



Modeling of Salient Pole Synchronous Machine

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Abstract- This paper proposes the modeling of salient pole synchronous machine. Synchronous machines are ac machines that have a field circuit supplied by an external dc source. Salient pole synchronous machine have salient pole or projecting poles with concentrated field windings. The rotor of salient pole synchronous machine is driven by external means producing a rotating magnetic field, which induces a three phase voltage within the stator winding. When the modulated stator current with higher frequency component would establish induced voltages in the rotor, it could be used for supplying power to rotating load. Simulation model of synchronous machine using Matlab is given.

NOMENCLATURE

i_a	Phase a, stator current A.
i_{ds}, i_{qs}	d,q axis stator current A.
r_s	Stator resistance Ω .
v_{ds}, v_{qs}	d,q axis stator voltage V.
v_f	Load voltage V.
λ_f	Rotor flux Wb.
$\lambda_{ds}, \lambda_{qs}$	d,q axis stator flux Wb.
L_{lf}	Rotor leakage inductance H.
L_{ls}	Stator leakage inductance H.
L_{md}, L_{mq}	d,q axis magnetizing inductance H.
R_f	Rotor resistance referred to stator Ω .
R_l	Load resistance Ω .
V_f	Load voltage referred to stator V.
θ_r	Rotor position rad.
P	Number of poles.

I. INTRODUCTION

A synchronous machine is an ac rotating machine whose speed under steady state condition is proportional to the frequency of the current in its armature. The magnetic

field created by the armature currents rotates at the same speed as that created by the field current on the rotor, which is rotating at the synchronous speed. Synchronous machines are used in many industrial applications due to their high power ratings and constant speed operation. The electrical and electromechanical behavior of most synchronous machines can be predicted from the equations that describe the three phase salient pole synchronous machine. These equations can be used directly to predict the performance of hydro and steam turbine synchronous generators and synchronous motors. The rotor of synchronous machine is equipped with field winding and one or more damper winding, which is magnetically unsymmetrical. Salient pole synchronous machines (SPSM) have salient pole or projecting poles with concentrated field windings. In synchronous motors, damper windings act as rotor bars and help in self starting of the motor. Salient pole synchronous machine is used to provide independent control of mechanical torque and deliver electric power. It provides mechanical torque to the rotating assembly and transmits electric power across an air gap to electric equipment mounted on the rotating assembly. The rotor is then driven by external means producing a rotating magnetic field, which induces a three phase voltage within the stator winding. Slip power recovery systems can provide both the mechanical and electrical power transmission, but these are coupled and not independently controllable. Contactless power delivery systems have been developed, but they either do not provide mechanical torque or the two energy forms are coupled. SPSM provides combination of machine action and transformer action. Transformer action relies on a change in flux vector.

The variation in the machine flux can then provide transformation of energy across air gap. In this paper, modeling of salient pole synchronous machine is proposed using Park's Transformation. Initially, stationary variables are converted into dq reference frame and in Park's Transformation. dq reference frame is converted into rotor reference frame.

II. MODELING OF SYNCHRONOUS MACHINE

The machine is modeled in rotor reference frame (or) Park's Transformation. The dq model eliminates time varying coefficients dependent on rotor position. The model considers direct and quadrature stator windings as shown in Fig. 1.

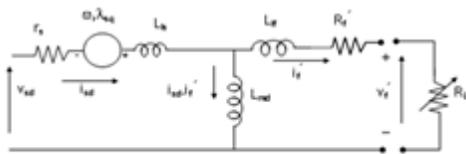
As synchronous machine is generally operated as generator, it is convenient to assume that the direction of positive stator current is out of the terminals. The voltage equations of stator and rotor are written as,

$$V_{abc} = -r_s i_{abc} + p \lambda_{abc} \quad (1)$$

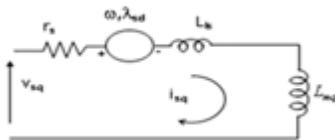
$$V_f = r_f i_f + p \lambda_f \quad (2)$$

The flux linkage equations is expressed as,

$$\begin{bmatrix} \lambda_{abc} \\ \lambda_{qdr} \end{bmatrix} = \begin{bmatrix} L_s & L_{sr} \\ (L_{sr})^T & L_r \end{bmatrix} \begin{bmatrix} -i_{abc} \\ i_{qdr} \end{bmatrix} \quad (3)$$



(a)



(b)

Fig. 1. Equivalent circuit for machine with unexcited field winding. (a) direct axis equivalent circuit.(b) Quadrature axis equivalent circuit.

The voltage equations in arbitrary reference frame is written as,

$$V_{qdos} = -r_s i_{qdos} + \omega \lambda_{qds} + p \lambda_{qdos} \quad (4)$$

III. PARK'S TRANSFORMATION

R.H. Park was the first to incorporate a change of variables in the analysis of synchronous machines. He transformed the stator variables to the rotor reference frame

that eliminates the time varying inductances in the voltage equations.

