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Modeling, control and stability analysis of grid connected PMSG based wind turbine assisted with diode rectifier and boost converter

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ABSTRACT

Permanent magnet synchronous generator (PMSG) based wind turbines (WTs) are widely used as grid connected energy sources. Usually, a PMSG based wind energy system is connected to the grid via machine side and grid side converters. From the machine side converter point of view, there are two types of PMSG-based WTs: PMSG with back-to-back voltage source converters, and PMSG assisted with diode rectifier and boost converter. Since most of the research works regarding the PMSG-based WTs are devoted to the former type, this paper deals with the elaborated controller design and stability analysis of the grid connected PMSG based WT assisted with diode bridge rectifier and boost converter. Hence, the linearized average dynamic model of the combined system comprising PMSG, diode rectifier and boost converter is presented. Based on the linearized model, the relation between the PMSG electromagnetic torque and boost converter current is extracted, and then system's control-loops are developed. Next, small signal stability of the full system comprising PMSG, boost-diode rectifier, dc-link capacitor, GSC, and corresponding controllers is presented and then impact of PMSG speed controller on the stability of the system is examined theoretically and by time domain simulations.

1. Introduction

Variable speed wind turbines (VSWTs) are widely employed in power system and wind energy conversion systems. The VSWT systems are usually based on doubly fed induction generators (DFIGs) or permanent magnet synchronous generators (PMSGs) [1–3]. Currently, due to simple structure, low maintenance cost, MPPT capability and operation at high power factor, the use of PMSG based WTs has attracted interest [4–8]. Therefore, large megawatt (MW) size WTs are established based on PMSG [4]. Usually, the wind energy conversion system with a PMSG is connected to the grid via ac-dc and dc-ac converters, known as machine side converter (MSC) and grid side converter (GSC) [9]. The MSC can be a pulse width modulation (PWM) voltage source converter (VSC) or a diode-bridge rectifier assisted by the boost converter, while the GSC is typically a VSC converter.

Hence, from the MSC point of view, there are two types of PMSG-based WTs: PMSG with back-to-back voltage source converters, and PMSG assisted with diode rectifier and boost converter. Since most of the research works regarding the PMSG-based WTs are devoted to the former type, this paper deals with the study and more elaborated analysis of the PMSG-based WT assisted with diode bridge rectifier and boost converter. Fig. 1 shows the block diagram of the PMSG based WT with diode-bridge rectifier comprising permanent magnet synchronous generator, diode-bridge rectifier, boost converter, and GSC.

The diode rectifier converts the PMSG variable output ac voltage to dc voltage and the boost converter increases the rectifier output dc voltage to a higher regulated dc voltage level suitable for the GSC operation. The boost converter controls the generator speed or the generator active power to catch maximum power from available wind power. The grid-side converter (GSC) is used to control the dc-link voltage and transfers the active power fed from the MSC to the grid. Meanwhile, it also regulates reactive power that the WT exchanges with the grid [10]. To the best knowledge of the author, less analytical work has been published in literatures regarding the control and performance analysis of the PMSG based WT equipped with diode rectifier and boost converter. Below, some papers, such as [11–20], dealing with this wind turbine type are given and described. Paper [11] studies the oscillation modes of the grid connected PMSG based WT to find out all types of oscillation modes, which are subsynchronous oscillation (SSO), subsynchronous control interaction (SSCI) and low-frequency oscillation, including frequency and damping of each oscillation mode. The Refs. [12–14] deal with the sensorless maximum power tracking in small wind turbines based on PMSG with diode bridge rectifier.

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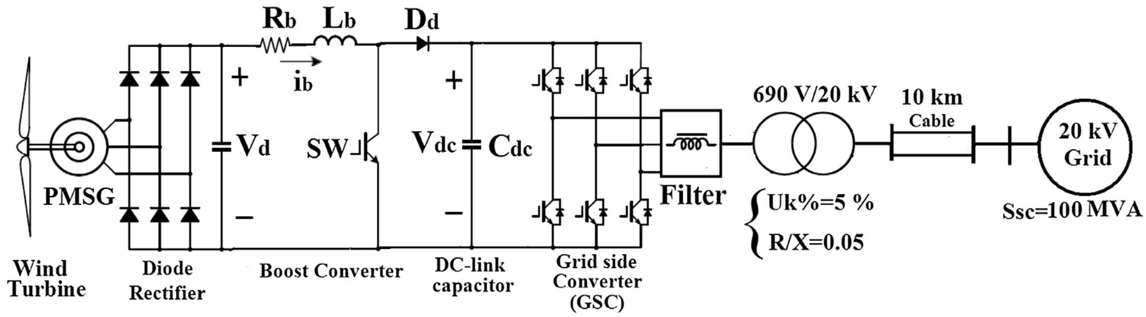

Fig. 1. System under study comprising PMSG based WT assisted with diode rectifier and boost converter.

