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Electrical Engineering

Elixir Elec. Engg. 115 (2018) 49690-49693

ISSN: 2229-712X

Analysis and Performance Simulation of Permanent Magnet Generator

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ARTICLE INFO

Article history:
Received: 14 December 2017;
Received in revised form:
25 January 2018;
Accepted: 2 February 2018;

Keywords
Permanent
Magnet,
Performance,
Loading,
Transient.

ABSTRACT

The ever increasing growth in the market of PM machines has necessitated the need for a careful simulation of the performance of the very important tools capable of taking electrical study to a higher level. Simulations have helped the process of developing new systems by reducing cost and time. Simulation tools have the capabilities of performing dynamic simulations of electric machines in a graphic environment so as to ease the development of new systems. This paper investigates the performance of permanent magnet generator, with the aid of MATLAB/SIMULINK®; a powerful software mathematical tool, for high performance numerical computation. A 230V, 4hp, 2-Pole permanent magnet generator is simulated. The permanent magnets are conspicuously embedded in its rotor. The objective of the paper is to explore the response of the torque components during various operating conditions. Simulation results showed that damper resistances and rotor inertia constant affect the start-up transients of the permanent magnet generator. That is, when the damper resistance and rotor inertia constant were increased there was an increase in the start-up transients. Equally, the responses to step changes in mechanical loading were also observed.

1.0 INTRODUCTION

It will be of great interest to model a permanent magnet synchronous generator of optimum rotor and stator configuration to achieve a high efficient machine. According to Leijon (2007), there are various advantages of using permanent magnet (PM) direct drive generator for extracting energy from tidal and marine currents. As stated in Spooner (1992), 'TORUS' is a "compact electrical machine particularly suitable for use as an engine-driven generator and which, when supplied via suitable switching circuits, can operate as a brushless DC motor to start the engine". The use of Neodymium Iron-Boron permanent magnets gives good efficiency and small overall size and weight. Initially, 'TORUS' was developed for use as a portable generator, as it provides low voltage DC output. For portable generating equipment lightness and compactness are of immense importance. High efficiency is also crucial, since it influences the quantity of fuel which must be carried.

The two main types of generators are geared generators and direct-driven generators. In Polinder (2006) the main aspects of generator design are highlighted with a comparison of five concepts of geared and direct-driven generators in wind turbine application. The concepts introduced are the doubly-fed induction generator with a three-stage gearbox (DFIG3G), the direct-drive synchronous generator with electrical excitation (DDSG), the direct-drive permanent-magnet generator (DDPMG), the permanent magnet generator with a single stage gearbox (PMGIG) and the double-fed induction generator with a single-stage gearbox (DFIGIG).

In Pellegrino (2003), it is concluded that the most promising permanent magnet machine field deals with direct-driven applications. The benefits of a direct-driven machine are influenced by the elimination of the gear. As a consequence, the problems associated with the efficiency, oil maintenance and pollution, and positioning precision can be alleviated. In Che Mong (1998), a line start interior permanent magnet motor was well studied and several good characteristics were outlined. In this work, the effects of changes in damper resistances and rotor inertia constant on the start-up transient of permanent magnet generator with permanent magnets embedded on the rotor are observed. The response of the generator to changes in mechanical loading is also observed. To achieve these, an equivalent circuit of the generator is first presented. Then mathematical model is derived from this circuit and thereafter this model is simulated using MATLAB/SIMULINK.

2.0 MATERIALS AND METHODS

The dc excitation of the field winding in a synchronous machine can be provided by permanent magnets. One obvious change with replacing the electrical excitation with a permanent magnet is the elimination of copper losses Rahman (1984). Machines so excited can offer simpler construction, low weight and size for the same performance, with reduced losses, and thus higher efficiency. The disadvantages are the price of permanent magnet materials (except for ferrites) that are relatively high, and that magnet characteristics change with time.

