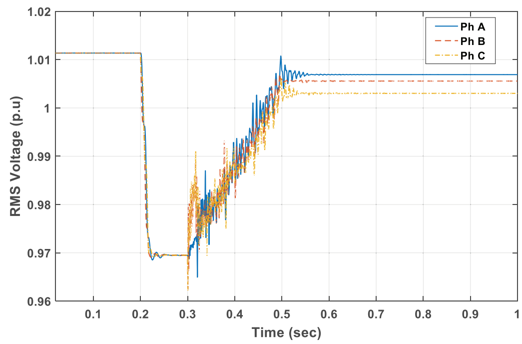


Figure 5 Three-phase RMS voltage at bus #1

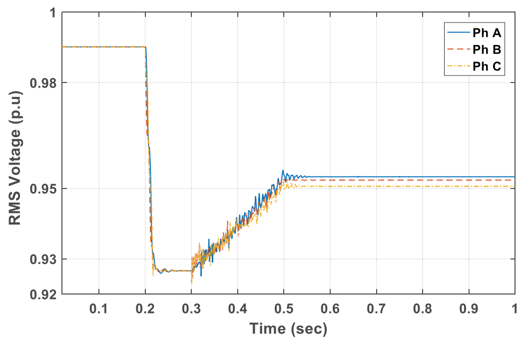


Figure 6 Three-phase RMS voltage at bus #4

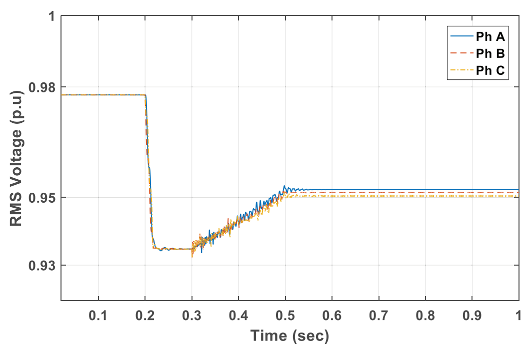


Figure 7 Three-phase RMS voltage at bus #10

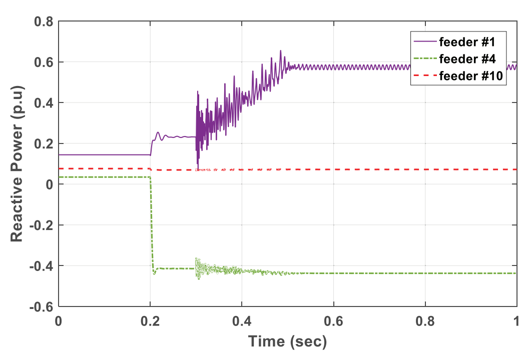


Figure 8 Reactive power curves of the three feeders during transition.

V. CONCLUSIONS

Multi-Port Solid State transformer is proposed to perform Volt VAR control in distribution system. The MPSST regulates the voltage at the feeder side in an independent manner through injection of reactive power. Distributed energy resources and energy storage can be plugged directly into the MPSST which allows local support of active and reactive power to the feeder sider. Power electronic inverters allow bidirectional flow of the power while the voltage is maintained. The results verify the capability of supporting the grid locally. Although the control strategy requires monitoring the voltage buses of the system, it can operate as open loop and monitoring the local bus. Further studies can be performed on applying MPSST in a larger test system and optimizing the location based on the bus type. These studies are out of the scope of this paper.

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