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Modelling and Analysis of Higher Phase Order (*HPO*) Squirrel Cage Induction Machine

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1. Introduction

The need for more power per volume, or mass and reliability has promoted the advancement of higher phase order (*HPO*) electric machines. The *HPO* machines are electric machines with the number of phases higher than the conventional arrangement of three (3). These machines are considered to have several advantages and useful applications. So far *HPO* machines have found applications in electric ship propulsion, hybrid electric vehicles and many other industrial applications (Yong Le A, et al, 1997), (Lipo T.A., 1980). Also, they can operate with an asymmetrical winding structure in the case of loss of one or more machine phases thus making them fault tolerant (Apsley J., et al, 2006).

In this chapter, an approach of modelling and analysis of the higher phase order machine will be explored where the stator has a symmetrical winding layout. The machine stator winding is connected to a balanced phase supply and the machine performance characteristics observed during normal operation and under fault conditions, both in loaded and unloaded conditions. The performance under fault is considered to demonstrate the fault tolerance of the machine. Though rating may fall during the loss of 1 or more phases due to fault, unlike the conventional 3-phase ones, does not stop the machine from running as long as the condition for the production of rotating magnetic field in the air-gap is met.

Furthermore, a six phase squirrel cage induction machine was investigated using the classical field analysis method, the generalised theory method and the finite element method (*FEM*). The six phase squirrel cage induction machine is modelled and simulated in Matlab\Simulink environment. Steady-state and the dynamic results characterising the performance of the six phase squirrel cage induction machine were generated. Laboratory tests were conducted on a constructed 1.5 kW experimental machine to validate the performance characteristics results obtained from the theoretical simulations. The results of the three methods used were



compared among themselves, and also with the experimental to appraise the suitability of each method for modelling and analysis of *HPO* machines. Even though six-phase machine is considered it is believed that the methods as applied in this work are generally applicable to *HPO* squirrel cage induction machine of any number of phases.

2. Mathematical modelling of the six phase squirrel cage induction machine

The arbitrary reference frame theory is used in the dynamic analysis of electrical machines. The highly coupled nature of the machine, especially the inductances within the winding makes it rather challenging to perform the dynamic simulations and analysis on this machine (Ogunjuyigbe A.S.O., 2009), (Krause P.C., Wasynczuk O., et al, 2002). By using this method as applied to the three phase case, a six-phase machine is also transformed to a four-phase machine with their magnetic axis in quadrature. This method is also commonly referred to as the *dqxy0102* transformation. Figure 1 shows the symmetrical layout of the machine in the natural reference frame, where the stator is represented by the six phase symmetrical winding and the rotor by the three phase winding.



Figure 1. The Machine Diagram in natural reference frame

The matrix transformation of the *dqxy*0102 and *abcxyz* for the stator phases is given in Equation (1) and Equation (2) as (Levi E., 2006):

$$\begin{bmatrix} f_{ds} \\ f_{qs} \\ f_{dxs} \\ f_{qys} \\ f_{os1} \\ f_{os2} \end{bmatrix} = \frac{2}{6} \begin{bmatrix} \cos(\theta) & \cos\left(\theta - \frac{\pi}{3}\right) & \cos\left(\theta - \frac{2\pi}{3}\right) & \cos\left(\theta - \pi\right) & \cos\left(\theta - \frac{4\pi}{3}\right) & \cos\left(\theta - \frac{5\pi}{3}\right) \\ \sin(\theta) & \sin\left(\theta + \frac{\pi}{3}\right) & \sin\left(\theta + \frac{2\pi}{3}\right) & \sin\left(\theta + \pi\right) & \sin\left(\theta + \frac{4\pi}{3}\right) & \sin\left(\theta + \frac{5\pi}{3}\right) \\ \cos(2\theta) & \cos\left(2\theta - \frac{2\pi}{3}\right) & \cos\left(2\theta - \frac{4\pi}{3}\right) & \cos(2\theta - 2\pi) & \cos\left(2\theta - \frac{8\pi}{3}\right) & \cos\left(2\theta - \frac{10\pi}{3}\right) \\ \sin(2\theta) & \sin\left(2\theta + \frac{2\pi}{3}\right) & \sin\left(2\theta + \frac{4\pi}{3}\right) & \sin(2\theta + 2\pi) & \sin\left(2\theta + \frac{8\pi}{3}\right) & \sin\left(2\theta + \frac{10\pi}{3}\right) \\ \frac{1}{2} & \frac{1}{2} & \frac{1}{2} & \frac{1}{2} & \frac{1}{2} & \frac{1}{2} & \frac{1}{2} \\ \frac{1}{2} & -\frac{1}{2} & \frac{1}{2} & \frac{1}{2} & \frac{1}{2} & \frac{1}{2} & \frac{1}{2} \\ \frac{1}{2} & -\frac{1}{2} & \frac{1}{2} & \frac{1}{2} & \frac{1}{2} & \frac{1}{2} \\ \frac{1}{2} & -\frac{1}{2} & \frac{1}{2} & \frac{1}{2} & -\frac{1}{2} \end{bmatrix} \begin{bmatrix} f_{as} \\ f_{bs} \\ f_{cs} \\ f_{ss} \\ f_{ss} \\ f_{ss} \\ f_{ss} \end{bmatrix}$$
(1)

