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A Solid State Transformer model for power flow calculations

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ABSTRACT

This paper presents the implementation of a Solid State Transformer (SST) model in OpenDSS. The goal is to develop a SST model that could be useful for assessing the impact that the replacement of the conventional iron-and-copper transformer with the SST can have on the distribution system performance. Test distribution systems of different characteristics and size have been simulated during different time periods. The simulations have been carried out assuming voltage-dependent loads and considering that power flow through either the HV/MV substation transformer or any of the MV/LV distribution transformers can be bidirectional. Simulation results prove that a positive impact should be expected on voltages at both MV and LV levels, but the efficiency of current SST designs should be improved.

1. Introduction

The future smart grid is being designed to mitigate or avoid consequences derived from power quality events (e.g., voltage sags), improve reliability indices (e.g., by reducing the number of interruptions and their duration), and increase the efficiency (e.g., by reducing losses) [1,2].

The increasing penetration of renewable generation and a fast implementation of the electric vehicle are just two trends that can stress the current grid by causing voltage variations larger than those the system can withstand.

One innovative solution to many of these problems is the Solid State Transformer (SST) [3–10]. This new device is foreseen as a component that might cope with many challenges of the future smart grid since it can enhance power quality performance and expand the capabilities of the conventional transformer: voltage sag compensation, instantaneous voltage regulation, harmonic compensation, power factor correction, auto-balancing, short-circuit protection, variable-frequency output, bidirectional power flows [11–13].

The paper presents the implementation of a MV/LV SST model in OpenDSS for power flow calculations. The goal is to make available a model that could assess the impact that this device can have on the distribution system operation; namely, the effect that the replacement of conventional transformers with SSTs could cause on voltages and energy losses at both MV and LV levels of a distribution system.

OpenDSS is a distribution system simulator that allows users to represent distribution systems with a great accuracy and carry out the calculations over a time period. OpenDSS can be used as either a stand-alone executable program or as a COM DLL that can be driven from some software platforms; e.g., MATLAB [14,15]. This work takes advantage of this capability: the procedure to solve distribution systems with SSTs has been implemented in MATLAB which is used to control OpenDSS execution.

The paper has been organized as follows. Section 2 summarizes the configuration and operation of the three-stage SST design. The model and the procedure implemented in OpenDSS to cope with distribution systems in which the SST replaces the conventional transformer are presented in Section 3. Three test systems have been used to assess the impact that the SST can have on voltages and energy losses; the description of the systems and a summary of the results are presented in Section 4. The main features and limitations of the SST design and those of the model presented here are discussed in Section 5. The main conclusions are summarized in Section 6.

2. Description of the Solid State Transformer

Several configurations have been proposed to achieve the functionalities of an AC-AC conversion that potentially suits the SST role [16,17]. Most of the SST configurations designed for field application have adopted the so-called three-stage configuration, whose technical design may be schematized as in Fig. 1. The basic block diagram for a MV/LV bidirectional SST includes, according to

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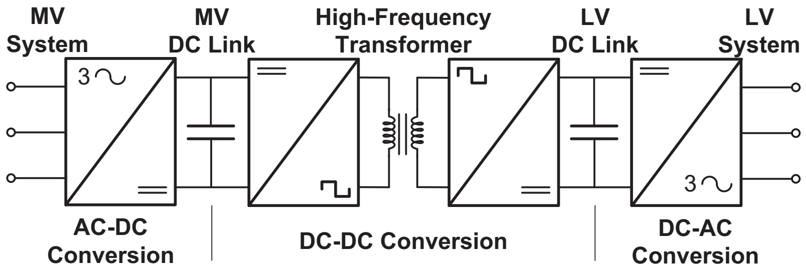

Fig. 1. Basic design of a Solid State Transformer.

this figure, three parts: a MV stage, an isolation stage, and a LV stage [18].

The front converter connected to the MV grid changes the three-phase power frequency AC voltages to a DC voltage, which is then converted back to AC, but with a higher frequency, by the second part of the MV stage. Thanks to the higher AC frequency, the magnetic properties of the intermediate high-frequency transformer core are better utilized and the transformer can be considerably smaller, while maintaining the same power capability. On the LV side, another converter transforms the high-frequency AC voltage to DC voltage. This is then converted back to the specific power frequency, 50/60 Hz. When the power flows from the secondary side (i.e., when the SST is acting as step-up transformer), the behavior is similar to that described above; basically, input and output stages swap functions.

