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ABSTRACT

The permanent-magnet synchronous machine (PMSM) drive is one of best choices for a full range of motion control applications. For example, the PMSM is widely used in robotics, machine tools, actuators, and it is being considered in high-power applications such as industrial drives and vehicular propulsion. It is also used for residential/commercial applications. The PMSM is known for having low torque ripple, superior dynamic performance, high efficiency and high power density.

This paper talks about the assumptions in permanent-magnet synchronous machine (PMSM) for modeling of permanent-magnet synchronous machine (PMSM) and it derives the equivalent circuit of permanent-magnet synchronous machine (PMSM).

INTRODUCTION

Electric motors are electromechanical machines, which are used for the conversion of electrical energy into mechanical energy. The foremost categories of AC motors are asynchronous and synchronous motors.

One of the types of synchronous motor is the PMSM. The PMSM consists of conventional three phase windings in the stator and permanent magnets in the rotor. The purpose of the field windings in the conventional synchronous machine is done by permanent magnets in PMSM. The conventional synchronous machine requires AC and DC supply, whereas the PMSM requires only AC supply for its operation. One of the greatest advantages of PMSM over its counterpart is the removal of dc supply for field excitation.

Types of PMSM

The PMSM are classified based on the direction of field flux are as follows;

1. Radial field
2. Axial field

Radial field: the flux direction is along the radius of the machine. The radial field permanent magnet motors are the most commonly used.

Axial field: the flux direction is parallel to the rotor shaft. The axial field permanent magnet motors are presently used in a variety of numerous applications because of their higher power density and quick acceleration.

METHODOLOGY

The motor axis has been developed using d-q rotor reference frame theory as shown in Figure 1. At any particular time, t, the rotor reference axis makes an angle θr with the fixed stator axis and the rotating stator mmf creates an angle α with the rotor d axis. It is viewed that at any time t, the stator mmf rotates at the same speed as that of the rotor axis.

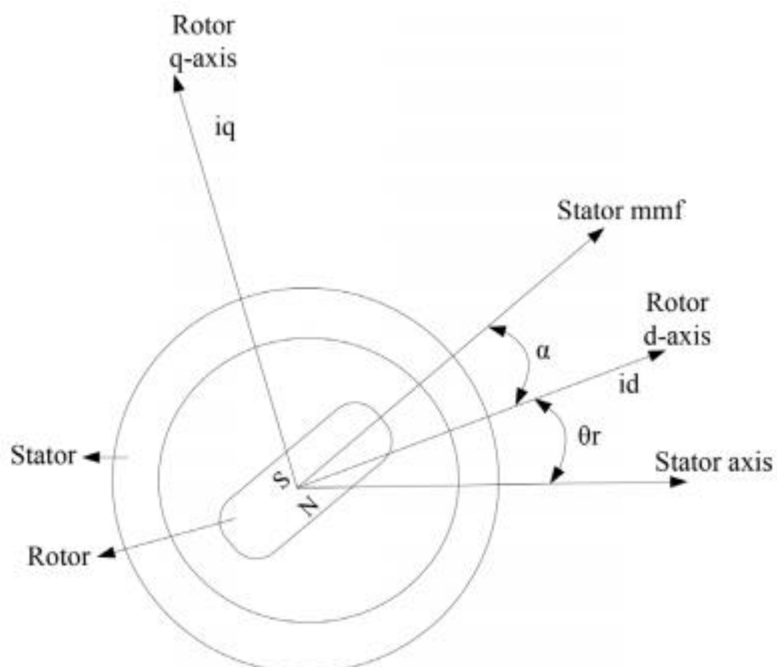

Figure 1: motor axis

The following assumptions are made so that the PMSM can be modelled without damper windings;

1. Saturation is neglected.
2. Induced EMF is sinusoidal in nature.
3. Hysteresis losses and eddy current losses are negligible.

4. No field current dynamics is present.

Mathematical equations for the model

Voltage equations for the model are given by

$$V_q = R_s i_q + \omega_r \lambda_d + \rho \lambda_q \text{ .... (1)}$$

$$V_d = R_s i_d - \omega_r \lambda_q + \rho \lambda_d \text{ .... (2)}$$

Flux linkages are given by,

$$\lambda_q = L_q i_q \text{ .... (3)}$$

$$\lambda_d = L_d i_d + \lambda_f \text{..............................(4)}$$

Substituting Eq. (3) and Eq. (4) into Eq. (1) and Eq. (2)

$$V_q = R_s i_q + \omega_r (L_d i_d + \lambda_f) + \rho (L_q i_q) \text{ .... (5)}$$

$$V_d = R_s i_d - \omega_r (L_q i_q) + \rho (L_d i_d + \lambda_f) \text{ .... (6)}$$

