Abstract:Objectives: To model Permanent Magnet Synchronous Generator based wind integrated system in MATLAB SIMULINK. Methods/StatisticalAnalysis: A step by step Simulink implementation of a permanent magnet synchronous generator using dq axis transformations of the stator and rotor variables in the arbitrary reference frame. At first the important formulas are stated and then according to these formulas a generalized model of a PMSG machine is developed. Then a transformer and an inductive load is connected with the PMSG. Findings: 1.5 MW permanent magnet synchronous generator is simulated in MATLAB SIMULINK. Its rated speed is 1500 rpm and number of poles is four. Inductive load is designed for 1 MW. The wind turbine system is also presented. Wind power is varied by using a timer. Improvement/Applications: When wind power is varying, the output from wind turbine is also varying according to the input. For regulating the output from PMSG, a controlled voltage source is placed.

Keywords: d-q transformations, Electromagnetic torque, MATLAB SIMULINK, Permanent Magnet Synchronous Generator(PMSG), Wind Integrated System, Wind power.

I. INTRODUCTION

Wind energy is a major source in renewable energy sector and wind power that which comes from air current flowing across the earth's surface. Wind turbines harvest this kinetic energy and convert it into electric power through any type of generators. Mainly the generators associated with wind turbine are PMSG or Doubly Fed Induction Generator (DFIG). The electricity produced by the generators is sent through transmission and then to distribution lines to feed the customers. Wind generation is one of the fastest growing sources of electricity and one of the fastest growing markets in the world today. With an average annual growth rate of more than 25 percent over the past decade, wind is the fastest growing sector of the energy industry all over the world. The advantages of wind energy are numerous and undoubtful, and the technology itself has taken a leap forward in recent years.

The wind energy conversion system (WECS) includes wind turbines, generators and control system for its normal and reliable operation and the system also possess interconnection apparatus. Wind Turbines are generally classified into horizontal axis wind turbines (HAWT) and vertical axis wind turbines (VAWT).

Modern wind turbines use HAWT with two or three blades and operate either in downwind or upwind configuration. The PMSG machine is the most efficient one in all electric machines since it has a movable magnetic material inside itself and the use of permanent magnets for the excitation results no extra electrical power for the excitation purpose. This feature also increases its efficiency. The recent invention of high-energy density magnets results the achievement of extremely high flux densities inside the PMSG. This results compact structure for PMSG than a same rated induction generator or a doubly fed induction generator. Also, the only heat production is on stator, which is easier to cool down than the rotor because it is on the periphery of the generator and cooling of a static portion is more easier than a revolving portion. Also, PMSG have very long lasting winding insulation, bearing, and magnet life length. It needs very few maintenance services because of its simplified mechanical design. Also, PMSG possess highest power-to-weight ratio. All the above advantages causes the usage of PMSG in wind integrated system.

II. DYNAMIC MODELING OF PMSG

The following assumptions are made to derive the dynamic model:

1. The stator windings are balanced with sinusoidally distributed magneto motive force (mmf).
2. The inductance versus rotor position is sinusoidal.
3. The saturation and parameter changes are neglected.
4. Rotor flux is concentrated along d axis.
5. Rotor flux is kept to be constant at given operating point.
6. Variations in rotor temperature with time is neglected.
7. Since no external source is connected to rotor magnets, no need of rotor equations.
The dynamic model of the permanent magnet synchronous generator (PMSG) is derived using a two-phase motor having phases in direct and quadrature axes. This approach is done because of the conceptual simplicity obtained with only one set of two windings on the stator also this is the method followed in generalized machine modeling. In PMSG, the rotor has no windings, only magnets. The magnets are modeled as a current source or a flux linkage source, concentrating all its flux linkages along only one axis. The flux linkages of the stator q and d windings are derived from first principles. The physical modeling of the machine is developed from which the circuit model is derived. Constant inductance for windings is obtained by a transformation to the rotor by replacing the stator windings with a fictitious set of d-q windings rotating at the electrical speed of the rotor. The equivalence between the three-phase machine and its model using a set of two-phase windings is derived and this approach is suitable for extending it to model an n-phase machine where n is greater than 2, with a two-phase machine. The transformation from the two-phase to the three-phase variables of voltages, currents, or flux linkages is derived in a generalized way. The transformation from abc frame to d-q frame is called Parks transformation. Derivations for electromagnetic torque involving the currents and flux linkages are obtained by using general equations. The differential equations describing the PMSG are nonlinear.

$$V_{ds} = \frac{r_d i_{ds} + P \lambda_{ds} - \omega_d \lambda_{qs}}{3}$$  \hspace{1cm} (1)

$$V_{qs} = \frac{r_q i_{qs} + P \lambda_{qs} - \omega_q \lambda_{ds}}{3}$$ \hspace{1cm} (2)

Where, \(P\) is the differential operator, \(V_{qs}\) and \(V_{ds}\) are the voltages in the q and d axes windings, \(i_{qs}\) and \(i_{ds}\) are the q- and d-axes stator currents, \(R_q\) and \(R_d\) are the q- and d-axes stator resistances, \(\lambda_{qs}\) and \(\lambda_{ds}\) are the stator q- and d-axes flux linkages.

