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MATRIC NUMBER : 15/ENG04/032

COURSE TITLE : INTRODUCTION TO NON-LINEAR SYSTEMS

COURSE CODE : EEE 566

QUESTION

Model the operation of a permanent magnet synchronous Machine.

Solution

What is a permanent magnet synchronous machine?

The Permanent-magnet synchronous machine (PMSM) drive is one of the 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 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.

MODELLING OF PMSM

For Proper simulation and analysis of the system, a complete modelling of the drive model is essential. The motor axis has been developed using d-q rotor reference frame theory as shown in the figure 1 below. At any Particular time t, the rotor reference axis makes an angle θ_r with the fixed stator axis and the rotating stator mmf ~~rotates at the same speed as that~~ creates an angle α with the rotor d axis. It is viewed at any time t, the stator mmf rotates at the same speed as that of the rotor axis.

The required assumptions are obtained for the modelling of the PMSM without damping windings.

1. saturation is neglected

2. Induced EMF is sinusoidal in nature

3. Hysterisis losses and Eddy current losses are negligible.

4. No field current dynamics.

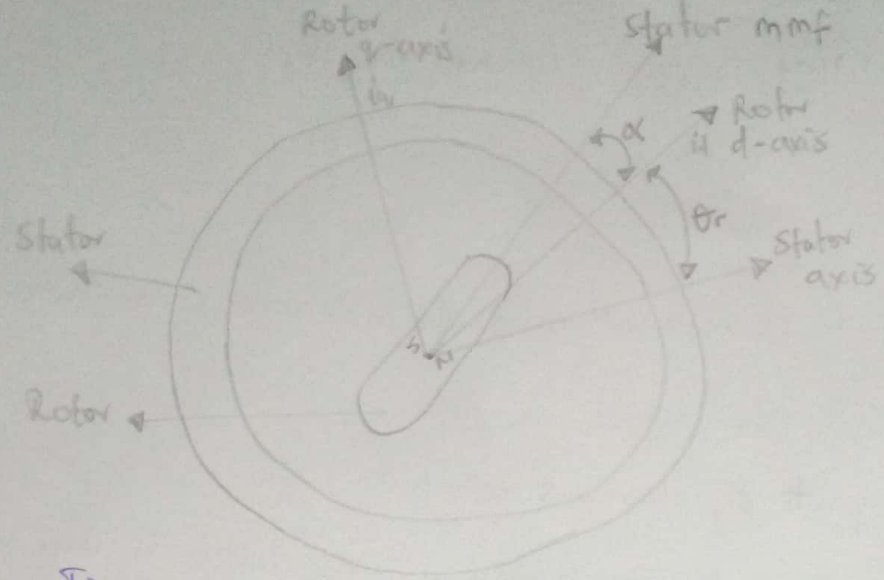

Figure 1: Motor axis

Voltage equations from the model are given by;

$$V_q = R_s i_q + W_r \lambda_d + P\lambda_q \quad \text{------} (1)$$

$$V_d = R_s i_d - W_r \lambda_q + P\lambda_d \quad \text{----} (2)$$

Flux linkages are given by;

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

$$\lambda_q = L_q i_q + \lambda_f \quad \text{---} (4)$$

substituting equation (3) and (4) into eqn (1) and (2)

$$V_q = R_s i_q + W_r (L_d i_d + \lambda_f) + P L_d i_d \quad \text{---} (5)$$

$$V_d = R_s i_d - W_r L_q i_q + P (L_d i_d + \lambda_f) \quad \text{---} (6)$$

Arranging equation (5) and (6) in matrix form,

$$\begin{pmatrix} V_q \\ V_d \end{pmatrix} = \begin{pmatrix} R_s + PL_q & W_r L_d \\ -W_r L_q & R_s + PL_d \end{pmatrix} \begin{pmatrix} i_q \\ i_d \end{pmatrix} + \begin{pmatrix} W_r \lambda_f \\ P\lambda_f \end{pmatrix} \quad \text{---} (7)$$

The developed torque motor is being given by,

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

The mechanical equation is,

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

Solving for the rotor mechanical speed from eqn (9)

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

and

$$\omega_m = \omega_r\left(2/P\right) \quad \text{----} (11)$$

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

Parks transformation and dynamic d-q modelling

The dynamic d-q modelling of the system is used for the study of motor during transient state 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 V_{abc} to V_{dqo} variables in rotor reference frame axes are illustrated in the equations.