The interior arrangement of permanent magnets is used in this work. This is because Lq>Ld, as will be seen from the simulation results. Note that electromagnetic torque becomes negative given above condition. There is also high saliency in this arrangement, and it can be used for high speed operation. High speed permanent magnet PM machines according to Co Huynh et al (2009) are typically used in micro turbine application due to their high power density and high efficiency characteristics. A good understanding of high speed PM machine characteristics, especially its losses, is

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critical to predict system performance and to ensure a reliable operation. Losses in PM machines just like in most electrical machines as reported in Oti et al (2014) and in Daut et al (2009) include but not limited to these three categories: (i) stator loss, (ii) rotor eddy current loss, and (iii) windage loss. The stator loss consists of copper loss and iron loss. The copper loss includes conventional I^2R loss and stray load loss due to skin effect and proximity effect. However, the magnets described here are well protected from centrifugal forces. A circuit diagram representation for a model of the permanent magnet generator is shown below:

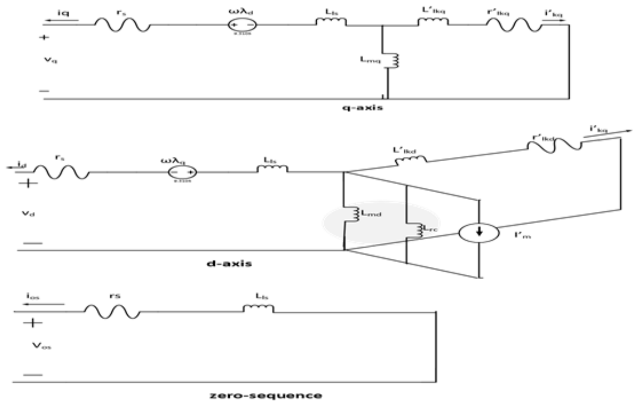

Figure 1. Equivalent qd0 circuit of a permanent magnet generator.

It has damper cage windings but no field winding. The permanent magnet inductance, L_{rc}, that is associated with its recoil slope, can be lumped with the common d – axis mutual inductance of the stator and damper windings and the combined d – axis mutual inductance denoted by L_{md}. The current I'_m is the equivalent magnetizing current of the permanent magnets, referred to the stator side. The equations derived from the circuit above are given below:

$$v_q = -r_s i_q + \frac{d\lambda_q}{dt} + \lambda_d \frac{d\theta_r}{dt} \quad (1)$$

$$v_d = -r_s i_d + \frac{d\lambda_d}{dt} - \lambda_q \frac{d\theta_r}{dt} \quad (2)$$

$$v_0 = -r_s i_0 + \frac{d\lambda_0}{dt} \quad (3)$$

$$0 = -r'_{kd} i'_{kd} + \frac{d\lambda'_{kd}}{dt} \quad (4)$$

$$0 = -r'_{kq} i'_{kq} + \frac{d\lambda'_{kq}}{dt} \quad (5)$$

The flux linkages are given below:

$$\lambda_q = -(L_q i_q + L_{mq} i'_{kq}) \quad (6)$$

$$\lambda_d = -(L_d i_d + L_{md} i'_{kd} + \underbrace{L_{md} i'_m}_{\lambda'_m}) \quad (7)$$

$$\lambda_0 = -L_{ls} i_0 \quad (8)$$

$$\lambda'_{kq} = -(L_{mq} i_q + L'_{kqkq} i'_{kq}) \quad (9)$$

$$\lambda'_{kd} = -(L_{md} i_d + L'_{kdkd} i'_{kd} + L_{md} i'_m) \quad (10)$$

The equations used to simulate the various blocks in SIMULINK are given below, and they are obtained as per unit values.

Qdo Voltage equations;

$$v_q^s = \frac{2}{3} v_a - \frac{1}{3} v_b - \frac{1}{3} v_c \quad (11)$$

$$v_d^s = \frac{1}{\sqrt{3}} (v_c - v_b) \quad (12)$$

$$v_0 = \frac{1}{3}(v_a + v_b + v_c) \quad (13)$$

$$v_q = v_q^s \cos\theta_r(t) - v_d^s \sin\theta_r(t) \quad (14)$$

$$v_d = v_q^s \sin\theta_r(t) + v_d^s \cos\theta_r(t) \quad (15)$$

Where

$$\theta_r(t) = \int_0^t \omega_r(t)\, dt + \theta_r(0) \quad (16)$$

(0) has a non – zero value.