Arranging Eq. (5) and Eq. (6) in matrix form

$$\begin{pmatrix} V_q \\ V_d \end{pmatrix} = \begin{pmatrix} R_s + \rho L_q & \omega_r L_d \\ -\omega_r L_q & R_s + \rho L_d \end{pmatrix} \begin{pmatrix} i_q \\ i_d \end{pmatrix} + \begin{pmatrix} \omega_r \lambda_f \\ \rho \lambda_f \end{pmatrix} \text{ .... (7)}$$

The developed torque motor is being given by

$$T_e = \frac{3}{2} \left(\frac{P}{2}\right) (\lambda_d i_q - \lambda_q i_d) \text{.................................... (8)}$$

The mechanical torque equation is

$$T_e = T_L + B\omega_m + J \frac{d\omega_m}{dt} \text{.. (9)}$$

Solving for the rotor mechanical speed form Eq. (9)

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

And

$$\omega_m = \omega_r \left(\frac{2}{P}\right) \text{ .... (11)}$$

In the above equations ω_r is the rotor electrical speed, ω_m is the rotor mechanical speed.

Parks transformation and dynamic d-q modeling

The dynamic d-q modelling of the system is used for the study of motor during transient state and as well as in the steady state conditions. It is achieved by converting the three phase voltages and currents to dqo axis variables by using the

Parks transformation. Converting the phase voltages variables Vabc to Vdqo variables in rotor reference frame axis are illustrated in the equations.

$$\begin{bmatrix} V_q \\ V_d \\ V_o \end{bmatrix} = \frac{2}{3}\begin{bmatrix} \cos\theta_r & \cos(\theta_r - 120) & \cos(\theta_r + 120) \\ \sin\theta_r & \sin(\theta_r - 120) & \sin(\theta_r + 120) \\ 1/2 & 1/2 & 1/2 \end{bmatrix}\begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix} \quad \text{.................... (12)}$$

Convert Vdqo to Vabc

$$\begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix} = \frac{2}{3}\begin{bmatrix} \cos\theta_r & \sin\theta_r & 1 \\ \cos(\theta_r - 120) & \sin(\theta_r - 120) & 1 \\ \cos(\theta_r + 120) & \sin(\theta_r + 120) & 1 \end{bmatrix}\begin{bmatrix} V_q \\ V_d \\ V_o \end{bmatrix} \quad \text{............................ (13)}$$

Equivalent circuit of PMSM

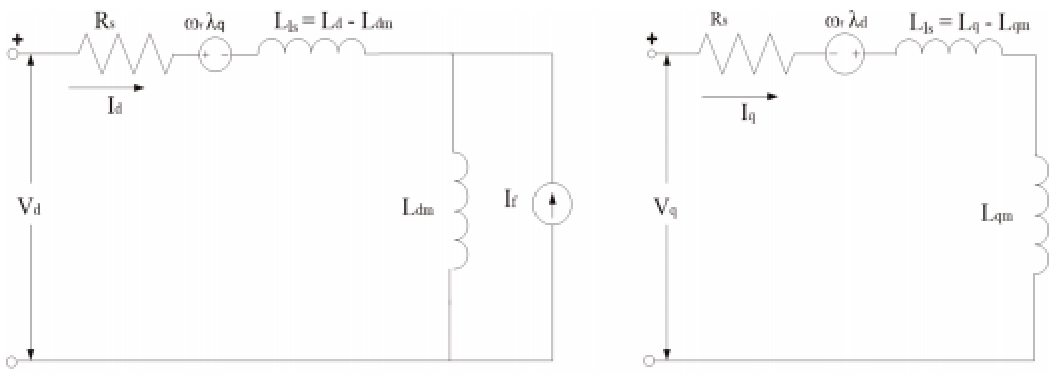

Figure 2: Equivalent circuit of PMSM without damper windings

$$\lambda_f = L_{dm} I_f \quad \text{...................................... (14)}$$

Nomenclature

i_d d-axis current

L_{dm} d-axis magnetizing inductance

L_d d-axis self-inductance

V_d d-axis voltage

ρ derivative operator

T_e develop electromagnetic torque

d direct or polar axis

ω_r electrical speed

i_f equivalent permanent magnet field current

L_s equivalent self-inductance per phase

λ_d flux linkage due d axis

λ_q flux linkage due q axis

λ_{dm} flux linkage due to rotor magnets linking the stator

B friction

J inertia

k_i integral control gain

T_L load torque

ω_{rated} motor rated speed

T_m motor torque

P number of poles

I_m peak value of supply current

λ_f PM flux linkage or field flux linkage

k_p proportional control gain

i_q q-axis current

L_{qm} q-axis magnetizing inductance

L_q q-axis self-inductance

V_q q-axis voltage

q quadrature or interpolar axis

θ_r rotor position

ω_m rotor speed

L self-inductance

L_{ls} stator leakage inductance

R_s stator resistance

i_a, i_b, i_c three phase currents

V_a, V_b, V_c three phase voltage

CONCLUSION

We have been able to model a permanent-magnet synchronous machine (PMSM) using the using d-q rotor reference frame theory, equations to show how the permanent-magnet synchronous machine (PMSM) works.