Modeling of a Rectifier Connected PMSG Applied in Wind Energy Conversion System Using State Machine Approach

M. Shahnazari, A. Vahedi

Abstract -- Accurate modeling of the wind energy conversion system is necessary to design and implementation of the control loop for the generator and the frequency converter, in order to extract maximum power from the wind and to investigate the effects of interconnection between wind farms and power system. In this paper the combination of a permanent magnet synchronous generator loaded with a diode rectifier, used in wind energy conversion system, is modeled using a state machine approach. The model is validated through comparison of the proposed model and the experimental results.

Index Terms - wind energy conversion system, permanent magnet synchronous generator, rectifier, state machine model.

I. INTRODUCTION

NOWADAYS, small wind-electric systems are among the most popular renewable energy options not only for electrification of remote sites but also for grid-interconnection. The more frequently adopted configurations of small wind generators consist of a permanent magnet synchronous generator (PMSG), directly coupled to the wind turbine. Among the two types of wind turbines, the geared drives and direct drives, the latter with simple drive train and higher overall efficiency, reliability and availability by omitting the gearbox, is more attractive [1].

Using PMSG improves the efficiency and reliability and reduces the weight and volume due to the absence of gearboxes and sliding contacts [2]. Although PMSG has some disadvantages such as high cost of PM materials and demagnetization of PM at high temperature, but in recent years, use of PMs is more attractive because their performance is improving and their cost is decreasing [overview of diff. wind]. According to these benefits, currently, several wind generator manufacturers such as Mitsubishi, Lagerwey and etc. are using these generators into their wind turbines and the largest capacity is up to 2MW on the market.

Though various topologies of PM machines are possible to be used for direct-drive wind turbines, the radial-flux PM (RFPM) machine with surface mounted magnets seems to be a better choice for low-speed, direct-drive large wind turbines due to its simple structure and reliability [3–4]. Also, there are different converter topologies applicable to permanent magnet wind generators. Many of these combinations use diode rectifier at the generator terminals since no external excitation current is needed. This is a major cost benefit in using PMSG [5].

Increased wind power generation, directly connected to transmission networks, has influenced the overall power system operation and planning in terms of power quality, security, stability and voltage control [6]. Therefore, the interconnection between wind farms and power system is a research topic that needs more attention. To investigate these influences, modeling and simulation of wind power system is essential. In addition, accurate modeling of the system is necessary to design and implementation of the control loop for the generator and the frequency converter, in order to extract maximum power from the wind.

Usually, the generator side diode rectifier is modeled as a gain block, neglecting its commutation angle and/or commutating reactance [7-9]. When the rectifier load current is increased, the commutation angle and the voltage drop due to the commutating reactance will be increased too. So, these effects can not be neglected for accurate modeling. Also, the bilateral coupling between the rectifier and the generator forces the dynamics to be strongly interconnected. An approach for modeling of such systems is a detailed description of the switching process and exact calculation of the waveforms, called switching model. Switching models are

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nonlinear, time and memory consuming and unsuitable for control purposes [10]. Since, the knowledge of the exact cyclic behavior of the system will not be used in many control applications, we can separate the two time scales involved: the cyclic and the average behavior.

There are two main ways to derive average models for diode rectifiers: parametric average value [11-13] and mathematical derivation methods [14-16]. The parametric method is very simple to implement and takes into account the nonlinearity effects, but it is time consuming and difficult to include and improve for model dynamics. In contrast, the mathematical derivation method is not subject to these limitations but the derived models have some implicit nonlinear equations that require a numerical iterative solution.

Based on the rectifier load level, the rectification process can be divided into three distinct modes: discontinuous, continuous and simultaneous commutation modes [16]. The mode selection is based on the commutation angle at the boundary of two modes that is defined by the rectifier load current and the generator flux linkage. Because the flux linkage of the generator is changing continuously, the mode searching conditions are also changing which increases the amount of calculation. In this paper the combination of a permanent magnet synchronous generator loaded with a diode rectifier, used in wind energy conversion system, is modeled using a state machine approach.

II. Modeling Problem

A. PM Synchronous Generator

With the assumption that the magnetic flux distribution in the rotor is approximately sinusoidal, the flux can entirely be described by a vector and thus the internal voltage E induced in the stator winding by the permanent magnet flux λ_{pm} can be expressed as: $E = \omega_e \lambda_{pm}$ where ω_e is the electrical speed. Under load conditions, the stator current Is and the stator reactance in the stator winding produce a magnetic field of its own, which is superposed to the field generated by the permanent magnets. Thus, the voltage U_s at the stator terminal of PMSG corresponds to the voltage induced by the total magnetic field. Aligning the direction of the d axis of the dq reference frame with the flux linkage, the mathematical model of the PMSG is given by:

$$v_{sd} = -r_s.i_{sd} - \omega_e.\lambda_{sq} + \lambda_{sd}$$
$$v_{sq} = -r_s.i_{sq} + \omega_e.\lambda_{sd} + \lambda_{sq} \quad (1)$$

$$\lambda_{sd} = -L_s.i_{sd} + \lambda_{pm}$$
$$\lambda_{sq} = -L_s.i_{sq} \quad (2)$$

Where v_{sd}, v_{sq}, i_{sd}, i_{sq}, λ_{sd}, and λ_{sq} are the d and q axis stator voltages, currents and flux linkages, respectively; r_s is the stator resistance, L_s is the stator inductance and λ_{pm} is the magnet flux linkage.

