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](image_url)

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.

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.

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.

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...
The resistance of winding is given by

\[ R = \frac{\rho_s \ell}{A} \]  

Where
- \( \rho_s \) is the stator phase angle
- \( p \) is number of poles
- \( N_1 \) is number of conductor per each slot
- \( N_s \) is the effective number of conductors
- \( N \) 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 for one phase is given in Fig. 8.

\[ R = \frac{2.10 \times 10^{-6}}{10^4 A_c} \]  

**B. Inductances calculation**

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

\[ L_{sn} = L_{ls} + \left( \frac{N_{con}}{p} \right) \frac{r_2 (r_2 - r_1)}{L_g} \]  

Magnetizing inductance of stator nth phase winding is

\[ L_{nms} = \left( \frac{\mu_0}{\pi} \right) \frac{N_{con} s_3}{L_g} \]  

Where the Resistivity of pure copper at 75°C is

\[ \rho_{75} = 2.10 \times 10^{-6} \text{ ohms per cm}^2 \]

**IV. DETERMINATION OF MACHINE PARAMETERS**

**A. Resistance Calculation**

The resistance of winding is given by

\[ R = \frac{\rho_s \ell}{A} \]  

Where \( \rho \) is the permeability of the free space and its value is \( 4\pi \times 10^{-7} \text{ H/m} \). \( L_0 \) is the leakage inductance of the nth phase stator winding and \( N_{con} \) 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 and inner radius respectively and \( (r_2-r_1) \) gives the length of the conductor. Where \( b \) represents the width of the slot. The stator-to-stator mutual inductances for a balanced N Phase stator are given by the equation

\[ L_{ms} = L_{ms} \cos \left( \frac{\theta + \theta_0}{N} \right) \]
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

\[
[V] = [L_s] [I] + [R_s] [I] + \rho [L_r] [I].
\]  

(12)

The above equation is in the form

\[
[V] = [L_s] [I] + \rho [L_r] [I].
\]  

(13)

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

Stator resistance matrix is given by

\[
[R_s] = \begin{bmatrix}
R_{s1} & \cdots & 0 \\
0 & \ddots & \vdots \\
0 & \cdots & R_{sN}
\end{bmatrix},
\]  

(14)

The inductance matrices in equation 12 are given below.

\[
[L_s] = \begin{bmatrix}
L_{s1} & \cdots & 0 \\
0 & \ddots & \vdots \\
0 & \cdots & L_{sN}
\end{bmatrix},
\]  

(16)

\[
[L_r] = \begin{bmatrix}
L_{r1} & \cdots & 0 \\
0 & \ddots & \vdots \\
0 & \cdots & L_{rN}
\end{bmatrix},
\]  

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

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

V.SYSTEM EQUATIONS

The equations which describe the electromagnetic and mechanical performance of an induction machine
The electromagnetic torque $T_e$ is related to the magnetic co energy $W_m$ as

$$ T_e = \frac{d}{d \theta} W_m $$  \hspace{1cm} (20) $$

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

$$ W_m = \frac{1}{2} [L_{dq}]^T [\delta i_d] [\delta i_q] $$ \hspace{1cm} (21) $$

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

$$ T_e = \frac{p}{2} [L_{dq}]^T \frac{d^2 \delta i_d}{d \theta^2} $$ \hspace{1cm} (22) $$

The steady state torque is shown in Figure 12.

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 $T_e$ 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 \( \omega_s \). And (23) can be represented in a state variable form as shown in (26).

\[
\frac{d}{dt}[\dot{I}_{dqr}] = [L_I^{-1}][\dot{V}_{dqr}] - [L_I^{-1}][R_I]I_{dqr}]
\] -----(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.

\[
T_e = \frac{3}{2}f_p \left( \frac{\psi_{d}^{*}}{L_i} - \frac{\psi_{q}^{*}}{L_i} \right)
\] -----(27)

![Fig.14. Stator and Rotor Phase currents in synchronously rotating reference frame model](image)

**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 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.

**REFERENCES**


**BOOKS**


