Electrical Power and Energy Systems 85 (2017) 153–163

Contents lists available at ScienceDirect

Electrical Power and Energy Systems

journal homepage: www.elsevier.com/locate/ijepes

A modular multilevel converter type solid state transformer with internal model control method

Yong Li [a], Jiye Han [a], Yijia Cao [a,*], Yunxuan Li [a], Jiamin Xiong [a], Denis Sidorov [b], Daniil Panasetsky [b]

[a] College of Electrical and Information Engineering, Hunan University, Changsha 410082, China
[b] Energy Systems Institute, Russian Academy of Sciences, Irkutsk 664033, Russia

ARTICLE INFO

Article history:
Received 14 February 2016
Received in revised form 20 July 2016
Accepted 2 September 2016

Keywords:
Modular multilevel converter
Solid state transformer
Internal model control
Synchronous rotating coordinate

ABSTRACT

To overcome the limitation of the existing topologies and control strategies of SST, a modular multilevel converter type solid state transformer (MMC-SST) with internal model control method is proposed in this paper. First, the structure and operating characteristics of MMC-SST are analyzed, and accordingly its mathematical model of input- and output-stage under synchronous rotating coordinate is established. Secondly, a new kind of dual-loop control structure combine with the internal model control (IMC) current inner loop and proportional integral (PI) voltage outer loop is developed, according to the characteristics of IMC. Lastly, a simulation model is established and the typical operating cases, i.e., the grid side voltage variation, load change, grid and load side power factor deviation, are simulated. Results show that the internal model control based MMC-SST can run stable under the required power factor, and the good performances such as fast voltage and current response speed, strong anti-disturb ability to load, and enhanced robustness on system operation are demonstrated.

1. Introduction

The solid state transformer (SST) is a new kind of power electronics-based smart power transformer that can realize flexible voltage conversion and energy transfer. With the development of energy internet system, solid state transformer as the energy router has gained more and more attention [1,2]. Furthermore, it enhances the power quality compatibility to both the grid and load sides of the transformer [3,4].

To data, several research results have been reported in the fields of SST topology and control strategy. There are several categories of SST widely used these years, traditional two or three-level voltage source converter type SST (VSC-SST), cascaded H-bridge converter type SST (CHB-SST) and modular multilevel converter type solid state transformer (MMC-SST) [5–7]. However, if the VSC-SST is applied to middle/high voltage systems, the power electronics devices in input-stage should be used in series or parallel, which involves the challengeable voltage- or current-balancing problems, respectively. To meet the need of middle/high voltage application, Cascaded H-bridge converter can be applied to SST to meet the need of middle/high voltage systems, but plenty of power electronics devices and high frequency transformers are needed in this construction. The large-scale use of high frequency transformer is disadvantageous to improve the power density, because the high frequency transformer takes large part of SST in size and weight. With the continuous development of MMC, application it to SST will be the inevitable developing trend in the future. The MMC is one kind of DC/AC power converter [8]. Its structure based on simple sub-modular (SM) provides scalability. Its structure based on simple sub-modular (SM) provides scalability, which is the key to achieve high voltage level application by using low voltage power devices. Power losses of the converter are significantly reduced due to the low switching frequencies of the individual SM. Also, its modularity results in good output voltage wave shapes, enabling the reduction of the output filters as well as of the voltage stress in the power devices [9,10]. Another feature of MMC is that it provides a high voltage DC link, thus no bulk DC capacitor is needed. The energy storage is distributed at the capacitors of each SM, which is benefit to system safety and reliability [11].

Besides, the control system of SST has a direct impact on the performance of the entire system. The design of SST controller is mostly based on the mathematical model established under dq rotating coordinate system, uses a dual-loop control method based on PI controller, and realizes the independent control of active and reactive power by dq decoupling control, enabling the system with a good response performance [12,13]. However, as the cross decoupling is needed in these controllers, and the effect of feedback decoupling is sensitive to the change of parameters, it is hard to

* Corresponding author.

http://dx.doi.org/10.1016/j.ijepes.2016.09.001
0142-0615/

realize the complete decoupling control. Meanwhile, these control methods must be always based on verified mathematical models, making the control algorithms becomes too sophisticated to implement. A proportional resonant (PR) current inner loop under two phase static coordinate is proposed [14], in order to deal with the problem of cross decoupling. The structure of this control method is simple, but the PR control applied in SST shows a weak anti-disturbance performance to non-fundamental frequency components.

To overcome the limitation of the existing topologies and control strategies of SST, a modular multilevel converter type solid state transformer (MMC-SST) with internal model control method is proposed in this paper. It is a new dual-loop control method, which consists of the inner current loop based on IMC controller and the outer voltage loop based on PI controller. By means of this control method, a faster transient response and strong anti-disturbance performance can be obtained. Further, the decoupling control problem under two phase rotating coordinate is avoided, which effectively reduces the complexity of control system.