Flux linkages

$$\psi_q = \omega_b \int \left\{ v_q - \frac{\omega_r}{\omega_b} \psi_d + \frac{r_s}{x_{ls}} \left(\psi_{mq} - \psi_q \right) \right\} dt \quad (17)$$

$$\psi_{mq} = x_{MQ} \left(\frac{\psi_q}{x_{ls}} + \frac{\psi'_{kq}}{x'_{lkq}} \right) \quad (18)$$

$$\psi'_{kq} = \frac{\omega_b r'_{kq}}{x'_{lkq}} \int \left(\psi_{mq} - \psi'_{kq} \right) dt \quad (19)$$

$$\psi_d = \omega_b \int \left\{ v_d + \frac{\omega_r}{\omega_b} \psi_q + \frac{r_s}{x_{ls}} (\psi_{md} - \psi_d) \right\} dt \quad (20)$$

$$\psi_{md} = x_{MD} \left(\frac{\psi_d}{x_{ls}} + I'_m + \frac{\psi'_{kd}}{x'_{lkd}} \right) \quad (21)$$

$$\psi'_{kd} = \frac{\omega_b r'_{kd}}{x'_{lkd}} \int (\psi_{md} - \psi'_{kd}) \quad (22)$$

The initial values of ψ_q, ψ_d, ψ'_{kq} and ψ'_{kd} are given below;

$$\psi_{qo} = \left(x_{ls} - I_{qo} \right) + x_{md}(-I_{do} + I'_m) \quad (23)$$

$$\psi_{do} = (x_{ls} - I_{do}) + x_{md}(-I_{do} + I'_m) \quad (24)$$

$$\psi'_{kq0} = x_{md}(-I_{do} + I'_m) \quad (25)$$

$$\psi'_{kd0} = x_{md}(-I_{do} + I'_m) \quad (26)$$

Electromagnetic Torque;

$$T_{em} = (\psi_d i_q - \psi_q i_d) \quad (27)$$

This is similar to the expression presented in Jixan and Jiani (2014) and can be expanded to,

$$T_{em} = \frac{3}{2}\frac{P}{2}(L_d - L_q) i_d i_q + \frac{3}{2}\frac{P}{2}\left(L_{md} i'_{kd} i_q - L_{mq} i'_{kq} i_d \right) + \frac{3}{2}\frac{P}{2} L_{md} i'_{kd} i_q \quad (28)$$

The above developed electromagnetic torque is separated into three components; a reluctance component, which is negative when Ld<Lq; an induction component which is an asynchronous torque; and an excitation component from the field of the permanent magnet. The equation used to obtain the load angle is given below;

$$\delta(t) = \int \frac{\omega_r(t) - \omega_e(t)}{\omega_b} \omega_b \quad (29)$$

Where

$$\frac{\omega_r(t) - \omega_e(t)}{\omega_b} = \int_0^T \frac{T_{em} + T_{mech} - T_{damp}}{2H} dt \quad (30)$$

H is the rotor inertia constant. Also,

$$Treluctance = (xd - xq) \quad (31)$$

$$T_{excitation} = i_q I'_m x_{md} \quad (32)$$

Winding Currents

As before, the windings currents can be expressed as

$$i_q = -\frac{1}{x_{ls}} \left(\psi_q - \psi_{mq} \right) \quad (33)$$

$$i_d = -\frac{1}{x_{ls}} (\psi_d - \psi_{md}) \quad (34)$$

We convert back to the abc form using the equations below

$$i_q^s = i_q \cos\theta_r(t) + i_d \sin\theta_r(t) \quad (35)$$

$$i_d^s = i_d \cos(t) - i_q \sin(t) \quad (36)$$

$$i_a = i_q^s + i_o \quad (37)$$

$$i_b = -\frac{1}{2} i_q^s - \frac{\sqrt{3}}{2} i_d^s + i_o \qquad (38)$$

$$i_c = -\frac{1}{2} i_q^s + \frac{\sqrt{3}}{2} i_d^s + i_o \qquad (39)$$

Table 1. Values of parameters for simulation.

Parameter	Value (p.u)
Stator leakage reactance	0.065
Leakage reactance of d-axis	0.543
Stator resistance	0.017
Leakage reactance of q-axis	1.086
Damper resistance of d-axis	0.054
Damper resistance of q-axis	0.108
Leakage damper reactance of d-axis	0.132
Leakage damper reactance of q-axis	0.132
Damping coefficient	0.000
Rotor inertia constant	***0.3s***

The machine is a 230V, 4-hp, 50Hz, 2-pole, three-phase machine. The base values used to get the above per unit values are; Z_{base} = 12.11Ω, I_{base} = 10.97A, V_{base} = 230V, S_{base} = 4.37 kVA, T_{base} = 13.91 Nm. Rotor speed = 3000rpm.