Depending on the phase delay (load angle) between the internal voltage E and the stator voltage V_s, the total magnetic field in the generator either increases or decreases as the current increases. Because of the fixed excitation of PMSG, the converter connected to the generator has to provide or consume reactive power. The active and reactive powers of the generator are thus controlled by its output converter through the generator stator voltage and current.

B. Stator-Rectifer State Machine

Fig.1 shows the single phase equivalent circuit of a rectifier connected PMSG. Among three distinct rectification

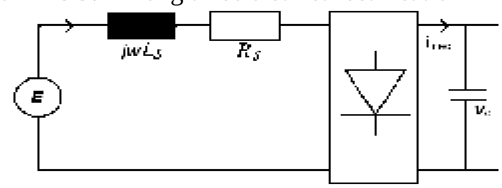


Fig. 1. Single phase equivalent circuit of a rectifier connected PMSG

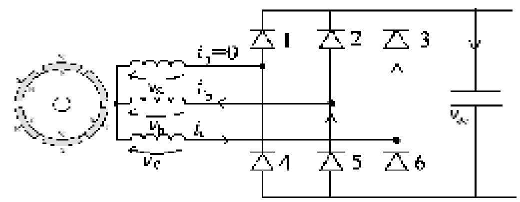


Fig. 2. Directions of the stator circuit currents in the first state

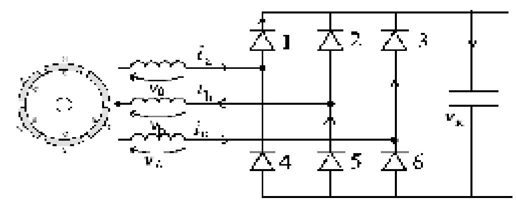


Fig. 3. Directions of the stator circuit currents in the second state

TABLE I
Odd and Even States of the Stator

Odd States	Cond. Phases	Even States	Cond. Phases
1	**cb**	**2**	**cb ↔ ab**
3	**ab**	**4**	**ab ↔ ac**
5	**ac**	**6**	**ac ↔ bc**
7	**bc**	**8**	**bc ↔ ba**
9	**ba**	**10**	**ba ↔ ca**
11	**ca**	**12**	**ca ↔ cb**

modes, the discontinuous commutation mode corresponding light load conditions is studied in this paper.

In this mode, the commutation of current is fast and ends before the next one begins. So, three and two diodes are in sequential conduction. Because of symmetry, one cycle of operation may be divided to six π/3 interval. Hence, there are 12 different phase current direction combinations in the stator circuit. Six combinations when two diodes are conducting (odd states) and six when three diodes conducting (even states). All possible stator states are presented in Table 1. The positive direction of the current is chosen from the stator winding to the rectifier. Also, the first letter indicates the positive current and the second the negative current. Fig.2 represents the directions of the stator circuit currents in the first state. When the diode resistance and threshold voltages are neglected, the voltage equation for the first state is given by:

$$v_c - v_b = 2r_s . i_c + 2L_s . \frac{di_c}{dt} + v_{dc} \quad (3)$$

The voltage equations for all the odd states (which two diodes conduct) have the same gain matrix and only the conducting phases change. During the commutation, all the stator phases are conducting. The direction of the currents in the second state are shown in Fig. 3.in the even states two voltage equations must be solved. These equations for the second state are expressed as:

$$\begin{bmatrix} v_c - v_b - v_{dc} \\ v_c - v_a \end{bmatrix} = \begin{bmatrix} -r_s & r_s \\ r_s & 2r_s \end{bmatrix} \begin{bmatrix} i_b \\ i_c \end{bmatrix} + \begin{bmatrix} -L_s & L_s \\ L_s & 2L_s \end{bmatrix} \begin{bmatrix} \frac{di_b}{dt} \\ \frac{di_c}{dt} \end{bmatrix} \quad (4)$$

The voltage equations for the rest of the even states are formed in the same way. Both the gain matrix and the phases change:

- State 4

$$\begin{bmatrix} v_a - v_b - v_{dc} \\ v_b - v_c \end{bmatrix} = \begin{bmatrix} -2r_s & -r_s \\ r_s & -r_s \end{bmatrix} \begin{bmatrix} i_b \\ i_c \end{bmatrix} + \begin{bmatrix} -2L_s & -L_s \\ L_s & -L_s \end{bmatrix} \begin{bmatrix} \frac{di_b}{dt} \\ \frac{di_c}{dt} \end{bmatrix} \quad (5)$$

- State 6

$$\begin{bmatrix} v_a - v_c - v_{dc} \\ v_a - v_b \end{bmatrix} = \begin{bmatrix} -r_s & -2r_s \\ -2r_s & -r_s \end{bmatrix} \begin{bmatrix} i_b \\ i_c \end{bmatrix} + \begin{bmatrix} -L_s & -2L_s \\ -2L_s & -L_s \end{bmatrix} \begin{bmatrix} \frac{di_b}{dt} \\ \frac{di_c}{dt} \end{bmatrix} \quad (6)$$

- State 8

$$\begin{bmatrix} v_b - v_c - v_{dc} \\ v_c - v_a \end{bmatrix} = \begin{bmatrix} r_s & -r_s \\ r_s & 2r_s \end{bmatrix} \begin{bmatrix} i_b \\ i_c \end{bmatrix} + \begin{bmatrix} L_s & -L_s \\ L_s & 2L_s \end{bmatrix} \begin{bmatrix} \frac{di_b}{dt} \\ \frac{di_c}{dt} \end{bmatrix} \quad (7)$$

- State 10

$$\begin{bmatrix} v_b - v_a - v_{dc} \\ v_b - v_c \end{bmatrix} = \begin{bmatrix} 2r_s & r_s \\ r_s & -r_s \end{bmatrix} \begin{bmatrix} i_b \\ i_c \end{bmatrix} + \begin{bmatrix} 2L_s & L_s \\ L_s & -L_s \end{bmatrix} \begin{bmatrix} \frac{di_b}{dt} \\ \frac{di_c}{dt} \end{bmatrix} \quad (8)$$

- State 12

$$\begin{bmatrix} v_c - v_a - v_{dc} \\ v_a - v_b \end{bmatrix} = \begin{bmatrix} r_s & 2r_s \\ -2r_s & -r_s \end{bmatrix} \begin{bmatrix} i_b \\ i_c \end{bmatrix} + \begin{bmatrix} L_s & 2L_s \\ -2L_s & -L_s \end{bmatrix} \begin{bmatrix} \frac{di_b}{dt} \\ \frac{di_c}{dt} \end{bmatrix} \quad (9)$$

The commutation between states is based on the voltage and currents. The state machine moves from an odd state to an even one, when the voltage of the non-conducting phase reaches he value of the conducting phase with the same polarity. In like manner, the state change from an even to an odd state takes place when one of the phases stops conducting as it reaches the zero current.

III. Model Validation with Experimental Data

The proposed model has been validated by measurements with a laboratory permanent magnet synchronous generator imitating the PM wind generator (Fig. 4)). A six-pulse bridge rectifier was connected to the generator and loaded with an RL branch to emulate the generator load. The machine under

Fig. 4. Laboratory test setup

TABLE II
PM Synchronous Generator Parameters

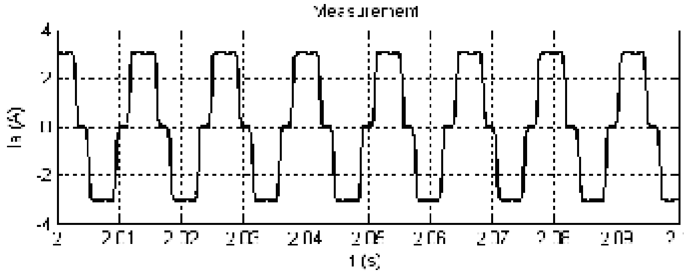
r_s=0.97 Ω	L_d=5.1 mH	L_q=5.1 mH	K_m=0.67 Nm/A
r_{kd}=15.41 Ω	L_{kd}=6.4 mH	r_{kq}=60.3Ω	L_{kq}=10.21 mH

study is a small 1.5 [kW], 85 [V], 2000 [rpm] PM synchronous generator which its parameters are listed in Table 2. The state machine model of the generator/rectifier was constructed and simulated in Matlab in order to fully compare its operation against experimental results.

In the following study, the system starts up with initial conditions corresponding to steady-state operation. Then, three phase terminal currents is measured and sampled by the data acquisition system. The sampling frequency was selected to be 5 [kHz]. The initial load resistance is 35 Ω which is changed to 17.5 Ω. Fig. 5 and Fig.6 represent the measured and simulated current I_a corresponding the load resistance 35 Ω and 17.5 Ω respectively.