Standardized voltages used by most utilities for MV distribution grids are usually equal or higher than 10 kV [19]; as a consequence, a realistic configuration of the SST, assuming Si-based technologies are used, must consider multilevel configurations for MV-side converters [20–22]. For rated line voltages above 10 kVrms, more than ten levels can be required if Si-based semiconductors with a blocking voltage below 2 kV are used [23]. An alternative to Si-based multilevel converters is the use of SiC semiconductors [24,25].

3. SST model for power flow calculations

3.1. SST model for OpenDSS implementation

The SST is modeled as a two-terminal element with the following behavior (see Fig. 2): (i) the secondary LV side provides the active and reactive power demanded by the LV loads while maintaining a constant voltage value at the secondary terminal (e.g., 1 p.u.); (ii) from the primary MV side the SST demands only active power. Since active power can flow through the SST in two directions, two operating modes are distinguished (see Fig. 2): *Load* and *Generation* modes.

The models implemented in OpenDSS can be used to represent single- and three-phase bidirectional SSTs. They use two separate elements: LV voltage sources and MV loads, which will be respectively referred to as SST load and SST voltage source; Fig. 3 shows the diagram corresponding to a single-phase SST running in *Load* mode. The figure should be modified in case the SST operated in *Generation* mode: the direction of the arrows should then show active power flowing from the secondary side to the primary side.

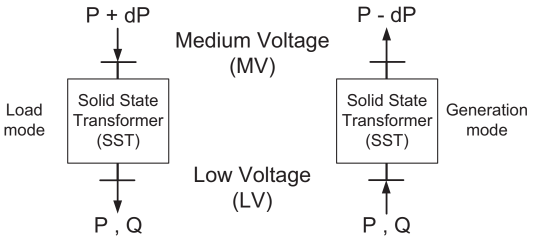

Fig. 2. Schematic operation of the SST.

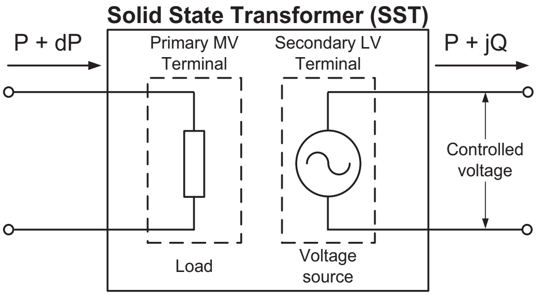

Fig. 3. SST model as implemented in OpenDSS (SST operates in Load mode).

When the active power flows from the MV terminal to the LV terminal, the ideal SST voltage source provides all active and reactive power required by the LV loads and maintains a constant voltage value at its terminals for a load value below a certain level (see discussion at the end of this subsection and in Section 5). The load will replicate the SST behavior seen from the MV network: the active power demanded by the MV-side load will be equal to the active power served by the LV source plus the SST losses. In case of power flow reversal (i.e., the active power flows from the LV terminal to the MV terminal), the SST load becomes negative, so the MV SST terminal injects into the MV system the active power supplied from the LV terminal minus the SST losses. Under any of these conditions, the SST does not demand or inject any reactive power from the MV primary terminal: all reactive power demanded by loads is provided by the LV internal capacitor bank (see discussion at the end of this subsection).

The basic relationships between active powers at both sides of the SST are, under the two operating modes, as follows:

$$P_P = \frac{P_S}{\eta} \quad Q_P = 0 \quad \text{in Load Mode} \tag{1a}$$

$$P_P = \eta P_S \quad Q_P = 0 \quad \text{in Generation Mode} \tag{1b}$$

where P_P and Q_P are respectively the active and reactive powers measured at the primary MV terminal of the SST, P_S is the active power measured at the secondary LV terminal, and η is the SST efficiency.

Considering the current developments, the SST efficiency is lower than that of a conventional iron-and-copper transformer, unless SiC semiconductors were used [24,25]. The presence of power converters introduces conduction and switching losses whose evaluation is not easy: power converter losses depend on the SST configuration and the strategies implemented to control the converters. Some work on SST losses and efficiency evaluation has been carried out to date; see [8,9,26–29]. Since it is assumed