MODELING OF A PERMANENT MAGNET SYNCHRONOUS MACHINE

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ABSTRACT

The permanent magnet synchronous machine (PMSM) is one of top picks for a full range of motion control purposes commonly used in actuators, machine tools, robotics, and is being taken into consideration for high power applications such as industrial drives and vehicle propulsion. It is also utilized in residential/commercial applications even though the PMSM boasts of a very high efficiency and power density, low torque ripple and advanced dynamic performance. This paper presents a mathematical model of synchronous electric machine based on permanent magnets.

Keywords: Permanent magnet, model, synchronous machine

1. Introduction

A synchronous electric motor is an AC motor in which the shaft's rotation is synchronized with the frequency of the supply current at steady state and the rotation length is exactly the same as the integral number of AC cycles. The most commonly used types of AC motors are synchronous motor and induction motor.

In both induction and synchronous machines, rotating magnetic field is produced by AC currents in the three-phase windings of the stator. The stator magnetic circuits and windings of induction and synchronous machines are the same to a great extent. In both cases, the three-phase system of stator currents produces revolving magnetomotive force and rotating field of magnetic inductance. The field revolves at the speed which is established by the angular frequency of the stator currents[1].

The distinction between the two is that in order to generate the magnetic field of the rotor, the synchronous motor rotates at a rate locked to the line frequency because it does not depend on current induction. By comparison, the induction motor needs a slip: to induce current in the rotor winding, the rotor must spin slightly slower than the alternating ACs. In simpler terms, permanent magnet synchronous electric motors in comparison with other electric motors have the best performance with respect to power/volume, torque/inertia, etc. Permanent magnet synchronous motor (PMSM) uses permanent magnets implanted in the steel rotor to generate a constant magnetic field. The stator holds windings connected to an AC supply to create a rotating magnetic field. The rotor poles lock to the rotating magnetic field at synchronous speed[2]. Permanent magnet synchronous motors are similar to brushless DC motors. Neodymium magnets are the most frequently used magnets in these motors. A synchronous generator PMSM with permanent magnets happens to be a key component of Electric power supply (EPS) system which is a primary power source for modern aircrafts conforming with the trend of the more electric aircraft (MEA), both civilian (Airbus, Boeing), as well as the military[3]. Other applications include a synchronous condenser, stepper motors, positioning machines, robot actuators and so on.

2. Construction and Types of PMSM

A permanent magnet synchronous motor comprises of a rotor and a stator. The stator is the stationary part. The rotor is the revolving part and is usually situated inside the stator of the electric motor, and there are also constructions with an external rotor (inside out electric motors). Synchronous machines have stator with three-phase windings and rotor with either excitation winding or with permanent magnets. The stator terminals are connected to a three-phase voltages and currents symmetrical system. The stator currents produce rotating magnetic field in the air gap of the machine. For correct operation of synchronous machine, the stator field has to rotate at the same speed as the rotor and an electromagnetic torque is created from interaction of the two magnetic fields[1].

The rotor consists of permanent magnets. Materials with high coercive force are used as permanent magnets. According to the rotor design, synchronous motors are divided into:

- electric motors with salient pole rotor
- electric motors with non-salient pole rotor.

Also, according to the design of the rotor, the PMSM are divided into:

- surface permanent magnet synchronous motor
- interior permanent magnet synchronous motor.

The stator consists of an outer frame and a core with windings. The most common design with two- and three-phase winding.

Depending on the stator design, a permanent magnet synchronous motor can be:

- with distributed winding
- with concentrated winding

Depending on the direction of field flux, PMSM are classified as follows:

- Radial field
- Axial field

The flux direction is along the radius of the machine in radial field while in axial field, the flux direction is parallel to the rotor shaft. The radial field permanent magnet motors are most frequently used while the axial field permanent magnet motors are used in a range of numerous applications because of their higher power density and quick acceleration[4].