In [12], the relationship between the DC voltage and the DC current is obtained in an optimal manner and then system is controlled from the DC side in the MPPT mode. In [15], a fractional order incremental conductance algorithm for the maximum power point tracking design of small PMSG wind power systems feeding the DC load is proposed. In [16], a sliding-mode control based scheme is proposed for grid connected PMSG based WTs equipped with diode rectifier and boost converter. In [17,18], a predictive control scheme is proposed for the control of WT and low-voltage ride-through enhancement, where the power conversion system contains a three-phase diode-bridge rectifier, a three-level-boost converter, and a neutral-point-clamped (NPC) inverter. In [19], a three-phase modular boost converter supplied from a PMSG and controlled using a linear quadratic regulator (LQR) is proposed for battery charging applications. Ref. [20] analyses operation of a stand-alone wind turbine system, including the PMSG, boost converter, and storage system, during wind speed and load variations. Even though the above mentioned publications have addressed some issues regarding the control and performance analysis of the PMSG based wind WTs assisted with diode rectifier and boost converter, however, accurately analytical work is still very rare for the elaborated controller design and wind turbine behavior analysis.

This paper deals with the elaborated controller design and stability analysis of the grid connected PMSG based WT assisted with diode bridge rectifier and boost converter. In this way, the linearized average dynamic model of the combined system comprising PMSG, diode rectifier and boost converter is presented. Based on the linearized model, the relation between the PMSG electromagnetic torque and boost converter current is extracted, and then system's control-loops are developed. Next, small signal stability of the full system comprising PMSG, boost-diode rectifier, dc-link capacitor, GSC, and corresponding controllers is presented and then impact of PMSG speed controller on the stability of the system is evaluated. At the end, results of theoretical analyses are verified by time domain simulations.

2. Steady state operation of PMSG with diode rectifier

In this section steady state model of the PMSG with 6-pulse diode rectifier assisted by the boost converter, see Fig. 1, is presented. Fig. 2 shows the one phase steady state equivalent circuit of a non-salient type PMSG, where X_s is the synchronous reactance, R_s is the stator resistance, and V_s and I_s are the stator phase voltage and current.

In Fig. 2, the positive direction for the stator current is assumed into the stator winding. E_g in Fig. 2 is the induced electromotive voltage in the stator winding and is given by $E_g = k\omega_r\psi_{pm}$, where ω_r is the electrical rotational speed of the generator, and ψ_{pm} is the amplitude of the flux linkage in the stator due to permanent magnet in the rotor (rotor flux linkage). The corresponding phasor equation can be expressed as

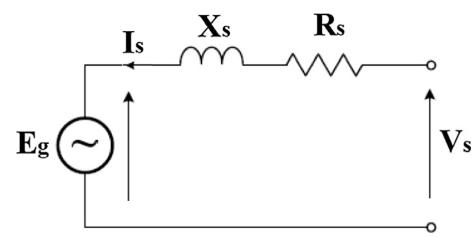

Fig. 2. One phase steady state equivalent circuit of a non-salient type PMSG.

$$E_g = R_sI_s + jX_sI_s + V_s \tag{1}$$

Typically, the boost converter, in Fig. 1, is operated in continuous conduction mode (CCM). This mode implies that the inductor current is continuous and is realized by a sufficiently large inductor at the input of the boost converter. In this study, it is assumed that the boost converter operates at CCM and thus its model is simplified as a dc current source from the rectifier point of view. Therefore, the diode rectifier also works at CCM because the boost converter at the output of the rectifier acts as a dc current source. Fig. 3 depicts the three phase steady state equivalent circuit of the PMSG assisted with diode rectifier and boost converter in the *abc* frame.

In Fig. 3, E_{ag}, E_{bg} and E_{cg} are the three phase induced electromotive voltages, and V_d and i_b are the output dc voltage and current of the diode rectifier, respectively. Also, since the stator resistance R_s is relatively small compared to X_s, it is neglected in Fig. 3 to simplify the analysis. Due to presence of synchronous reactance X_s, the current commutation in the diode rectifier is not instantaneous causing the rectifier output dc voltage drop. From [21], the output average dc voltage of the diode rectifier is given as:

$$v_d = \frac{3\sqrt{3}}{\pi}|E_g| - \frac{3}{\pi}X_si_b \tag{2}$$

where $|E_g|$ is the amplitude of the stator phase induced voltage.

3. Average dynamic modeling of the PMSG with diode rectifier

The purpose of this section is to find a linear model representation of the system consisting of the PMSG, diode rectifier and boost converter. This is obtained by combining the lineraized average models of the PMSG, diode rectifier and boost converter.

3.1. PMSG average model

For dynamic modeling of PMSG system, it is common to use dynamic dq model of the machine. Due to nonlinearity of the diode