Parameters Determination of Grid Connected Interior Permanent Magnet Synchronous Generator

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Abstract— Renewable energy sources are being utilized as a reliable alternative to the traditional energy sources for electricity production. Among these renewable sources, wind energy has the largest and fastest penetration into power systems. This paper introduces a method for measurement of the equivalent-circuit parameters of an interior permanent magnet synchronous generator (IPMSG) used in a wind energy system which utilizes a full scale converter between the generator and the utility grid. The conventional two-axis IPMSG model is modified to include the saturation effect of the inductance in the q-axis including self-inductance values in the d- and q-axes, the stator resistance and also the PM flux-linkage. The modified model of the IPMSG is grid connected using full scale back to back converters which are used in grid active and reactive power control.

Keyword— interior permanent magnet machines, d-and q-axis inductances, synchronous generator, wind energy generation, grid connection, active and reactive power control.

I. INTRODUCTION

Due to an increased demand on environmental sustainability and the depletion of ordinary energy sources, as a viable source of clean and renewable energy, wind power has gained notable emphasis in electrical power generation [1]. Since wind power generators must keep their output frequency identical to the grid frequency, most wind turbines currently operate at constant speeds. However, variable- speed generation has a higher energy capturing and converting efficiency than a fixed-speed system. In variable speed wind turbines, the speed of the generator is varied to achieve maximum coefficient of performance for the turbine. With the generator speed control, the turbine is able to operate at the maximum power line [2]. Full scale back to back converters are used as to adjust the generator voltage and frequency to match those of the grid.

Among the many types of generators used in wind energy systems, permanent magnet synchronous generators are used for variable speed operation. There has been an increasing interest in using IPMSG with direct driven wind turbine over the traditional externally excited synchronous machine due to a significant reduction in magnet prices as well as magnetic material characteristics improvement.

Synchronous-machine stability-constant determination has become a topic of considerable research interest by the power utility industry [3-9]. Part of the reason, is due to the increasing demand for more accurate performance evaluation of electric generators and other components of the power system networks, to ensure stability and reliable operation of the power system as a whole. Today, power generator models describe the transient and sub transient behavior of the rotor and armature flux linkages in response to stator currents and field excitations. However, the problem posed by this complex description is that the required parameters are often inaccurate or completely unknown [10]. There have been a number of reports and papers describing test methods for synchronous-machine parameters determination [3-9].

The accuracy of calculating the steady-state performance of permanent magnet (PM) synchronous generators depends on the accuracy of calculating the synchronous reactances in the d- and q-axes [11]. PM synchronous generators sometimes have a complicated structure, and numerical or analog modeling is necessary to obtain an accurate distribution of the magnetic field. This distribution is very helpful to correctly estimate the form factors of the rotor and stator magnetic flux densities. The finite element method (FEM) makes it possible to find the d-and q-axis synchronous reactances and mutual (armature reaction) reactances by computing the corresponding inductances, e.g., [12-17]. It can be done by using the flux linkage and magnetic vector potential concept or energy stored in the winding. Recently, two modern FEM techniques in ac machines analysis have emerged: current/energy perturbation method [18] and time-stepping analysis [3], [7]. These methods are especially suitable for transient analysis of converter-fed PM synchronous machines.

The measurement of the synchronous reactances for small PM synchronous generators seems to be more difficult [19]. There are several methods for the measurement of synchronous reactances of medium and large synchronous machines [20-22] but the assumptions made do not allow one to apply these methods to small PM synchronous generators.

This paper introduces a method for calculating the equivalent-circuit parameters of an interior permanent magnet synchronous generator (IPMSG), by considering the cross saturation between direct-axis (d-axis) and quadrature-axis (q-axis). The conventional two-axis IPMSG model is modified to include the saturation effect of the q-axis inductance. Therefore, the parameters of the machine should be evaluated to estimate its performance.

The simulated IPMSG model is used for a medium voltage grid coupled wind turbine where the active and reactive power of the grid is controlled via the grid side converter. The control of the active and reactive power is done through the control of the d-axis and q-axis grid currents.

II. IPMSG WIND TURBINE SYSTEM CONNECTED TO MEDIUM VOLTAGE GRID

A. Overall System Description and IPMSG Parameters Measurement

As mentioned earlier, to examine the behavior of IPMSG both in transient and steady state operation require full knowledge of the machine's parameters. A block diagram of an IPMSG wind energy system used for a 1.5MW medium voltage (MV) grid interfacing is shown in figure (1) and the data for the simulated system can be found in table (1) in Appendix A. Full system description will be fully demonstrated in the proceeding sections.

