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An integrated control system for sparse matrix converter interfacing PMSG with the grid

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A B S T R A C T

This paper presents an integrated control system for Sparse Matrix Converter (SMC) to interface Permanent Magnet Synchronous Generator (PMSG) based wind turbine unit with the power grid. A carrier based PWM technique is extended and adapted for the SMC. Details of the proposed switching strategy and derivations of the modulation functions for both the rectifier and inverter stages of the SMC are presented. The inverter stage is controlled to regulate the speed of the PMSG for maximum power extraction. In addition, the rectifier stage of the SMC is controlled to deliver the generated active power from the PMSG to the grid at the required power factor to satisfy the reactive power demand. Moreover, the proposed interface system is adaptively synchronized with the grid. The Multi-Output Recursive Least Square (MO-RLS) algorithm is proposed to estimate the phase angle of the grid voltage. Furthermore, active damping scheme is integrated with the proposed control system to attenuate the oscillations caused by the LC filter of the rectifier stage. Numerical simulations are conducted to investigate the effectiveness and the fast dynamic performance of the proposed control system based on MO-RLS even during the speed disturbance. The proposed interface system succeeds to control active power with the desired power factor demand and to damp the oscillations of the SMC current and voltage.

Introduction

During the last decades, variable-speed wind turbine based on Permanent Magnet Synchronous Generator (PMSG) attracted considerable interest [1]. Many power electronic converters are used to interface the PMSG with the grid such as back-to-back voltage source converters [2], dc-link boost chopper converters [3], and ac/ac converters. The ac/ac converters, where no storage elements are used, can be classified into three topologies. The first topology is the ac voltage controllers, known as ac choppers, which can be used to change only the effective value of the output voltage without controlling the output frequency [4]. The second type is the cycloconverter which is used when the output frequency is much lower than the input source frequency. The output voltage of the cycloconverter is synthesized through periods of the input waveform [5,6]. The third topology is the Matrix Converters (MCs) which converts the ac input to ac output with variable amplitude and frequency [7–9]. The MCs are divided into Direct Matrix Converter (DMC) and Indirect Matrix Converter (IMC) [10]. The disadvantages of the DMC are the high number of devices and the complexity of its control and commutation process [11–13]. The IMC is a two-stage converter topology which is similar to the conventional inverter-converter topology but without dc-link energy storage elements [14]. All the desired features of the DMC topology, such as sinusoidal input current and sinusoidal output voltage, four-quadrant operation, and controllable power factor are achieved by the IMC topology. With the same number of devices as the DMC, the two-stage arrangement of the IMC simplifies its control and overcomes the commutation problems of the DMC [15].

The rectifier stage of the IMC supports the dc link voltage and the inverter stage controls the output voltages. The rectifier stage of the IMC is capable of operating with both positive and negative dc-link voltage polarities. However, only the positive polarity of the dc-link voltage is allowed to prevent the damage of the inverter stage. Sparse Matrix Converter (SMC) is introduced to reduce the rectifier stage circuit complexity [16]. For SMC, shown in Fig. 1, the number of semiconductor switches is reduced to fifteen despite of eighteen switches of the IMC topology. The control system of the SMC is close to that of the IMC but with some modifications [17].

The Space Vector Modulation (SVM) technique is used to control the SMC [18,19]. However, the SVM demands a computational complexity which sophisticates its practical implementation. The carrier based Pulse Width Modulation (PWM) technique is

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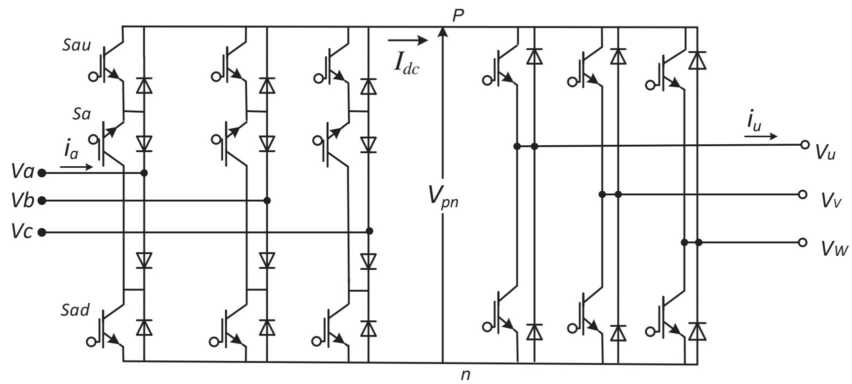

Fig. 1. Sparse matrix converter topology.

implemented to control the IMC [20]. This technique supersedes the SVM by its simplicity and low computational demand. In this paper, the carrier based PWM technique is extended and adapted for the SMC.