The rotor windings of synchronous machine are different. Therefore, the change of variables offers no advantage in analysis of rotor circuits. The voltage equations in rotor reference frame is obtained by setting speed of the arbitrary reference frame equal to rotor speed, $\omega = \omega_r$.

$$V_{qdos}^r = -r_s i_{qdos}^r + \omega_r \lambda_{qds}^r + p \lambda_{qdos}^r \quad (5)$$

$$V_{qdr}^r = r_r i_{qdr}^r + p \lambda_{qdr}^r \quad (6)$$

The flux linkage equations are expressed in rotor reference frame by setting $\theta = \theta_r$.

$$\begin{bmatrix} \lambda_{qdos}^r \\ \lambda_{qdr}^r \end{bmatrix} = \begin{bmatrix} k_s^r L_s (k_s^r)^{-1} & k_s^r L_{sr} \\ \frac{2}{3} (L_{sr})^T (k_s^r)^{-1} & L_r \end{bmatrix} \begin{bmatrix} -i_{qdos}^r \\ i_{qdr}^r \end{bmatrix} \quad (7)$$

The transformation from rotor reference frame to arbitrary reference frame is obtained by the following matrix,

$${}^r K = \begin{bmatrix} \cos(\theta - \theta_r) & -\sin(\theta - \theta_r) & 0 \\ \sin(\theta - \theta_r) & \cos(\theta - \theta_r) & 0 \\ 0 & 0 & 1 \end{bmatrix} \quad (8)$$

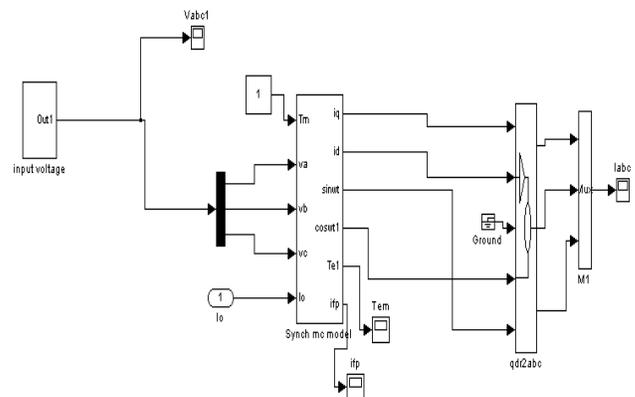


Fig. 2. Simulink diagram of synchronous machine model

Voltage and flux equations transformed from rotor reference frame to arbitrary reference frame are expressed as,

$$\begin{bmatrix} V_{qs} \\ V_{ds} \\ V_f' \end{bmatrix} = \begin{bmatrix} \cos(\theta - \theta_r) - \sin(\theta - \theta_r) & 0 \\ \sin(\theta - \theta_r) & \cos(\theta - \theta_r) & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} V_{qs}^r \\ V_{ds}^r \\ V_f'^r \end{bmatrix} \quad (9)$$

$$\begin{bmatrix} \lambda_{qs} \\ \lambda_{ds} \\ \lambda_f' \end{bmatrix} = \begin{bmatrix} \cos(\theta - \theta_r) - \sin(\theta - \theta_r) & 0 \\ \sin(\theta - \theta_r) & \cos(\theta - \theta_r) & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} \lambda_{qs}^r \\ \lambda_{ds}^r \\ \lambda_f'^r \end{bmatrix}$$

IV. SIMULATION RESULTS

Matlab is used to represent the simulink model of synchronous machine. Fig. 2. represents the simulink diagram of three phase synchronous machine model.

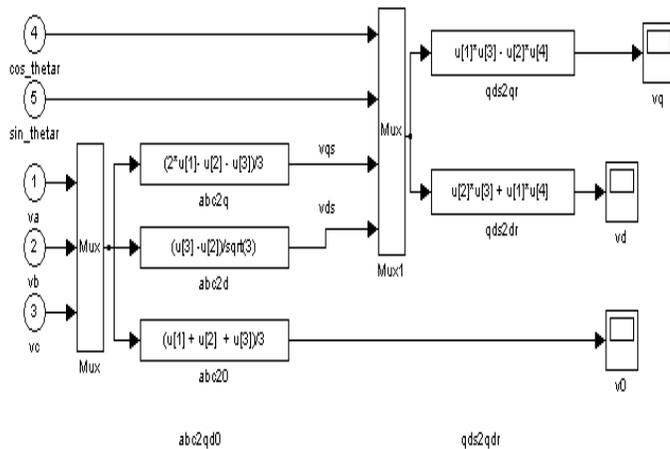


Fig. 3. Electrical sub model for voltage transformation in synchronous machine.

