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MODELING OF AXIAL FLUX INDUCTION MACHINE WITH SINUSOIDAL WINDING DISTRIBUTION

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Abstract—Axial Flux Machines are favorable option for Low speed applications because of the flexibility to have higher pole number. In this paper, an overview of axial flux machine is given in the first part. In the second part, the lumped parameters are determined for the axial flux induction machine which has sinusoidal winding distribution. And a model is developed based on the system equations derived in the environment of MATLAB.

Key words : Axial flux induction machine, Modeling, MATLAB, Parameter determination, Sinusoidal winding distribution.

I. INTRODUCTION

BASED on the flux direction in the air gap, electromechanical energy conversion machines are classified into Radial Flux Machines and Axial Flux Machines.

The working principle involved in both the axial flux and a radial flux machine are same but differs in its construction [2, 8]. In conventional radial flux machines the conductors are placed in parallel and the direction of air gap flux is radial to the shaft axis where as in the axial flux machines the conductors are placed in radial to the shaft and air gap flux is parallel to the shaft axis.

In axial flux machines the stator has ring structure and rotor is disc shaped. The radial length from the from the stator inner radius to the outer radius is the active part to produce the torque and the axial length is dependent on the proper yoke design of the stator and the rotor i.e., the flux density in the stator and rotor yokes. Though the number of poles increases the active radial part of the machine remains unchanged and the axial length depends on the flux density in stator and rotor yokes [3]. Thus the axial flux machine has the flexibility in having higher pole number which let the machine to be an attractive alternative for the low speed applications [4]. Furthermore it has high efficiency, high power and torque densities and low rotor losses [1, 3].

II. TYPES OF AXIAL FLUX MACHINES

As per the working principle for every conventional radial flux machine there will be a corresponding axial flux machine. Usually these machines can have single or multiple air gaps as shown in Fig.1. The multiple air gap axial flux machines have N stators and N+ 1 rotor for internal stator external rotor [ISER] type machines and N+1 stators and N rotors for external stator and internal rotor [ESIR] type machines. In ISER type machine, stator is

sandwiched between rotors which let the machine to have less end windings in stator with

which there will be a significant improvement in machine efficiency. Where as in ESIR type machine, as the rotor is sandwiched between the stators, the magnetic pull on rotor can be avoided but with the large end winding on stator the efficiency of the machine is very poor comparatively.

Fig.1-(a) Single air gap AFM (b) Multi air gap AFM

Based on the flux direction in the stator core the two topologies can be derived from ISER. One is North-North (NN) type topology and the other is North-South (NS) type topology and these topologies are illustrated in Fig. 2. In NN type ISER machine the stator can have either back to back winding or lap winding and the stator core must be wide enough to facilitate the return flux path as the direction of the main flux is axial in the air gap and both axial and radial in the stator core. Where as in NS type ISER machine the stator can have lap winding which lets the machine to have more copper because of the large end winding and the stator core requirement is less comparatively because of the direction of main flux is axial in both the air gap and the stator core. Furthermore these are classified into Slotted type and Non Slotted type. In Non-Slotted type axial flux machine there is only NN type topology which consists of stator with tape wound iron core and windings wrapped around the core with back to back connections. Where as in Slotted type axial flux

machine there are both NN type and NS type topologies.

Based on the above classification different types of permanent magnet synchronous machines and induction machines are derived. The permanent magnet synchronous machines are classified into surface mounted permanent magnet [SMPM] and Interior permanent magnet [IPM] machines of which surface mounted permanent magnet machines have been used increasingly with high energy magnets. The surface mounted permanent magnet synchronous machines depending upon the stator structure they can be either Non-slotted or Slotted type. The Non-slotted is of only NN type as discussed earlier called TORUS Non slotted NN-type SMPM synchronous machine and is illustrated in Fig.2.

In Slotted type, as discussed earlier, two different topologies are derived depending on the direction of main flux path called TORUS Slotted NN type SMPM synchronous machine and TORUS Slotted NS type SMPM synchronous machine and are illustrated in the Fig.3.

Fig.2-TORUS Non-slotted NN-type SMPM machine

Fig.3- (a) TORUS Slotted NN-type SMPM machine. (b) TORUS Slotted NS-type SMPM machine

Recently a new axial flux SMPM machine topology has been introduced [7], in which the DC field winding is placed in between two stator cores and rotor consists of permanent magnets and Iron pieces. Depending on the excitation of field winding the air gap flux may increase or decrease. This field controlled PM machine topology is introduced to avoid the problem of injecting the demagnetizing currents into the d-axis of the machine and hence

overcomes the limitations of PM machines. The structure of this topology is illustrated in Fig.4.