For modeling, a PMSG machine, parks transformation should be done. The basic principle of parks transformation is, the mmf of three phase and two phase can be rendered equal in magnitude by making anyone of the following changes.

i) By changing magnitude of the two phase currents.

ii) By changing number of turns of the two phase windings.

iii) By changing both magnitude of currents and number of turns.

The parks transformation used for PMSG modeling is:

$$V_{ds} = \frac{V_a - \frac{V_b}{2} - \frac{V_c}{2}}{3} \sqrt{2}$$ \hspace{1cm} (3)

$$V_{qs} = \frac{\sqrt{3}V_b}{2} - \frac{3\frac{V_c}{2}}{3} \sqrt{2}$$ \hspace{1cm} (4)

Fig. 2. shows the parks transformation block.

Fig. 1. A two phase PMSG

The windings are displaced in space by 90 electrical degrees and the rotor windings placed at an angle \(\theta_0\) from the stator d-axis winding. It is assumed that the q-axis leads the d-axis to a anti-clockwise direction of rotation of the rotor. A pair of poles is assumed in this figure, but it is applicable for any number of pairs of poles with slight modification. Note that \(\theta_0\) is the electrical rotor position and not the mechanical rotor position. The \(d\)- and \(q\)-axes stator voltages are derived as the sum of the resistive voltage drops and the derivative of the flux linkages in the respective windings as:

$$V_{ds} = \frac{r_d i_{ds} + P \lambda_{ds} - \omega_d \lambda_{qs}}{3}$$  \hspace{1cm} (1)

$$V_{qs} = \frac{r_q i_{qs} + P \lambda_{qs} - \omega_q \lambda_{ds}}{3}$$ \hspace{1cm} (2)

And the PMSG machine is modeled as PMSM, then by providing a negative torque it acts as PMSG. In wind integrated system, when PMSM is connected to wind turbine it normally acts as a PMSG due to the torque provided by the wind turbine. The following equations are flux equations used in the modeling.
The flux equation block in modeling is shown in fig.3.

\[
P \lambda_d = V_d - i_d r_s + \omega_r \lambda_{qs} \quad (5)
\]

\[
P \lambda_q = V_q - i_q r_s + \omega_r \lambda_{ds} \quad (6)
\]

The flux equation block in modeling is shown in fig.3.

Next portion to model is the electrical subsystem. For that, the relation between flux linkages and current is used, and the equations are as shown below\(^4\),

\[
L_d i_d = \lambda_d - \lambda_{af} \quad (7)
\]

\[
i_q = \frac{\lambda_q}{L_q} \quad (8)
\]

The electrical subsystem is shown in fig.4.

Next portion is the mechanical part. Here the numbers of phases, poles, inertia constant, frictional factor are coming into picture. The PMSG is three phase machine and it is designed to have four poles. (ie, two pole pairs). The equation for electromagnetic torque is\(^4\),

\[
3(\lambda_d i_q - \lambda_q i_d) = T_e \quad (9)
\]

And the following figure shows the mechanical part in the modeling.

The following table shows the parameter used in the modeling of PMSG machine.

<table>
<thead>
<tr>
<th>TABLE 1</th>
<th>Rating of PMSG</th>
</tr>
</thead>
<tbody>
<tr>
<td>Power generated</td>
<td>1.5 MW</td>
</tr>
<tr>
<td>Rated speed</td>
<td>1500 rpm</td>
</tr>
<tr>
<td>Stator resistance</td>
<td>1.25 Ω</td>
</tr>
<tr>
<td>d axis inductance</td>
<td>0.00225 H</td>
</tr>
<tr>
<td>q axis inductance</td>
<td>0.006 H</td>
</tr>
<tr>
<td>Stator leakage inductance</td>
<td>0.0334 H</td>
</tr>
<tr>
<td>Permanent magnet flux</td>
<td>0.4832 Wb</td>
</tr>
<tr>
<td>No. of pole pair</td>
<td>2</td>
</tr>
</tbody>
</table>

Fig. 6 shows the wind integrated system having PMSG and the load is designed as 1 MW.
Fig. 7. Output of the PMSG machine

Fig. 8. Electromagnetic torque of the PMSG machine

The above two figures (fig.7 and fig.8) shows the output voltage of PMSG having voltage range of 240 V and electromagnetic torque in range of 100 Nm.

Fig. 9. Rotor speed of the PMSG

The rpm of the designed PMSG is 1500rpm.

Fig.10. shows the output torque of wind turbine used in this model. This torque is given to the PMSG machine as input and this torque is expressed as in pu. Also, this torque is varied according to the available wind power. Wind power is varied using a timer block. The output and time duration of outputs can be changeable according to the timer block settings.

IV. CONCLUSION

Modeling of PMSG is machine is done in MATLAB SIMULINK and is presented. PMSG Machine model is developed by using generalized machine equations (for synchronous machines having permanent magnets) and converted it into two phase machine by means of variable transformations which included in several blocks in modeling. The PMSG machine based wind integrated system modeling is also presented.

V. REFERENCES


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