A 1.5kW experimental IPMSG scaled down prototype is used to demonstrate how parameters are being measured. The tests conducted show how saturation affects the parameters under investigation.

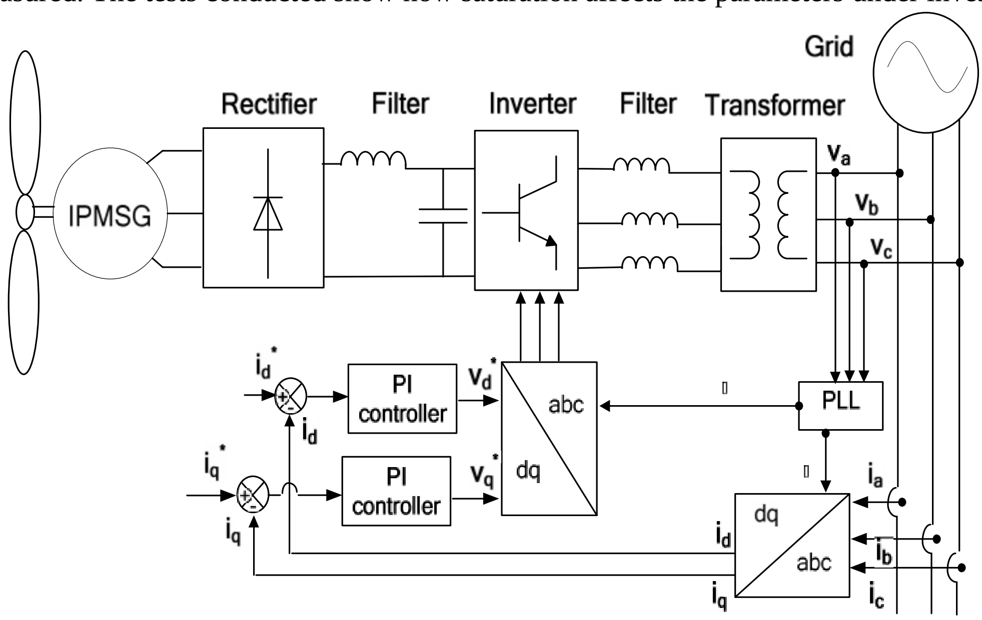


Figure 1: IPMSG Grid Connected Wind Energy System

i- Stator resistance R_a

The armature resistance can be measured by conventional DC test with subsequent correction to obtain the AC value [23-24]. From the test, the value of the stator resistor was found to be $R_a = 0.096\Omega$.

ii- PM flux linkage ϕ_f

The flux linkage of the permanent magnet, Φ_f can b e obtained by measuring the no-load line-to-line r.m.s voltage V_{nL} of the generator while it is driven through the shaft at a constant speed of ω. The flux linkage is the slope of the plot between the no-load voltage and the angular speed. The measured value of the permanent magnet flux linkage ϕ_f was found to be 0.36wb as seen from figure (2).

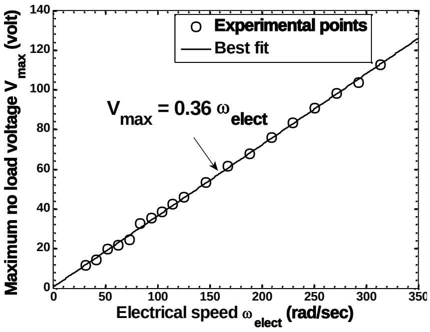
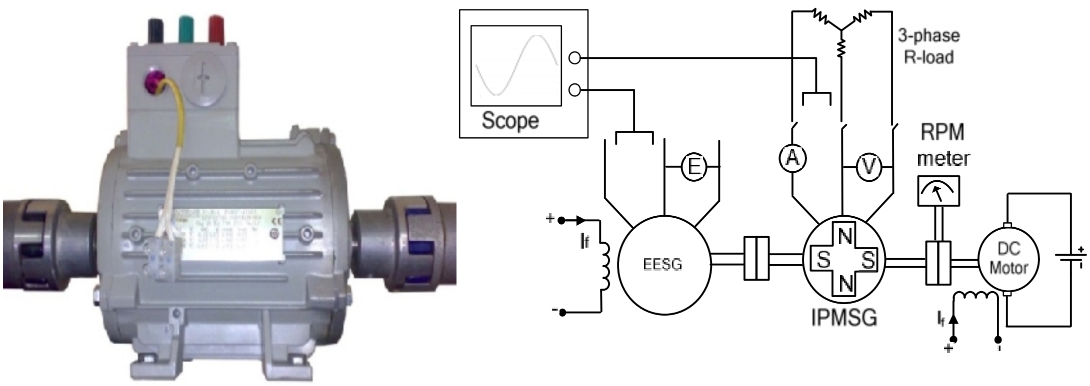