3.0 RESULTS

The graphs representing the simulated performance characteristics are shown below.

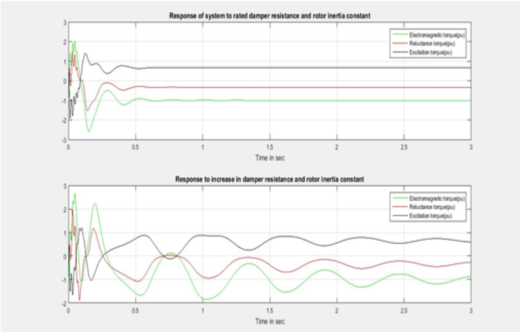

Figure 2. Response to increase in damper resistance and rotor inertia constant.

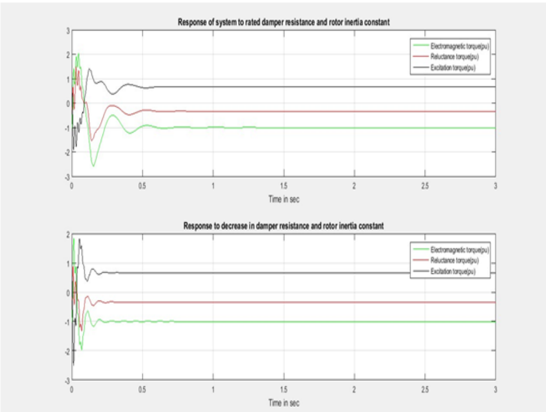

Figure 3. Response to decrease in damper resistance and rotor inertia constant.

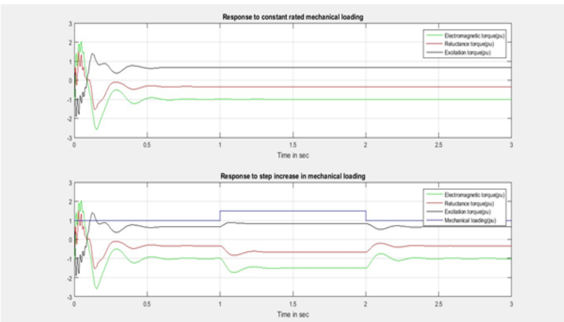

Figure 4. Response to step increase in mechanical loading.

4.0 DISCUSSIONS

The performance of the machine is tested under various start-up and loading conditions. The components of the machine to be examined under various conditions are the various torque components. The effect of some parameters such as the rotor inertia constant and the resistance of the damper windings on the start-up transients are observed. The machine is started from steady state values. This means that the initial conditions of the integrators used are not zero. This is to minimize the simulation start-up transients.

From figure 2, there is increase in start-up transients with increase in damper resistance and rotor inertia constant. The rotor inertia constant was increased by five times its rated value, while the damper resistances were increased 1.5 times its rated value. The system attained steady state at a time greater than 3 seconds.

Figure 3 shows that start-up transients are much reduced when the damper resistances and rotor inertia constants are reduced. While the rotor inertia constant is reduced to 0.1s (since KVA ≅ KW), the damper resistances are reduced by half its rated value. Steady state is achieved at a time less than 0.5s.

Figure 4 shows the response of the system to step increase in mechanical loading. The mechanical torque, which is synonymous with the load demand on the generator, was increased to 1.5 its rated value within a time range of one second. The increase is a step increase. It can be observed that there is an increase in excitation torque at the time of step increase in mechanical load, while electromagnetic and reluctance torques decreased within this time frame.

5.0 CONCLUSIONS

This paper has, objectively examined the effect of damper resistances and rotor inertia constant on the performance of a permanent magnet generator with permanent magnets embedded in the rotor. The result was sequel to careful use of the mathematical model of the system as derived cum the equations got from the model that were used to perform simulations. The damper resistances, rotor inertia constant and the mechanical loading of the system were varied and the results shown. The results obtained showed that increase in damper resistances and rotor inertia constant increases the start-up transients of the machine. Also, step changes in mechanical loading of the machine at 1.5 times above rated value, does not lead to loss of synchronism of the system. The results obtained will be very useful to core industrialists and machine designers.

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