Fig.4- Field Controlled SMPM Axial Flux Machine.

Likewise there are different topologies of axial flux induction machines are derived. Axial flux Induction [AFI] machines are of slotted type. They can be either single air gap or multiple air gap. In single stator double rotor type structure the rotors can have two independent shafts driving two different loads and hence two different speeds can be obtained at a time. Furthermore two different topologies are derived in slotted type based on the direction of main flux in the stator core as discussed earlier called Slotted NN-type AFI machine and Slotted NS-type AFI machine which are illustrated in the Fig.5.

Fig.5- (a) Slotted NS-type AFI machine. (b) Slotted NN-type AFI machine

III. SINUSOIDAL WINDING DISTRIBUTION

In the conventional uniform winding distribution, the number of conductors in each slot is same and this winding configuration gives a stepped wave of MMF in the air gap as shown in Figure.6. This non-sinusoidal mmf consequently associated with harmonics and causes for generation of non-sinusoidal emf in armature windings. Furthermore it produces ripples in torque which leads to vibrations, noise and finally degrades the machine performance.

By using the Sinusoidal Winding Distribution, the mmf distribution wave can be made almost close to sinusoidal and the above mentioned drawbacks can be eliminated. In this configuration, each phase winding is placed in all the slots and number of conductors per slot varies with the position of slot as

shown in Fig.7. The reference axis is taken from the slot having maximum number of conductors. The conductor distribution for a p pole machine having N phases is given by

$$N_s(\theta_s) = \frac{N_s}{p} \cos \left(\frac{p}{2} \theta_s - 2\pi \left(\frac{n-1}{N} \right) \right) \quad \text{---- (1)}$$

Where

θ_s is the stator phase angle

p is number of poles

N_s is number of conductor per each slot

N_e is the effective number of conductors

n determines the phase

N determines the total number of phases

For convenience, a sinusoidally distributed balanced three phase winding is considered in stator for a 12 pole machine and the simulation results of conductor distribution and hence the mmf distribution is shown in the Fig.8.

Fig.6- Air gap MMF with Uniform Winding Distribution

Fig.7- Sinusoidal winding distribution for one phase.

IV. DETERMINATION OF MACHINE PARAMETERS

A. Resistance Calculation

The resistance of winding is given by

$$R = \frac{\text{Resistivity} \times \text{Length of the conductor}}{\text{Cross section area of the conductor}} \quad \text{----- (2)}$$

Where the Resistivity of pure copper at 75° C is

$$\rho_{75} = 2.10 \times 10^{-8} \text{ ohms per cm}^2$$

Therefore the resistance can be expressed as

$$R = \frac{2.10 L_c}{10^6 A_c} \text{ ohms at } 75^\circ \text{C} \quad \text{---- (3)}$$

B. Inductances calculation

The self inductance of the nth phase stator winding is given by

$$L_{ns} = L_{ls} + \left[\frac{N_{tns}}{p} \right]^2 \frac{\pi \mu_0 (r_2 - r_1) b_s}{L_g} \quad \text{----(4)}$$

Fig.8- MMFs with Sinusoidal winding distribution for the stator 3 phases.

Magnetizing inductance of stator nth phase winding is

$$L_{mns} = \left[\frac{N_{tns}}{p} \right]^2 \frac{\pi \mu_0 (r_2 - r_1) b_s}{L_g} \quad \text{----- (5)}$$

Where μ_0 is the permeability of the free space and its value is $4\pi \times 10^{-7}$ H/m., L_{ls} is the leakage inductance of the nth phase stator winding and N_{tns} is the number of turns in the nth phase stator winding. From the Fig.9, r_2 and r_1 are the stator core outer radius and inner radius respectively and $(r_2 - r_1)$ gives the length of the conductor. Where b_s represents the width of the slot. The stator-to-stator mutual inductances for a balanced N Phase stator are given by the equation

$$L_{mns(k+j)} = L_{mns} \cos \left[2\pi \left(\frac{(k+j) - N}{N} \right) \right] \quad \text{---- (6)}$$

Fig.9-Section of Stator surface.