$$\begin{bmatrix} f_{as} \\ f_{bs} \\ f_{cs} \\ f_{cs} \\ f_{zs} \end{bmatrix} = \begin{bmatrix} \cos(\theta) & \sin(\theta) & \cos(2\theta) & \sin(2\theta) & 1 & 1 \\ \cos\left(\theta - \frac{\pi}{3}\right) & \sin\left(\theta + \frac{\pi}{3}\right) & \cos\left(2\theta - \frac{2\pi}{3}\right) & \sin\left(2\theta + \frac{2\pi}{3}\right) & 1 & -1 \\ \cos\left(\theta - \frac{2\pi}{3}\right) & \sin\left(\theta + \frac{2\pi}{3}\right) & \cos\left(2\theta - \frac{4\pi}{3}\right) & \sin\left(2\theta + \frac{4\pi}{3}\right) & 1 & 1 \\ \cos(\theta - \pi) & \sin(\theta + \pi) & \cos(2\theta - 2\pi) & \sin(2\theta + 2\pi) & 1 & -1 \\ \cos\left(\theta - \frac{4\pi}{3}\right) & \sin\left(\theta + \frac{4\pi}{3}\right) & \cos\left(2\theta - \frac{8\pi}{3}\right) & \sin\left(2\theta + \frac{8\pi}{3}\right) & 1 & 1 \\ \cos\left(\theta - \frac{5\pi}{3}\right) & \sin\left(\theta + \frac{5\pi}{3}\right) & \cos\left(2\theta - \frac{10\pi}{3}\right) & \sin\left(2\theta + \frac{10\pi}{3}\right) & 1 & -1 \end{bmatrix} \begin{bmatrix} f_{ds} \\ f_{qs} \\ f_{dss} \\ f_{dss$$

Likewise, the rotor matrix transformation between ABC and *dq0* is also given in Equation (3) and Equation (4) as (Jimoh A.A., Jac-Venter P, Appiah E.K., 2012):

$$\begin{bmatrix} f_{dr} \\ f_{qr} \\ f_{or} \end{bmatrix} = \begin{bmatrix} \cos \beta & \cos \left(\beta - \frac{2\pi}{3} \right) & \cos \left(\beta - \frac{4\pi}{3} \right) \\ \sin \beta & \sin \left(\beta + \frac{2\pi}{3} \right) & \sin \left(\beta + \frac{4\pi}{3} \right) \\ \frac{1}{2} & \frac{1}{2} & \frac{1}{2} & \frac{1}{2} \end{bmatrix} \begin{bmatrix} f_{ar} \\ f_{br} \\ f_{cr} \end{bmatrix}$$
(3)

$$\begin{bmatrix} f_{ar} \\ f_{br} \\ f_{cr} \end{bmatrix} = \begin{bmatrix} \cos\beta & \sin\beta & 1 \\ \cos\left(\beta - \frac{2\pi}{3}\right) & \sin\left(\beta - \frac{2\pi}{3}\right) & 1 \\ \cos\left(\beta - \frac{4\pi}{3}\right) & \sin\left(\beta + \frac{4\pi}{3}\right) & 1 \end{bmatrix} \begin{bmatrix} f_{dr} \\ f_{qr} \\ f_{or} \end{bmatrix}$$
(4)

Where *f* can be expressed as the voltage, current or the flux linkage and the subscript *ABC-XYZ* represents the phases of the machine winding.

