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Dynamic average modeling of a bidirectional solid state transformer for feasibility studies and real-time implementation

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ABSTRACT

Detailed switching models of power electronics devices often lead to long computing times, limiting the size of the system to be simulated. This drawback is especially important when the goal is to implement the model in a real-time simulation platform. An alternative is to use dynamic average models (DAM) for analyzing the dynamic behavior of power electronic devices. This paper presents the development of a DAM for a bidirectional solid-state transformer and its implementation in a real-time simulation platform. Several case studies have been carried out in order to evaluate the behavior of the model under different operating conditions, check its feasibility for power quality improvements and explore the implementation in a real-time simulation platform.

1. Introduction

Real-time simulation platforms are widely used for transient simulation of power systems, testing of protection devices or rapid control prototyping [1–3].

The use of detailed switching models for power electronics devices often requires the use of very short time-step sizes (i.e., equal or shorter than 1 μs), which implies long simulation times and limits the size of the system that can be practically analyzed. This is a very important drawback for implementing power systems with a high penetration of power electronic converters in real-time simulation platforms [4,5].

This limitation can be mitigated by using the so-called dynamic average models (DAM). A DAM approximates the behavior of a converter by applying the moving average operator at the switching frequency to the detailed switching model. With this technique, the switching effects are removed from the model, but the dynamic behavior is preserved [6–8].

DAMs can reproduce with a high accuracy the transient behavior of the original detailed switching model but using a larger time step size, permitting in this way a fast simulation of systems with many power electronic converters, and facilitating the implementation of transient models in real-time simulation platforms. That is, DAMs appear as an adequate representation of power electronic converters when the goal is to implement models in real-time simulation platforms.

This paper is aimed at applying DAM techniques for analyzing the dynamic behavior of the solid state transformer (SST) [9–16]. Some previous work related to dynamic average modeling of SST was presented in [17,18].

The SST is foreseen as a fundamental component that might cope with many of the challenges of the future smart grid [19,20]. As compared to the conventional transformer, the SST has a smaller size, enhances the power quality performance, and expands the list of capabilities. For the integration of the SST it can be crucial the possibility of controlling bidirectional power flows [21]. The detailed model of the bidirectional SST was presented by the authors in [22]. Previous works illustrating the role of a SST as part of a power system or detailing its real-time implementation were presented in [23,24], respectively.

The goals of this paper are: (i) to develop and test a DAM of a bidirectional SST for implementation in a real-time simulation platform, (ii) analyze the feasibility of the SST as a power system

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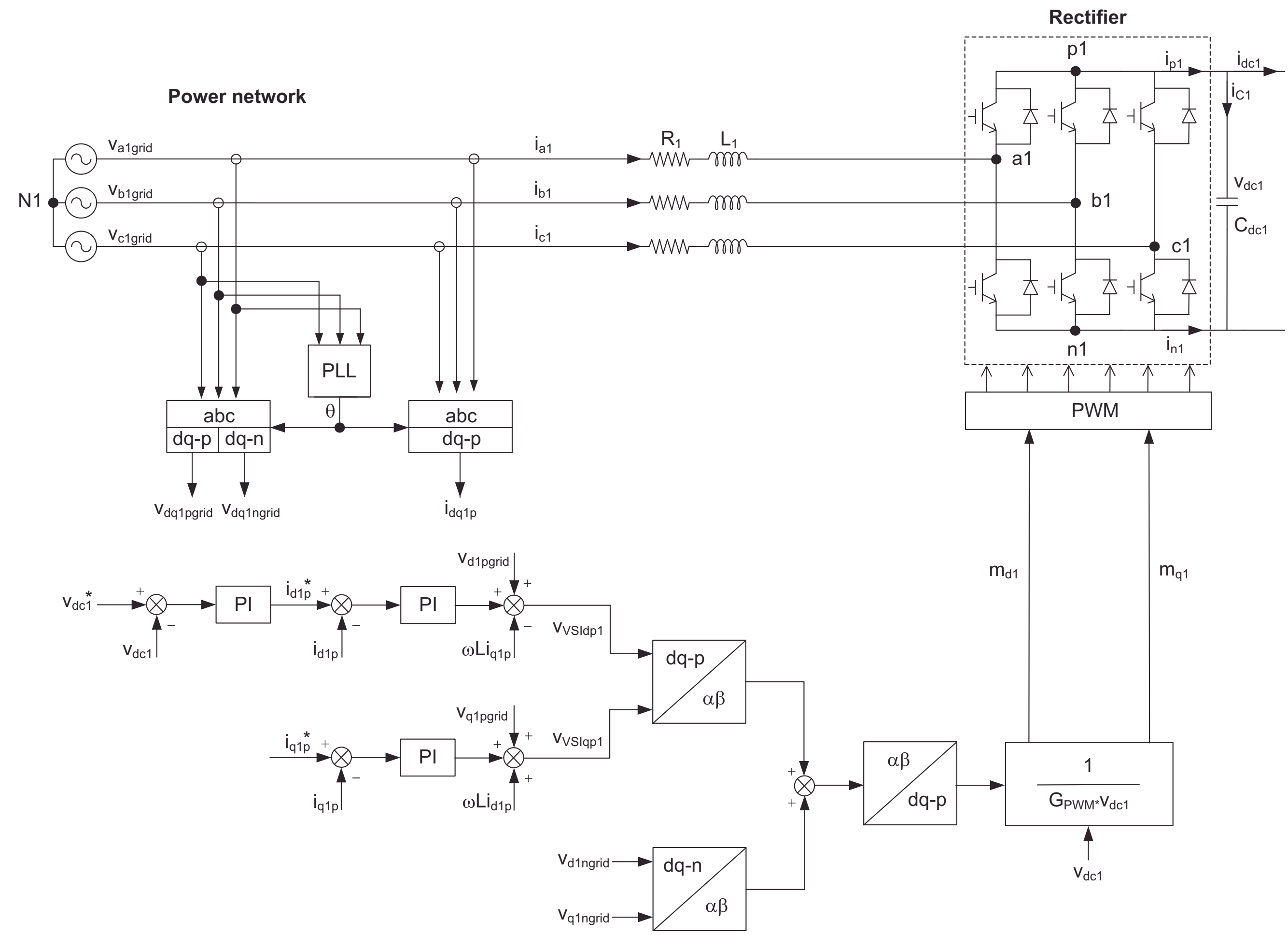