Several methods have been proposed to estimate the phase angle of the grid voltage. The Phase Locked Loop (PLL) is widely used for phase angle tracking. The main disadvantage of the PLL is its reliance on PI controllers which introduce instability problem [21–23]. Adaptive techniques such as the Hilbert filtering [24] and the H_∞ filtering algorithm [25] are employed to estimate the phase angle. Despite their accuracy, these algorithms demands large computational effort which complicate their on-line implementation. The Recursive Least Square (RLS) technique is introduced to estimate the phase angle of a single-phase signal [26].

This paper presents an integrated control system for the SMC to interface PMSG based wind turbine unit with the grid. A carrier based PWM technique is extended and adapted for the SMC. Moreover, the proposed control is based on phase estimation of the grid voltage to adaptively synchronize the interface system. Furthermore, active damping scheme is utilized to suppress the resonance of the LC filter at the grid-side. The performance of the proposed integrated control approach for PMSG interface system based on SMC is tested by using the MATLAP/SIMULINK simulation package. The results are discussed to demonstrate the potential of the proposed techniques.

The proposed carrier based PWM technique for the SMC

The SMC is assembled from a rectifier at the input stage and an inverter at the output stage as shown in Fig. 1. The rectifier, which consists of nine semiconductor switches and twelve diodes, is connected to the grid and acts as a Current Source Bridge (CSB). The inverter stage of the SMC is connected to the generator terminals and acts as a Voltage Source Bridge (VSB). To avoid short circuit at the inverter stage, the rectifier stage is maintaining the dc-link voltage V_{pn} at positive polarity. The dc-link current I_{dc} can be either positive or negative allowing for bidirectional power flow. Moreover, the CSB is utilized to control the reactive power injected to the grid. The inverter stage utilizes the dc-link voltage to control the active power flow. The next subsections present the proposed switching technique for the CSB and the VSB stages of the SMC. Unlike the SVM, the carrier based PWM technique is simple and its computational burden is low. The SVM is realized for the VSB control by dividing the space vector into six sectors and the switching period, T_s, is divided into three intervals; T_a, T_b for the neighboring vectors of the sector, and T_0 for the zero vector, which are given by

$$\begin{aligned} T_a &= m_o T_s \sin(60^\circ - \alpha) \\ T_b &= m_o T_s \sin(\alpha) \\ T_0 &= T_s - T_a - T_b \end{aligned} \tag{1}$$

where $m_o = \sqrt{3}V^*/V_{pn,}$ is the modulation index and V^* is the magnitude of the desired fundamental phase-voltage. To minimize the number of switching and guarantee waveform symmetry, the calculated dwell times are deployed into seven-segments switching sequence every period [27]. The same procedure is applied for the CSB to control the current instead of voltage and T_0 is set to zero to avoid open circuit in the CSB. To implement the SVM technique, the controller has to calculate the intervals T_a, T_b, T_0 instantaneously during each sector which requires high computational demands. On the contrary, the carrier based PWM technique requires only the reference voltage to be generated and a triangular carrier. Further, the value of m_o requires modifications for SMC as shown in the next subsections.

Modulation of the CSB stage

Due to the lack of any storage element in the link between the CSB and the VSB stages of the SMC, the dc-link voltage cannot be held constant. For sinusoidal ac supply current, the dc-link voltage is switched between the two consecutive highest line voltages of the grid. For example, if the line voltages v_{ab} and v_{ac} are the highest available line voltages, the dc-link voltage is either v_{ab} or v_{ac} as shown in Fig. 2 where zero CSB power factor angle is assumed.

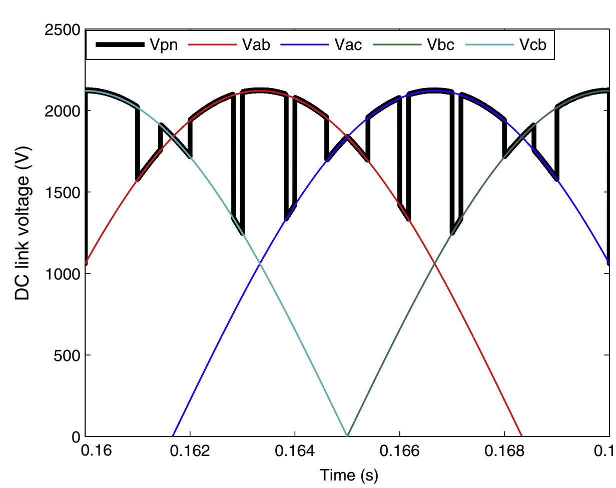

Fig. 2. The dc-link voltage generated by the rectifier stage of the SMC.