In developing the equations which describe the behaviour of the six phase induction machine the following assumptions were made:

- **1.** The air-gap is uniform.
- 2. Eddy currents, friction and windage losses and saturation are neglected.
- 3. The windings are distributed sinusoidally around the air gap.
- 4. The windings are identical.

2.1. Voltage and flux linkage equations

The voltage equation of the six phases (*abcxyz* to *dqxy0102*) is derived using the similar concept as applied to the three phase case (Jimoh A.A., Jac-Venter P, Appiah E.K., 2012). The symmetrical *dqxy0102* voltage equation with flux linkage as state variables is expressed as (Appiah E.K., et al, 2013):

$$V_{ds} = r_s \left(\frac{\lambda_{ds} - \lambda_{md}}{l_{ls}}\right) + \frac{d}{dt}\lambda_{ds} - \omega\lambda_{qs}$$

$$V_{qs} = r_s \left(\frac{\lambda_{qs} - \lambda_{mq}}{l_{ls}}\right) + \frac{d}{dt}\lambda_{qs} + \omega\lambda_{ds}$$
(5)
(6)

$$V_{dr} = r_r \left(\frac{\lambda_{dr} - \lambda_{md}}{l_{lr}}\right) + \frac{d}{dt} \lambda_{dr} - (\omega - \omega_r) \lambda_{qr}$$
(7)

$$V_{qr} = r_r \left(\frac{\lambda_{qr} - \lambda_{mq}}{l_{lr}}\right) + \frac{d}{dt}\lambda_{qr} + (\omega - \omega_r)\lambda_{dr}$$
(8)

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$$V_{dxs} = r_r \left(\frac{\lambda_{dxs}}{l_{ls}}\right) + \frac{d}{dt} \lambda_{dxs}$$
⁽⁹⁾

$$V_{qys} = r_s \left(\frac{\lambda_{qys}}{l_{ls}}\right) + \frac{d}{dt} \lambda_{qys}$$
(10)
$$V_{os1} = r_s \left(\frac{\lambda_{os1}}{l_{ls}}\right) + \frac{d}{dt} \lambda_{os1}$$
(11)

$$V_{os2} = r_s \left(\frac{\lambda_{os2}}{l_{ls}}\right) + \frac{d}{dt} \lambda_{os2}$$
(12)

The flux linkage equations are expressed as current dependent variables (Levi E., 2006):

$$i_{ds} = \frac{\lambda_{ds} - \lambda_{md}}{l_{ls}} \tag{13}$$

$$i_{qs} = \frac{\lambda_{qs} - \lambda_{mq}}{l_{ls}} \tag{14}$$

$$i_{dr} = \frac{\lambda_{dr} - \lambda_{md}}{l_{lr}}$$

$$i_{qr} = \left(\frac{\lambda_{qr} - \lambda_{mq}}{l_{lr}}\right)$$
(15)
(16)

$$i_{dxs} = \left(\frac{\lambda_{dxs}}{l_{ls}}\right) \tag{17}$$

$$i_{dys} = \left(\frac{\lambda_{dys}}{l_{ls}}\right) \tag{18}$$

$$i_{os1} = \left(\frac{\lambda_{os1}}{l_{ls}}\right) \tag{19}$$

$$i_{os2} = \left(\frac{\lambda_{os2}}{l_{ls}}\right)$$
(20)
The mutual inductances between the stator and the rotor are given as:
$$\lambda_{md} = L_m (i_{ds1} + i_{dr})$$
(21)

$$\lambda_{mq} = L_m \left(i_{qs1} + i_{qr} \right) \tag{22}$$

Where λ is the flux linkage, L_m the magnetizing inductance and Ll_s and Ll_r are the stator and rotor inductances respectively.