The amplitude of the simulated and measured currents are almost equal. The small discrepancy is due to the inaccuracy of the model and the machine parameters. The shape of the simulated current is in good agreement with the measured current. The trapezoidal shape of the phase currents can be explained by the commutation between diodes.

Also, Fig. 7 shows the transient comparison between measurement and simulation results when the load resistance changes suddenly. These figures indicate that the simulated and measured responses are in good agreement and thereby verifying the proposed model. As can be seen from these figures, the rectifier operates in discontinuous rectification mode. The phase currents do not immediately start to flow to the opposite direction after reaching zero, and the system stays in an odd state for a while.



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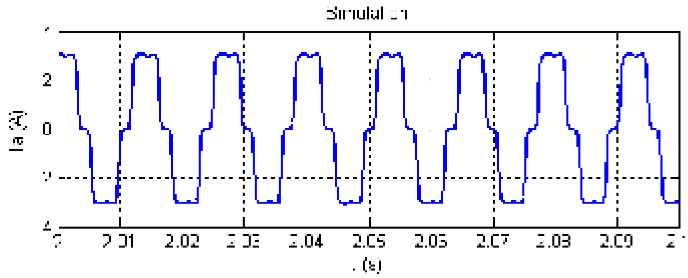

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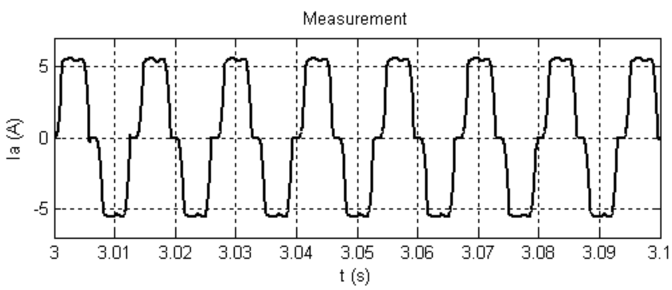
Fig. 5. Measured and simulated current I_a (load resistance 35 Ω)



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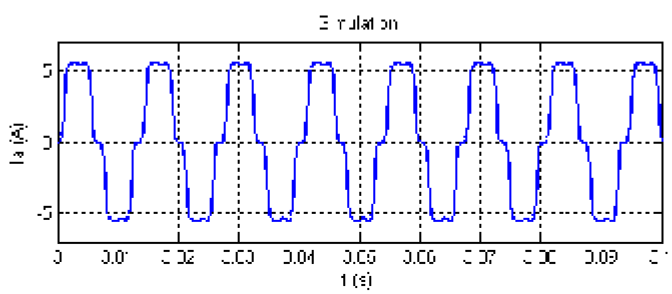

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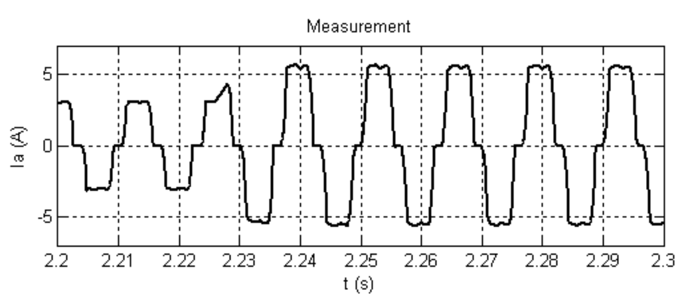
Fig. 6. Measured and simulated current I_a (load resistance 17.5 Ω)



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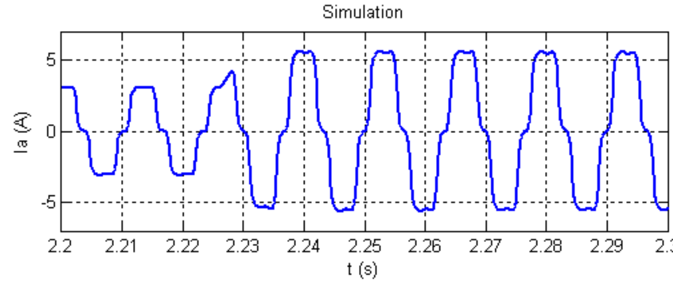

(b)

Fig. 7. Measured and simulated current I_a (step change in load resistance)

IV. Conclusions

The state machine approach was used to model a rectifier connected permanent magnet synchronous generator, for use in wind energy conversion systems. Among three distinct rectification modes, the discontinuous commutation mode corresponding light load conditions was studied in this paper. There are 12 different phase current direction combinations in the stator circuit. The voltage equation(s) for each state must be solved to calculate the phase currents. Both simulated and measured results for a PM synchronous machine were presented. Comparison of these results shows that the proposed model can predict all the major characteristics of the machine.

V. References

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