And $L_{mks}(k+i) = L_{m}(k+i) \cos \theta_r$ ----- (7)

Where k represents the kth stator phase and i ranges from 1 to N-k. Likewise the rotor self inductances, rotor to rotor mutual inductances can be determined.

Now the mutual inductances between stator and rotor phases can be given as.

$$L_{mkskr} = L_{sr} \cos(\theta_r) \text{ ----- (8)}$$

Where θ_r is the angular displacement of rotor, k_s and k_r represent kth phase of stator and rotor respectively.

And

$$L_{sr} = \left[\frac{N_{ms}}{p} \right] \left[\frac{N_{mr}}{p} \right] \frac{\pi \mu_0 (r_2^2 - r_1^2) \frac{b_s}{2}}{L_g} \text{ ----- (9)}$$

Where N_{mr} represents the number of turns in the rotor nth phase winding

And also mutual inductance between kth stator phase and (k+i)th rotor phase is given as

$$L_{mks}(k+i) = L_{sr} \cos \left[\theta_r + 2\pi \left[\frac{(k+i) - K}{N} \right] \right] \text{ -- (10)}$$

$$L_{m}(k+i) = L_{sr} \cos \left[\theta_r - 2\pi \left[\frac{(k+i) - K}{N} \right] \right] \text{ -- (11)}$$

For convenience three phases are considered in both stator and rotor. The simulated results for the time varying mutual inductances between stator and rotor are shown in Fig.10.

V.SYSTEM EQUATIONS

The equations which describe the electromagnetic and mechanical performance of an induction machine

are independent of air gap flux direction. For convenience three phases are considered in both stator and rotor and the system equations of an axial flux induction machine in matrix form are

$$\begin{bmatrix} V_s \\ V_r \end{bmatrix} = \begin{bmatrix} R_s & 0 \\ 0 & R_r \end{bmatrix} \begin{bmatrix} I_s \\ I_r \end{bmatrix} + p \begin{bmatrix} L_s & L_{sr} \\ L_{rs} & L_r \end{bmatrix} \begin{bmatrix} I_s \\ I_r \end{bmatrix} \text{ ----- (12)}$$

The above equation is in the form

$$[V] = [R][I] + p[L][I] \text{ ----- (13)}$$

The resistance matrix in (12) is given below and the resistance values can be calculated from (3). Stator resistance matrix is given by

Fig.10-Mmutual inductances between stator phase A and Rotor three phases

$$[R_s] = \begin{bmatrix} R_{1s} & \dots & 0 \\ \vdots & \ddots & \vdots \\ 0 & \dots & R_{ns} \end{bmatrix} \text{ ----- (14)}$$

Rotor resistance matrix is

$$[R_r] = \begin{bmatrix} R_{1r} & \dots & 0 \\ \vdots & \ddots & \vdots \\ 0 & \dots & R_{nr} \end{bmatrix} \text{ ----- (15)}$$

The inductances matrices in equation 12 are given below.

$$[L_s] = \begin{bmatrix} L_{1s} & \dots & L_{1n} \\ \vdots & \ddots & \vdots \\ L_{ns} & \dots & L_{nn} \end{bmatrix} \text{ ----- (16)}$$

$[L_s]_{n \times n}$ matrix represents the self and mutual inductances of the stator N phases. The diagonal elements represent self inductances of stator N phases which can be obtained from (4) and (5). And off diagonal elements represents mutual inductances between stator N Phases which can be calculated from (6) and (7).

Likewise, the self and mutual inductances of the rotor phases can be obtained.

$$[L_{sr}] = \begin{bmatrix} L_{sA} & \dots & L_{sN} \\ \vdots & \ddots & \vdots \\ L_{rA} & \dots & L_{rN} \end{bmatrix} \text{-----(17)}$$

$$\text{And } [L_{rs}] = [L_{sr}]^T \text{----- (18)}$$

$[L_{sr}]$, $[L_{rs}]$ are the mutual inductance matrices between stator and rotor phases. The diagonal elements can be obtained from equations (8) and (9). And off diagonal elements can be calculated from (10) and (11). Thus the self and mutual inductances of an induction machine with N number of stator and rotor phases and also mutual inductances between rotor and stator phases can be obtained from section IV.