2.2. Mechanical equations voltage and flux linkage equations

The mechanical equations for the six phase squirrel cage induction machine comprises of the electromagnetic torque and the speed as expressed in Equations (23) and (24). These equations are derived using the same concept of the three phase case (Ogunjuyigbe A.S.O., 2009), (Krause P.C., Wasynczuk O., et al, 2002).

$$T_{em} = \left(\frac{6}{2}\frac{P}{2}\right) \left(\lambda_{ds1}i_{qs1} - \lambda_{qs1}i_{ds1}\right)$$
(23)

$$J\left(\frac{2}{P}\right)\frac{d\omega_r}{dt} + T_L = T_{em}$$
(24)

Where *P* is number of poles, *J* is moment of inertia, T_{em} is the electromagnetic torque, T_L is torque connected to the shaft, and ω_r is the angular rotational speed of the rotor.

2.3. Equivalent circuit

The equivalent circuit diagram of figure 2 summarises the voltage and flux linkage equations of the six phase squirrel cage machine in *dqxy0102* transformation. The figure 2 (a) and figure 2 (b) illustrates the equations with its corresponding stator and rotor mutual coupling of the machine as expressed in equations (5)-(8) and (13)-(16). From the equivalent circuit presentation, only these equations take part in the electromechanical energy conversion process.

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Figure 2. The *dqxy0102* equivalent circuit of the six phase squirrel cage induction machine (a) The *q* equivalent circuit (b) The *d* equivalent circuit, (c) The *h* non-coupling equivalent circuit

There is no mutual coupling in the equations (9)-(12) and (17)-(20) as presented in figure 2(c) where h denotes xy0102 voltage equations. These equations do not take part in the energy conversion process and therefore contribute to losses in the system. (Aroquiadassou G., Mpanda-Mabwe A., 2009).

3. Modelling of six-phase squirrel cage induction machine under fault conditions

The operation of the machine under fault is considered here to demonstrate its fault tolerance ability. This machine consists of a symmetrical six phase supply with a fault at the stator terminal, assuming the phase *a* winding. To investigate the performance of the machine under faulty conditions, the open and short circuit faults were simulated for both no-load and loaded states of operation. The winding arrangement for an open circuit in phase *a* is as shown in figure 3. The short circuit faults winding arrangement between the phases *a* and *b* is shown in figure 4.



Figure 3. Arrangement of the machine under fault for open circuit in phase a stator winding



Figure 4. Arrangement of the machine under short circuit in phases a and b stator winding.

3.1. Open circuit fault

With phase *a* opened the machine is modelled for ease of referral in the stationary reference frame where ω =0 is substituted in equation (5). The open circuit fault is simulated by simply assuming that the current ceases to flow in phase *a* after a normal steady state current, and an open circuit voltage is assumed across the open circuit terminals (Singh G.K., Pant V., 2000), (Krause P.C., Thomas C.H., 1965). The machine is assumed to be operating as a motor, hence a balanced six phase supply is applied to the stator. The six phase squirrel cage induction machine has no neutral connections and therefore, all the zero sequence currents are zero before the fault. However, at the loss of a phase the machine operates in asymmetry, and zero sequence current flow in the rest of the winding.

For a balanced six phase, the total phase currents may be expressed as:

$$I_{as} + I_{bs} + I_{cs} + I_{xs} + I_{ys} + I_{zs} = 0$$
(25)

From equation (2), assuming θ =0, the stator current of phase *a* is expressed as:

$$I_{as} = I_{ds1} + I_{dxs} \tag{26}$$

From equation (26), as $I_{as} = 0$,

$$I_{ds1} = -I_{dxs} \tag{27}$$

The open circuit voltage is also expressed as:

$$V_{as} = V_{ds1} + V_{dxs} \tag{28}$$

Putting I_{ds1} =0 into equation (13) and (21) and back substituting into equation (5) gives the new *d*-axis voltage equation as:

$$V_{ds} = \frac{d}{dt} \left(\frac{L_m}{L_m + L_r} \right) \lambda_{dr}$$
⁽²⁹⁾

There is no mutual coupling between the stator and the rotor winding of the *x*-axis voltage. As such, putting I_{dxs} =0 into equation (9) gives the new *x*-axis voltage as:

$$V_{dxs} = 0 \tag{30}$$

Back substituting equations (29) and (30) into (28) gives the open circuit voltage as:

$$V_{as} = \frac{d}{dt} \left(\frac{L_m}{L_m + \dot{L_r}} \right) \lambda_{dr}$$
(31)

Where $L_s = L_{ls} + L_{lr}$ and $L_r = L_{lr} + L_m$.