Fig. 1. Bidirectional SST implementation: high-voltage side configuration and control.

component embedded in a distribution system, and (iii) explore power quality improvements that the SST may add when replacing the conventional transformer. The paper presents the model of a three-stage SST with a detailed description of the topology and control strategy of each stage, summarizes the steps made to obtain an average model of the entire SST, presents the performance of the average SST model in front of several common power quality problems, and discusses the main aspects of its real-time implementation.

2. SST model and control strategies

2.1. SST topology

The basic block diagram for the bidirectional SST includes three parts: a high-voltage stage, an isolation stage, and a low-voltage stage [22]. Figs. 1–3 show a detailed and feasible topology of the SST plus the control strategy selected for each part. The input voltage at power frequency is first converted into dc voltage by the HV-side three-phase pulse width modulated (PWM) ac/dc converter working as rectifier, see Fig. 1. The isolation stage includes the high-frequency transformer, and the two corresponding HV- and LV-side H-bridge voltage source converters (VSC). The HV-side converter shown in Fig. 2 converts the HV dc voltage into a high-frequency square-wave voltage applied to the primary of the high-frequency transformer. In the secondary side, the transformed high-frequency square-wave signal is converted into a LV dc voltage by the LV-side converter, see Fig. 2. Finally, the LV-side three-phase PWM dc/ac converter shown in Fig. 3 works as inverter and provides the output power-frequency ac waveform to LV loads.

When the power flow comes from the secondary side, in case it operates in generation mode, the transformer behavior is similar to that described above. Basically, input and output stages swap functions, so the converters, the respective switching strategies and control methods must be properly designed to work under bidirectional power flow conditions.

The SST model has been implemented in MATLAB/SIMULINK, a simulation environment used by some real-time platforms [25].

2.2. Input stage – high-voltage side front-end converter

The input stage is implemented by means of a three-phase PWM converter [26,27]. The *abc*-frame model for the PWM converter is as follows (see Fig. 1):

$$\frac{d}{dt} i_{i1} = -\frac{R_1}{L_1} i_{i1} - \frac{1}{L_1}(v_{i1o} - v_{N1o}) - \frac{1}{L_1} v_{i1grid} \tag{1}$$

where $i \in a, b, c$, i_{i1} are the HV-side *abc* grid currents, v_{i1o} are HV side *abc* converter voltages (referred to a fictitious dc-link midpoint "*o*"), v_{i1grid} are the HV side *abc* grid voltages (referred to the grid neutral point "N1"), v_{N1o} is the HV grid neutral to dc-link converter midpoint voltage, L_1 is the HV side filter inductance, and R_1 is the HV side filter resistance.

Many control algorithms have been proposed for the operation of PWM rectifiers under unbalanced input voltage conditions. A simple but very effective strategy, the voltage oriented control