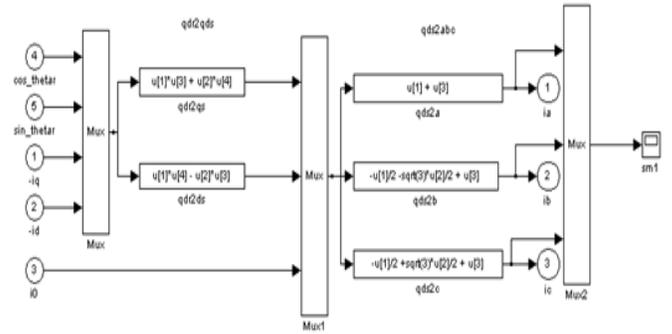


Fig. 4. Electrical sub model for current transformation in synchronous machine.

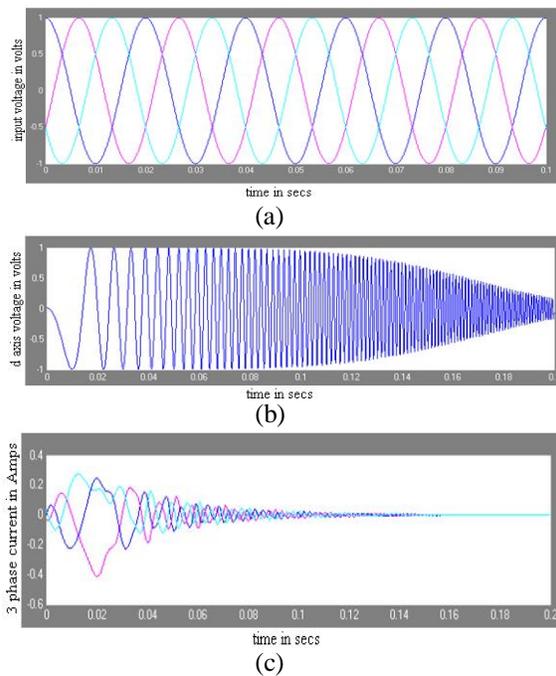
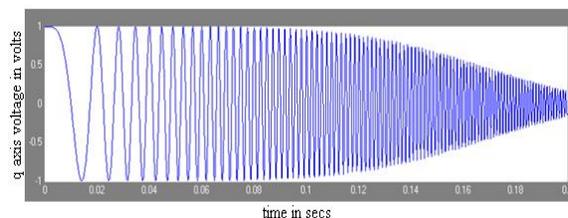


Fig. 5. (a) input voltage supply, V_{abc} (b) d axis voltage, V_d (c) three phase current, i_{abc}



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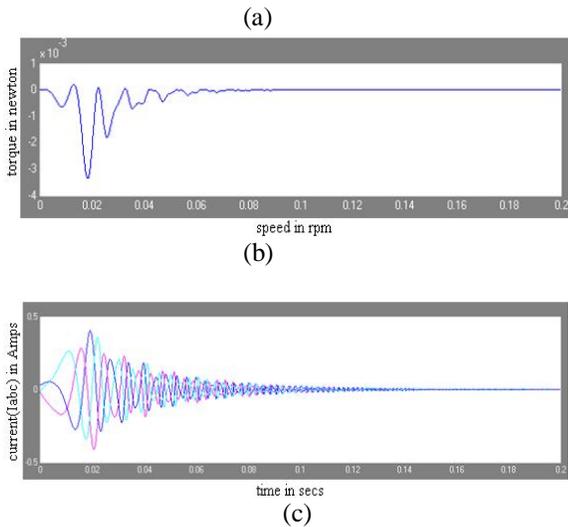


Fig. 6. (a) q axis voltage, V_q (b) electromagnetic torque (c) three phase current (sinusoidal), I_{abc}

The simulation results of d and q axis voltages are obtained from voltage transformation model of synchronous machine as shown in Fig. 3.

Fig. 5(a) represents the input voltage provided to the machine. The d axis voltage when transformed to rotor reference frame is illustrated in Fig. 5(b).

Fig. 6(a) represents the q axis voltage. Fig. 6(b) represents the negative torque as the machine operates as generator. The three phase current obtained by the transformation of rotor reference frame to machine variables is sinusoidal as shown in Fig. 6(c).

V. CONCLUSION

Salient Pole Synchronous Machine can be used to provide independent control of torque and electric power. Modeling of synchronous machine using Park's Transformation is proposed in this paper. Initially, in synchronous machine modeling, stationary reference frame is converted into arbitrary reference frame. Using Park's Transformation, arbitrary reference frame is transformed into rotor reference frame. MATLAB is used to simulate the corresponding currents and voltages in different frames.