The open circuit voltage in equation (31) is placed across the open circuit terminal in the simulation.

3.2. Short circuit fault simulations

In this section we consider a short circuit between two phases during a normal operation of the machine. For this instance, the balanced six phase total phase voltages may be expressed as:

$$V_{as} + V_{bs} + V_{cs} + V_{xs} + V_{ys} + V_{zs} = 0$$
(32)

With phase *a* and phase *b* short circuited, the line to line voltage between these two phases become zero. The short circuit fault is simulated by putting this line voltage to zero, implying the connection of phase *a* to phase *b* at a certain point at a time t when the fault occurs.

3.3. Classical field analysis

In this section, the classical field analysis is used to determine the magnetic field distribution in the air-gap of the machine. With this magnetic field distribution, the performance behaviour of the machine at steady state was determined using the equivalent circuit in figure 2. The corresponding smooth air-gap flux density distribution of the stator and the rotor is given in more details by (Appiah E.K. *et al*, 2013):

$$B_{gs}(\theta,t) = \frac{\mu_0 MMF(\theta,t)}{l_g}$$

$$B_{gr}(\theta,t) = \frac{\mu_0 MMF_r(\theta,t)}{l_g}$$
(33)

The permeance factor Λ is expressed as (Jimoh A. A., 1986):

$$\Lambda = \frac{1 - y}{\left[(a - y)(b - y) \right]^{\frac{1}{2}}}$$
(34)

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$$\theta = \frac{g}{\pi} \left[-In \left| \frac{1+p}{1-p} \right| + In \left| \frac{b+p}{b-p} \right| + 2\frac{b_{os}}{l_g} + a \tan \frac{p}{\sqrt{b}} \right] - 0.5 \frac{b_{os}}{l_g}$$
(35)

Where B_g represents the flux density distribution of the stator and the rotor, *MMF* represents the magnetomotive force, l_g represents the air-gap length, μ_o represents the permeability of air, θ represents space, and t represents time. The six phase air-gap power can be expressed as:

$$P_{ag} = 6 \left| I_r' \right|^2 \frac{R_r'}{s}$$
(36)

Where:

$$s = \frac{\omega_s - \omega_r}{\omega_s}, R_2 = R'_r \tag{37}$$

The electromechanical power and torque of the machine is expressed as:

$$P_{em} = P_{ag} \left(1 - s \right) \tag{38}$$

$$T_{em} = \frac{P_{ag}}{\omega_s}$$
(39)
Similarly, the input power, output power and the power factor are also expressed as:

$$P_{in} = P_{ag} 6 \left| I_r \right|^2 R_s \tag{40}$$

$$P_{out} = P_{ag} - P_{loss} \tag{41}$$

$$PF = \frac{P_{in}}{6V_s I_s} \tag{42}$$

Also *s* denotes the slip, ω_s is the synchronous speed, ω_r is the rotor speed, P_{in} is the input power, V_s is the supply voltage, I_s is the stator supply current, *PF* is the power factor, P_{ag} is the air-gap power, P_{em} is the electromagnetic power, P_{out} is the output power, P_{loss} is the losses-which includes stator and rotor winding losses, core loss, windage and friction and other stray losses- and the subscripts *s* and *r* denotes the stator and the rotor respectively.

As the permeance factor of equation (34) is superimposed on the flux density distribution expressed in equation (33), the effects of slot opening on the flux density distribution is accounted.

3.4. Finite element analysis

In this section, the finite element analysis using a two dimensional Quickfield software package is used to evaluate the performance behaviour of the machine. The magnetic vector potential is employed in the numerical solution to give the magnetic flux density distribution. The magnetic vector potential is expressed as (Pyrhonen T. P., Valeria H., 2008), (Appiah E.K., Jimoh A. A., et al, 2013):

$$\vec{B} = \nabla \times \vec{A} \tag{43}$$

$$B_x = \frac{\partial A_x}{\partial y} \tag{44}$$

$$B_{y} = \frac{\partial A_{y}}{\partial x} \tag{45}$$

For a two dimensional problem of the vector potential, the Poisson equation is expressed as:



The performance behaviour of the machine at steady state was evaluated by loading the machine in *AC* magnetics in Quickfield software. The governing equation for the slip and torque is given by (Appiah E.K. *et al*, 2013):

$$\omega_r = -s\omega_s + \omega_s \tag{47}$$

The torque derivation of the *FEA* is given as:

$$T = \frac{1}{2} \int_{s} ((rxH)(n.B) + (rxB)(n.H) - (rxn)(H.B)ds$$
(48)

where *r* is a radius vector of the point of integration and *n* denotes the unit vector normal to the surface.