2. Topology and mathematical modeling of MMC-SST

The topology of MMC-SST is shown in Fig. 1. In this topology, MMC is used at the input stage, the input-series output-parallel (ISOP) isolated type DC/DC converter is adopted at the isolation stage, and the three phase voltage source inverter (VSI) is used at the output stage. More specifically,

(1) MMC is used as the grid-tie converter at the input stage, which transforms the AC voltage into the DC voltage and vice versa, since MMC is a bidirectional converter. The withstand voltage level is enhanced by increasing the number of sub-modules in each arm, which enables SST to be applied to middle- or high-voltage systems. By the adoption of carrier phase-shifting PWM modulation [15], high equivalent switching frequency can be obtained with low switching frequency applied sub-modules, which can significant reduce the harmonic content injected into grids and the switching power losses of the system. With an appropriate control of input stage, the system can operate at unity power factor or a given power factor according to the reactive power demand.
(2) The isolation stage is connected with a series of the same DC-DC converter units by means of ISOP, and each DC/DC conversion unit is composed of a single phase full bridge inverter, a high frequency transformer (HFT) and a single phase full bridge rectifier in series. The isolated DC-DC converter is a bidirectional converter because the dual active HBs are used. The LV DC side can be DC loads or DC resources (such as the photovoltaic cell or the energy storage battery).
(3) The three phase voltage source inverter at the output stage is connected with the three-phase load via LC filter branches. The function of the inverter is to transform the DC voltage to three-phase AC voltage for the AC loads.

The comparison on the main characteristics of MMC-SST and the traditional SST are listed in Table 1. It can be seen that the main performances of the SST, i.e., the power losses, the power density, the number of HFTs and IGBTs of SST, the power quality improvement, is better than the traditional SST, which makes the proposed MMC-SST a system with cost-efficiency and application value.

2.1. Mathematical modeling of MMC-SST input stage

The equivalent circuit diagram of MMC-SST input stage is shown in Fig. 2. Each arm is connected in series by a reactor and several same sub-modules (SM), and each SM is composed of a half-bridge converter and a DC energy storage capacitor. By controlling the on-off status of two insulated gate bipolar transistor (IGBT) in each half-bridge converter, SM capacitor can be put into or cut out from the current flow path to shaping the current on this arm [14].

As shown in Fig. 2, according to Kirchhoff's current law (KCL), the current of phase k (k = a, b, c) is

$$i_k = i_{nk} - i_{pk} \tag{1}$$

According to Kirchhoff's voltage law (KVL), the voltage in upper and lower arms of each phase can be respectively expressed as

$$\begin{cases} v_{sk} - \left(\frac{v_{Hdc}}{2} - v_{pk}\right) = -L\frac{di_{pk}}{dt} + r_s i_k + L_s\frac{di_k}{dt} \\ v_{sk} - \left(-\frac{v_{Hdc}}{2} + v_{nk}\right) = L\frac{di_{nk}}{dt} + r_s i_k + L_s\frac{di_k}{dt} \end{cases} \tag{2}$$

where v_{sk} and i_k (k = a, b, c) are the voltage and the current at the grid side, respectively; r_s and L_s denote the equivalent resistance and inductance of line and converter; L is the inductance of MMC arm; and v_{pk}, v_{nk} and i_{pk}, i_{nk} are separately the voltage and current on MMC's upper and lower arms.

Let $v_{rk} = (v_{nk} - v_{pk})/2$ and $L_0 = L/2 + L_s$, and combine with (2), the following expression can be obtained,

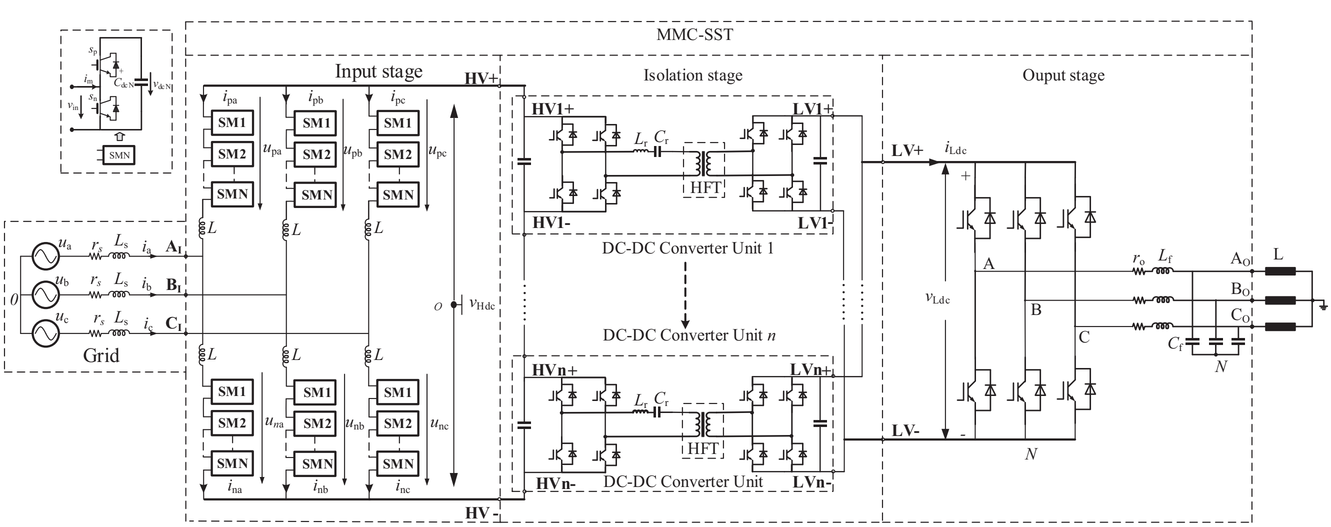

Fig. 1. The proposed topology of MMC-based solid state transformer.