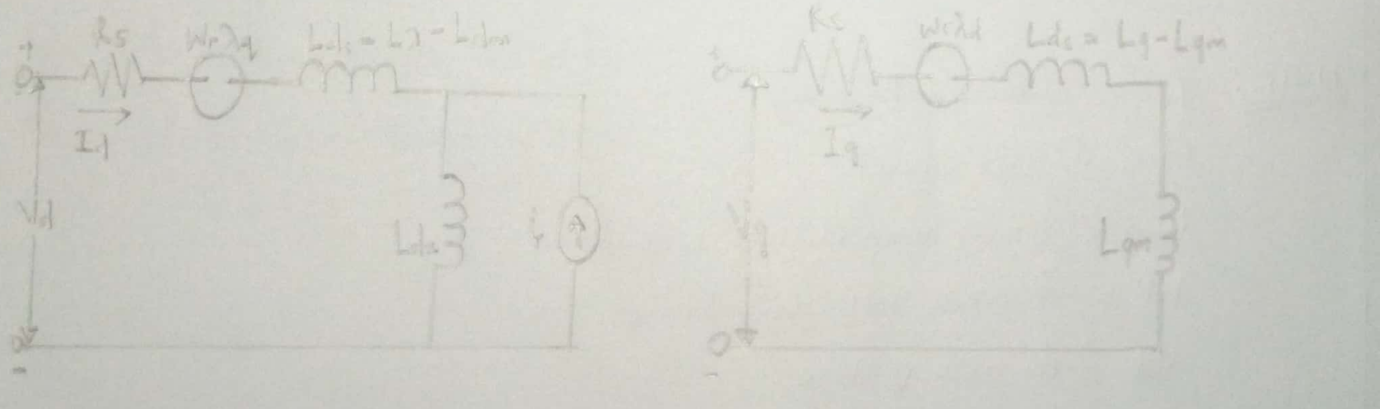

Figure 2: Equivalent circuit of PMSM without damper windings.

$$\begin{bmatrix} V_q \\ V_d \\ V_0 \end{bmatrix} = \frac{2}{3}\begin{bmatrix} \cos\theta_r & \cos(\theta_r - 120) & \cos(\theta_r + 120) \\ \sin\theta_r & \sin(\theta_r - 120) & \sin(\theta_r + 120) \\ 1/2 & 1/2 & 1/2 \end{bmatrix}\begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix} \quad \text{---} (12)$$

Convert V_{dqo} to V_{abc}

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

Equivalent Circuit of PMSM

Equivalent circuit is essential for the proper simulation and designing of the motor. It is achieved and derived from the d-q modelling of the motor using the voltage equations of the stator. From the assumption, rotor d axis flux is represented by a constant current source which is described through the following equation,

$$\lambda_f = L_{dm}\, i_f \quad \text{---- (14)}$$

where λ_f, Field flux linkage; L_{dm}, d-axis magnetizing inductance; i_f, equivalent permanent magnet field current.

Figure 2 shows the equivalent circuit of PMSM without damper windings.

NOTE: f_c = crossover frequency

i_d = d-axis current

L_{dm} = d-axis magnetising inductance

L_d = d-axis self-inductance

V_d = d-axis voltage

p = derivative operator

T_e = develop electromagnetic torque

d = direct or polar axis

w_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.

T_L = Load torque

B = friction

J = Inertia

P = Poles amount [number of poles]

λ_f = PM flux linkage or field flux linkage

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

T_{ref} = reference motor torque

θ_r = rotor position

W_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