The geometry of the whole machine was developed using the software package. Two boundary conditions were used for this analysis within the entire structure: the Dirichlet's boundary condition for the outer layer of the machine structure and the homogeneous Neumann boundary condition for the change over from one geometry or medium to another such as from the core to the air-gap and vice versa. The automatic meshing of the machine geometry which is generated by the software and spread over the whole cross section is shown in figure 6(a (i)). The field solution is now obtained by running the mesh geometry in the software solver by solving the Maxwell's equation. The machine winding has been excited with balanced stator currents for no-load and full load conditions.

4. Simulation results

In this section, the simulation results for the three methods; the generalised theory of machine, the classical field, and the finite element analysis are presented. The dynamic performance behaviour of the machine was determined using the derived mathematical modelling in *dqxy0102* (generalised theory), and implemented in Matlab/Simulink environment. This simulation results are generated in the Matlab/Simulink environment for the machine performance characteristics, during normal operation and under fault conditions in loaded and unloaded conditions. The performance behaviour of the machine at steady state was determined using the equivalent circuit, and the models implemented in Matlab for classical field analysis and Quickfield environment for *FEA*. The effect of slot opening on the magnetic flux density distribution of the air-gap for the field and other results obtained from finite element analysis are shown in the remaining part of the section.

4.1. Magnetic flux density distribution of the classical field

To obtain the air-gap flux density distribution the permeance factor distribution, which reflects the effects of the slot openings, is superimposed on the flux density distribution. If saturation is to be accounted for, the *B*-*H* characteristics of the magnetic core would have been incorporated in the flux density distribution (Jimoh A. A., 1986). Figure 5 shows the permeance flux density distribution and the air-gap flux density distribution, for the no load and the full load conditions.



Figure 5. The plot of air-gap flux density (i) no-load, (ii) full load conditions

4.2. Magnetic flux density distribution of the FEA

In this section, the automatic meshing of the machine and the magnetic flux lines are shown in figure 6 (a).The colour map of the magnetic flux line shows that most of the portion of the yoke is under high flux density. The effect of slot opening on the magnetic flux density distribution of the air-gap is shown in figure 6 (b), for no-load and rated load condition. This is achieved by clicking the mid-air-gap of the whole geometry in Quickfield. The magnetic saturation of the materials is taken care of by the magnetization curve.

4.3. Steady state analysis

This section presents the results of the analysis of the machine in steady state for the three methods; the generalised theory of machine, the classical field and the finite element analysis. For test performance under load condition the machine has been loaded to approximately 125% of rated torque. The values obtained for torque, efficiency, input power, output power, power factor and reactive power were respectively plotted against the loading as shown in figures 7-9. Experimental measurements were also plotted on the same curve for validation of the theoretical work. The machine performance characteristics increase with increasing load. The range of loading of the machine from 0 to 0.2 per unit shows that the three scenarios under study have the same effects until they begin to deviate from each other. However, the case of the reactive power is different in such that it deviates from each other from 0 to 125% of the rated load. It is further observed during the load study that the reactive power at start is high but decreases with loading and vice versa for the active power. The difference in deviation could be so because of the rotor losses when the machine is being loaded. The effect of the reactive power at start gives a very poor power factor to the machine but the performance improves with loading. The experimental results validate the theoretical model and are plotted alongside those of the three methods.