The operating principle of a synchronous motor is centered on the interaction of the revolving magnetic field of the stator and the constant magnetic field of the rotor. The concept of the rotating magnetic field of the stator of a synchronous motor as stated earlier is identical as that of a three-phase induction motor. The magnetic field of the rotor, interacting with the synchronous AC current of the stator windings creates torque forcing the rotor to revolve. The permanent magnets positioned on the rotor of the PMSM create a constant magnetic field. At a synchronous speed of rotation of the rotor with the stator field, the rotor poles interlock with the rotating magnetic field of the stator and in this regard, the PMSM cannot start off when connected directly to the three-phase current network[5].

3. Modeling of PMSM

The motor axis has been established using d-q rotor reference frame theory such that at any particular time t, the rotor reference axis is making an angle θr with the fixed stator axis and the rotating stator magnetomotive force creates an angle α with the rotor d axis. It is observed that at any time t, the stator mmf revolves at the same speed as that of the rotor axis[4].

According to [4], the following assumptions are acquired for the modeling of the PMSM without damper windings.

- Saturation is neglected.
- Induced EMF is sinusoidal in nature.
- Hysteresis losses and Eddy current losses are negligible.
- No field current dynamics.

Voltage equations are given by:

$$v_q = R_s i_q + \omega_r \lambda_d + \rho \lambda_q \tag{1}$$

$$v_d = R_s i_d - \omega_r \lambda_q + \rho \lambda_d \tag{2}$$

Flux linkages are given by:

$$\lambda_q = L_q i_q \tag{3}$$

$$\lambda_q = L_q i_q + \lambda_f \tag{4}$$

Substitute equations (3) and (4) into equations (1) and (2)

$$v_q = R_s i_q + \omega_r (L_d i_d + \lambda_f) + \rho L_d i_d \tag{5}$$

$$v_d = R_s i_d - \omega_r L_q i_q + \rho (L_d i_d + \lambda_f) \tag{6}$$

Arrange equations (5) and (6) in Matrix form

$$\begin{pmatrix} v_q \\ v_d \end{pmatrix} = \begin{pmatrix} R_s + \rho L_q & \omega_r L_d \\ -\omega_r L_q & R_s + \rho L_d \end{pmatrix} \begin{pmatrix} i_q \\ i_d \end{pmatrix} + \begin{pmatrix} \omega_r \lambda_f \\ \rho \lambda_f \end{pmatrix} \tag{7}$$

The developed torque motor is given by:

$$T_e = \frac{3}{2}\left(\frac{\rho}{2}\right)\left(\lambda_d i_q - \lambda_q i_d\right) \tag{8}$$

The mechanical torque equation is given by:

$$T_e = T_L + B\omega_m + J\,\frac{d\omega_m}{dt} \tag{9}$$

Obtaining rotor mechanical speed ω_m from equation (9) by making it subject of formula:

$$\omega_m = \int\left(\frac{T_e - T_L - B\omega_m}{J}\right)dt \tag{10}$$

Also,

$$\omega_m = \omega_r\left(\frac{2}{p}\right) \tag{11}$$

Where:

ω_r is Rotor electrical speed

ω_m is Rotor mechanical speed

p = Number of poles

J = Rotating inertia of motor

B = damping coefficient

TL = Loading torque

L_d and L_q stand for the equivalent inductances in dq coordinates

The dynamic d-q modelling of the system is achieved by converting the three phase voltages and currents to dqo axis variables by using the Parks transformation. This conversion of phase voltages variables V_{abc} to V_{dqo} variables in rotor reference frame axis are shown below:

$$\begin{bmatrix} v_q \\ v_d \\ v_o \end{bmatrix} = \frac{2}{3} \begin{bmatrix} \cos\theta_r & \cos(\theta_r - 120) & \cos(\theta_r + 120) \\ \sin\theta_r & \sin(\theta_r - 120) & \sin(\theta_r + 120) \\ 1/2 & 1/2 & 1/2 \end{bmatrix} \begin{bmatrix} v_a \\ v_b \\ v_c \end{bmatrix} \tag{12}$$

4. Conclusion

The paper presents a study on permanent magnet synchronous machine stating the construction, types and mode of operation of a synchronous motor as well as the mathematical modeling which could very well be used for the simulation using Simulink.

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