To obtain the instantaneous stator and rotor phase currents, (13) has to be represented in the state space form

$$\frac{d}{dt} [I] = [L]^{-1} [V] - [L]^{-1} [R] [I] \text{----- (19)}$$

The above differential equation is solved by using Runge-kutta method in MATLAB. The simulation is done for the three phase axial flux induction machine and the results are shown in the Fig.11.

To obtain a simulation model considering the dynamics of an induction machine, the electromagnetic torque is to be calculated. The electromagnetic torque T_e is related to the magnetic co energy W_{co} as

$$T_e = \frac{d}{d\theta_r} W_{co} \text{---- (20)}$$

Fig.11-Three phase stator and rotor currents.

By neglecting the non-linearity of the magnetic system, the energy stored in the magnetic field is equal to the magnetic co energy and is expressed as

$$W_{co} = \frac{1}{2} [I_s]^T [I_r]^T \begin{bmatrix} [L_s] & [L_{sr}] \\ [L_{rs}] & [L_r] \end{bmatrix} \begin{bmatrix} [I_s] \\ [I_r] \end{bmatrix} \text{----(21)}$$

From (20) and (21), the electromagnetic torque obtained can be expressed as

$$T_e = \frac{P}{2} [I_s]^T \frac{d[L_{sr}]}{d\theta_r} [I_r] \text{----(22)}$$

The steady state torque is shown in Figure 12.

Fig.12- Steady state torque.

The generalized d-q axes model of an Axial Flux Induction Machine is represented in the Fig.13. Any particular reference frame model can be derived by substituting the appropriate frame speed and position in the generalized reference model. Reference frames rotating at an arbitrary speed are called arbitrary reference frames and other frames are particular cases of this arbitrary reference frame.

Fig.13- Generalized model of an Axial Flux Induction Machine

System equations in arbitrary reference frame are represented in the matrix notation as

$$[V_{dqsr}] = [R] [I_{dqsr}] + p[L] [I_{dqsr}] \text{-----(23)}$$

$$[R] = \begin{bmatrix} R_s & \omega_s L_s & 0 & \omega_s L_m \\ -\omega_s L_s & R_s & -\omega_s L_m & 0 \\ 0 & (\omega_s - \omega_r) L_m & R_r & (\omega_s - \omega_r) L_r \\ -(\omega_s - \omega_r) L_m & 0 & -(\omega_s - \omega_r) L_r & R_r \end{bmatrix} \text{-----(24)}$$

$$[L] = \begin{bmatrix} L_s & 0 & L_m & 0 \\ 0 & L_s & 0 & L_m \\ L_m & 0 & L_r & 0 \\ 0 & L_m & 0 & L_r \end{bmatrix} \text{---- (25)}$$

Where p represents the differential operator $\frac{d}{dt}$.

The reference frame can be a Stator reference frame, Rotor reference frame or Synchronously rotating reference frame. Stator reference frame model is used when stator variables are required to be actual and rotor variables can be fictitious, facilitating the elegant simulation of stator controlled induction motor drives. Rotor reference frame model is useful where the switching elements and power are controlled on the rotor side. This model will find use in the simulation of the motor drive system. Synchronously rotating reference frame transforms the sinusoidal inputs into dc signals. This model is useful where the variables in the steady state need to be DC quantities. Some high performance control schemes use this model to estimate the control inputs.

This model facilitates the simulation of vector control methods of induction motor.

In synchronously rotating reference frame model, the speed of the reference frame is ω_s . And (23) can be represented in a state variable form as shown in (26).

$$\frac{d}{dt} [I_{dqsr}] = [L]^{-1} [V_{dqsr}] - [L]^{-1} [R] [I_{dqsr}] \quad \text{---(26)}$$

The above differential equation is solved by using Runge-kutta method in MATLAB to obtain the d-q axis currents of both stator and rotor. The simulation results are shown in Fig.14.

The electromagnetic torque can be obtained by simulating (27) and the simulation result is shown in Fig.15.

$$T_e = \frac{3P}{2} L_m (i_{ds} i_{qr} - i_{dr} i_{qs}) \quad \text{--- (27)}$$

Fig.14. Stator and Rotor Phase currents in synchronously rotating reference frame model

VI.CONCLUSIONS

The formulae have been presented to obtain the sinusoidal winding distribution for axial flux induction machine, to determine the parameters of an induction machine. Also a

Fig.15. Steady state torque in synchronous reference frame

model has been developed in a MATLAB simulation environment using the equations. The model thus

introduced here can be used in or any other low speed direct drive applications.

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