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Figure 6. (a) (i) mesh of the full geometry, (ii) magnetic flux lines, (b) (i) air-gap magnetic flux density distribution at no-load, (ii) air-gap magnetic flux density distribution at full load



Figure 7. The steady state (i) electromagnetic torque, (ii) input power versus load



Figure 8. The steady state (i) output power, (ii) efficiency versus load



Figure 9. The steady state (i) power factor, (ii) reactive power versus load

4.4. Dynamic analysis

Steady-state analysis is not always sufficient in determining the behaviour of an electrical machine. The behaviour of the machine under changing conditions is also necessary. The dynamic model will show the exact behaviour of the machine during transient and or dynamic periods. The derived voltage, flux linkage and mechanical equations for the squirrel cage six phase induction machine is implemented in Matlab/ Simulink as follows:

- **1.** All partial differential variables are converted to integral variables. This concept is similarly applicable to the three phase case (Chee Mun Ong, 1998).
- **2.** The flux linkage equations are resolved into state variables and current as dependent variables. (Ogunjuyigbe A.S.O., 2009), (Krause P.C., Wasynczuk O., et al, 2002).
- **3.** The entire equations are then modelled, implemented and simulated within the Matlab/ Simulink environment.

4.4.1. Simulation of healthy machine

The dynamic and transient simulation of the six phase squirrel cage induction machine is done in the arbitrary reference frame. The Simulink model built using equations (5-24) is shown in figure 10. Figure 10a shows the complete model of the six-phase machine system, while the power block is represented in Figure 10b. The power supply block converts the machine variables from the balanced *abcxyzs* supply voltage to the *dqxy0102* using the Park transformation matrix. This is used as an input to supply the squirrel cage induction machine which is modelled in the *dqxy0102* reference frame. The simulation of these models is carried out with all the phases connected. Two scenarios: (1) at no load and (2) at rated load were investigated. The free acceleration characteristics under no-load and rated load are shown in figure 11.

The results in figure 11 show that the speed settles a little below synchronous speed at 314.1 rad/sec for the 50 Hz supply system. It is to be noted that the friction and the windage losses have been neglected in this model and as such the speed is almost equal to the synchronous speed. This effect is shown in the torque versus speed curve, and the speed versus time. From the theoretical simulations, it is observed that the starting current is about 10.8 A as compared to the rated current of 1.8 A. At the steady state settling of the current at no-load, the current is not zero but is at 0.8 A. This accounts for the magnetizing current present in the machine at no-load. The speed versus time, torque versus speed curve characteristics and the waveforms of the two stator currents, phases *a* and *x*, are as shown in figure 11a. The machine settles into a steady state at about 1.8 seconds.

Furthermore, the results of figure 11b show that the speed of the machine settles at rated load to 293.194 rad/sec, corresponding to a slip of 0.07. The simulation was done by applying the rated load of 1 pu at the time of 2.5 seconds, after the settling of the free oscillation at no-load. It is observed that the current immediately increased to show the presence of load. The speed versus time, torque versus speed curve characteristics and the waveforms of the two stator currents, phases *a* and *x* for sudden increase in load are as shown in figure 11b.



Figure 10. The Simulink representation for the healthy six phase squirrel cage induction machine model (a) The main block, (b) The conversion from *abcxyzs* supply voltage to *dqxy0102* block



Figure 11. The healthy machine (a) no-load simulation results of (i) speed-time, torque-speed, (ii) starting transient characteristics of phase *a* and phase *x* currents, (b) rated-load simulation results of (i) speed-time, torque-speed, (ii) starting transient characteristics of phase *a* and phase *x* currents in loaded conditions

4.4.2. Simulation results of faulty machine under open circuit condition

Equation (31) is used to obtain the performance characteristic of the machine under no-load and loaded conditions during fault. The Simulink representation of the open circuit voltage (*Vop*) model block is represented in figure 12. This is replaced with the supply voltage (*a*-phase)

using a signal builder as a timer, via a multiport switch for the simulation. The fault was created at a time 4 seconds, and the simulated results are shown in figure 13.

From the occurrence of fault at 4 seconds, the current in the faulty phase *a* is zero as expected. The amplitude of the oscillations in phase *x* rose to reach a constant value. Although there is no much significant change in speed during this period, the torque lead to oscillations as shown in the torque versus speed curve of figures 13a and 13b. This is true especially in loaded conditions when the amplitude of torque oscillations is nearly twice that observed in no load conditions. During the full load condition the speed dropped from 314 to about 280 rad\secs which is demonstrated in the step liked waveform in figure 13b. This created the oscillations in the performance characteristics. Although the machine was able to run at the rated torque under fault, severe precautions must be taken into account in other not to damage the entire winding of the machine. The speed versus time, torque versus speed, torque versus time curves and the waveforms of the two stator currents, phases *a* and *x* are as shown in figures 13 a and 13 b for no-load and rated load conditions respectively.