Figure 2: Relationship between electrical speed and maximum phase voltage for IPMSG no load test

iii- D-Q axis inductances Ld and Lq

A scheme is proposed to measure the load angle δ of the machine by coupling the proposed IPMSG with a DC motor from one side and with an externally excited synchronous machine (EESG) from the other side as shown in figure (3). Thus, the DC motor will drive the two synchronous generators, where the no-load voltage of the two machines will be recorded and synchronized on a dual beam scope. The no-load EMF's of IPMSG and of EESG operating as generators should be in phase. Thus, the same positions of the IPMSG and EESG rotors with regard to the same phase windings can be found. When the IPMSG is loaded with a pure resistive load in which case, there is no need to a wattmeter, the load angle (which indicates rotor position) will be the difference between the output load voltage of the IPMSG machine and the no load voltage of the externally excited synchronous generator.



(a) (b)

Figure 3: Connection diagram of the proposed method to measure the load angle δ.

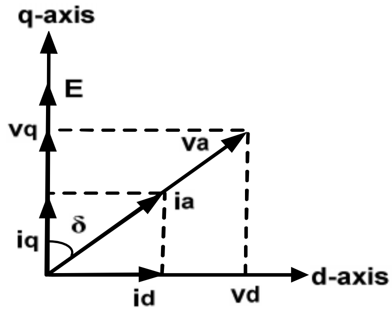


Figure 4: Phasor Diagram at Unity Power Factor

The stator voltage equations of an IPMS Generator at steady- state are:

$$v_d = -R_a i_d + \omega L_q i_q \quad (1)$$

$$v_q = -R_a i_q + \omega \phi_f - \omega L_d i_d \quad (2)$$

From Figure 2, the relationship between load angle and d- and q-axis stator voltages and currents can be given as follows [20]:

$$\lfloor v_d \quad v_q \rfloor^T = v_a \; [sin\delta \quad cos\delta]^T \quad (3)$$

$$\lfloor i_d \quad i_q \rfloor^T = i_a \; [sin\delta \quad cos\delta]^T \quad (4)$$

Substituting (3) and (4) into (1) and (2), the d-and q-axis inductances can be calculated as follows:

$$L_d = \frac{\omega\phi_f - v_q - R_a i_q}{\omega i_d} \quad (5)$$

$$L_q = \frac{v_d + R_a i_d}{\omega i_q} \quad (6)$$

Using the above results, the relationship between the d-axis linkage ϕ_d and the d-axis current i_d at speed=1500 rpm is shown in figure (5).

Taking the best fit of the two curves of figure (5), the relation between ϕ_d and i_d can be described by the following equation:

$$\phi_d = 0.186 i_d + 0.36 \quad (8)$$

Since, $\phi_d = L_d i_d + \phi_f$ (9)

From the above equations, the measured value of the d-axis inductance L_d is found to be 0.186 H. The measured d-axis inductance of the prototype IPMSG is shown in figure (6), where L_d is almost constant. Figure (5) shows how much L_d is affected by the air gap. Similarly, the relationship between the q-axis flux linkage ϕ_q and the q-axis stator current i_q is drawn, as shown in figure (7). Figure (7) shows how magnetic saturation affects the value of the q-axis inductance as L_q is affected by the iron of the magnetic core .

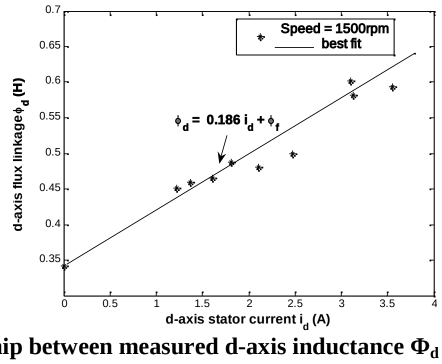


Figure 5: Relationship between measured d-axis inductance Φ_d and d-axis current i_d

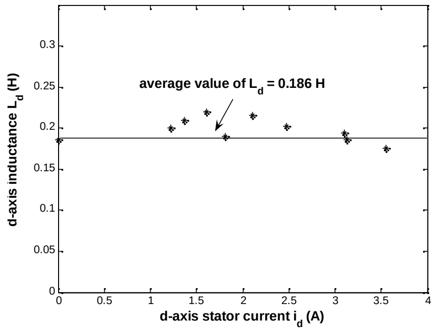


Figure 6: Relationship between measured d-axis flux linkage L_d and d-axis current i_d

The measured q-axis inductance of the prototype IPMSG is shown in figure (8). It is found that, L_q depends on the q-axis current. Thus, before magnetic saturation ($i_q < 0.4$A), L_q is almost constant, where,

$$\phi_q = L_q i_q \quad (10)$$

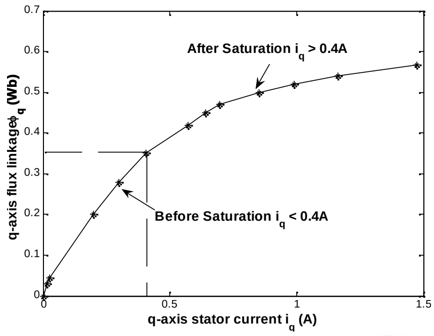


Figure 7: Relationship between measured q-axis flux linkage Φ_q and q-axis stator current i_q

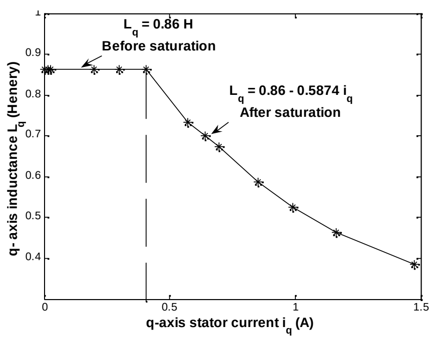


Figure 8: Relationship between measured q-axis inductance Lq and q-axis stator current iq

Therefore, the average value of the measured q-axis inductance Lq is found to be 0.86 H. The relation between measured q-axis inductance and q-axis current after magnetic saturation is determined by:

$$L_q = 0.86 - 0.5874 i_q \quad (11)$$

The flux linkage of the permanent magnet φ_f, can be obtained from the proposed scheme used to measure the load angle δ of the machine. From figure (4), it is clear that the relation between φ_d and i_d can be described by (8). Therefore, by comparing (8) with (9), the measured value of the permanent magnet flux linkage ϕ_f is found to be 0.357 wb. This matches well with the value obtained from the no-load test.

Figure (9) shows the Simulink model of the IPMSG while taking into account the saturation effect of the q-axis inductance. The input to this system is the speed, where both the d-axis inductance L_d and the PM flux- linkage φ_f are practically constants.

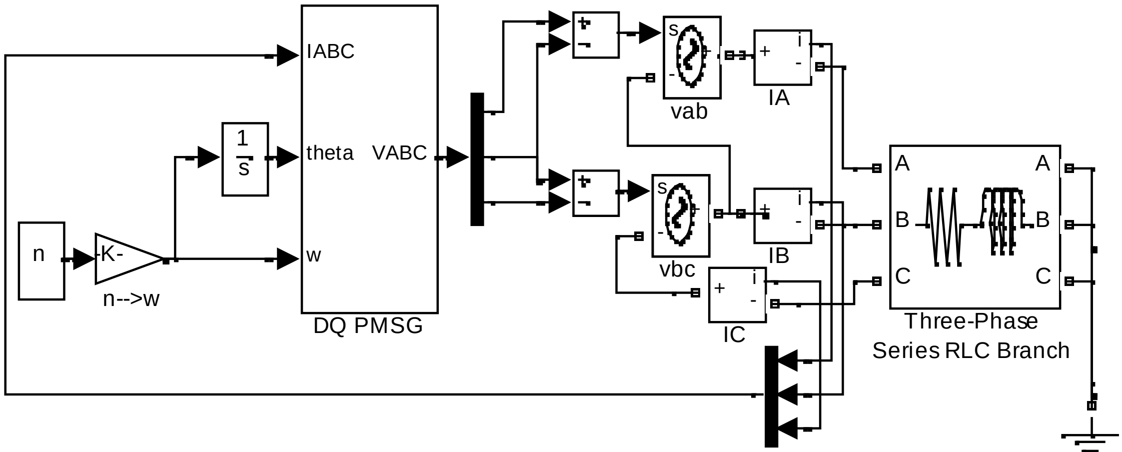


Figure 2: Simulink model of the IPMSG

The machine is loaded experimentally at nominal speed and loaded with R,L and C loads, where the external characteristics (relation between the load voltage and current) from theoretical and experimental tests are compared and showed good matching.

B. Grid Connection with Active and Reactive Power Control

For a direct driven PM generator wind power generation system, the amplitude and frequency of the output voltage are not constant due to the variable speed and fixed excitation of the permanent magnets. Therefore, the output power should be converted into AC power with constant voltage and constant frequency through AC/DC/AC converter as seen in figure (1) for grid coupling. Several topologies have been adopted in literatures for the possible configurations of the AC/DC/AC [25-26]. The simulation is based on a 1.5 MW PMSG wind turbine using the mathematical model described earlier with the MV system parameters of table (1). The control topology in the synchronous reference frame is being adopted in this paper is based on using a 3-phase diode rectifier for the AC/DC conversion and a sinusoidal PWM voltage source inverter (VSI) for the DC/AC conversion for grid interfacing with MV network. The VSI is interfaced to the MV grid through an L- filter and a three phase Δ- Y transformer. As seen from figure (1), the use of phase locked loop (PLL) along with the desired active and reactive power command, sets the desired current being injected into the grid through i_d^* and i_q^*.The simulation results of the MV grid connected PMSG can be seen in figure (10) to figure (14) which shows the generator current as well as the DC link voltage, active and reactive power exported to the grid.

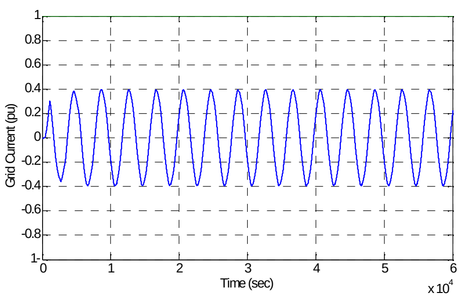


Figure 3: Grid Current (pu)

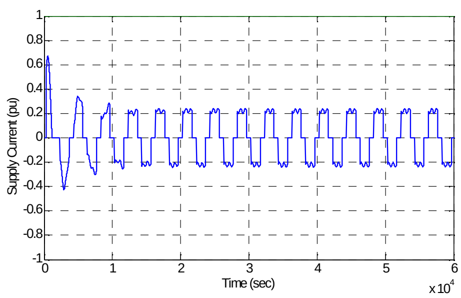


Figure 4: IPMSG Current (pu)

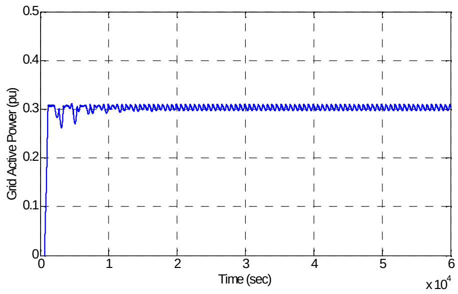


Figure 5: Grid Active Power (pu)

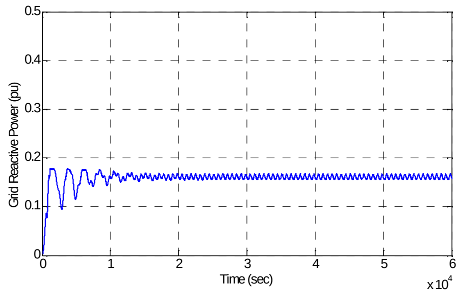


Figure 6: Grid Reactive Power (pu)

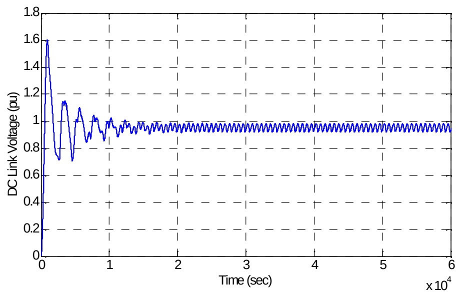


Figure 7: DC Link Voltage (pu)

III. CONCLUSION

This paper presents a practical method for deriving the synchronous machine parameters including the self-inductance values in the d- and q-axes, the stator resistance and also the PM flux-linkage. On the basis of simulation results from the machine model using Simulink and experimental work, the identified models have shown good agreement with the machine responses obtained from the experimental results. The simulated model has been used for simulation of a 1.5 MW IPMSG based wind energy system, where grid active and reactive power are controlled.

IV. APPENDIX

Data for 1.5 MW Permanent Magnet Synchronous Generator was obtained from [27]:

Parameter	Rating
Base power P_b(MVA)	1.5
Base voltage V_b(V)	$690/\sqrt{3}$
Base frequency f_b(Hz)	11.5
Pole pairs of PMSG	40
WT inertia constant (pu)	4.8
PMSG inertia constant (pu)	0.5
Shaft stiffness (pu)	2
Rated generator torque (pu)	1
Rated generator line voltage (pu)	1
Generator inductance in the d frame (pu)	0.7
Generator inductance in the q frame (pu)	0.7
Generator stator resistance (pu)	0.01
Flux of the permanent magnets (pu)	0.9

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