Figure 12. The Simulink representation for the unhealthy (open circuit) six phase squirrel cage induction machine model



Figure 13. The open circuit (a) no-load simulation results of (i) speed-time, torque-speed, torque-time (ii) starting transient characteristics of phase *a* and phase *x* currents, (b) rated-load simulation results of (i) speed-time, torque-speed, torque-time (ii) starting transient characteristics of phase *a* and phase *x* currents in loaded conditions

4.4.3. Simulation results of faulty machine under short circuit condition

The short circuit voltage is achieved by making the supply voltages equal to zero by short circuiting two phases using the signal builder. The Simulink representation of the short circuit voltage model blocks is represented in figure 14. For the theoretical analysis of short circuit, a fault was created at 4 seconds for phases *a* and *b* after the machine started from standstill at no-load. The simulation of the rated load was done by applying the load at 2.5 seconds after the free oscillation settling of the no-load.

In this instance currents in both phase a and phase x are subject to oscillations having the same impact on the torque as in the open circuit fault but simply the amplitude of the oscillations appearing is slightly greater. Conversely, the speed drops and oscillates around a certain average value. From the effects of the short circuit simulated below on the torque and speed, it is apparent that this is a case of the most severe fault. However, the performance of the machine is not critically affected. The results, shown in figure 15 are the speed versus time, torque versus speed, torque versus time curves and the waveforms of the two stator currents, phases a and x for no-load and rated load conditions.



Figure 14. The Simulink representation for the unhealthy (short circuit) six phase squirrel cage induction machine model

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Figure 15. The shot circuit (a) no-load simulation results of (i) speed-time, torque-speed, (ii) starting transient characteristics of phase *a* and phase *x* currents, (b) rated-load simulation results of (i) speed-time, torque-speed, (ii) starting transient characteristics of phase *a* and phase *x* currents in loaded conditions

5. Experimental validation

In order to validate the theoretical results with the experimental results, the experimental set up shown in figure 16 is utilised. The experimental results are used to validate the theoretical model. The set up consists of an induction motor which was reconstructed to a six phase machine, data acquisition equipment, torque transducer and computer system for waveform acquisition and a six phase supply. The machine performance at steady state has been plotted alongside the theoretic figures 7-9.





The dynamic simulations of the stator currents have been observed for the machine performance characteristics during normal operation and under fault conditions, both in loaded and unloaded conditions. These are shown in the figures 17 and 18. Given a fault condition, the current drawn at full load under fault condition is higher than that of the no load. This means that operating the machine for a long period of time under full load fault without de-rating can damaged the machine winding. The good agreement, shown by the curves, between theoretical and experimental results tends to validate the model.



Figure 17. The experimental results, (i) no-load, (ii) loaded condition



6. Application possibility in electric vehicles (EV) and hybrid electric vehicles (HEV)

In view of the need to reduce the continued dependency on petroleum as a source of energy for powering cars and the drive to reduce CO_2 emissions, EV/HEV has received huge research interest. The applications of HEV range from small cars to buses, and even trucks. Researchers are generally working towards developing more efficient drive systems for EV/HEV vehicles. With different vehicle applications and requirements, it is clear that no single electric motor design fits all. As such motors designed for electric vehicle applications have to meet rigorous

demands, with space limitations and the driving environment key factors. Reports of achievements has demonstrated that the specific performance characteristic of HPO machines matches the technical demands of HEV and also has the potential to further improve its quality. HPO machines finds application in areas where high power, high torque as well as high reliability is demanded. This is because it has a reduced amplitude and increased frequency of torque oscillation, reducing the rotor harmonic current per phase without increasing the voltage per phase, lowers the dc-link current harmonics, high fault tolerance (in the case of loss of one or more phases), reduction of required power rating per inverter leg and increase torque per ampere for the same volume of machine. HPO has been utilised also for integrated stator/ alternator in HEV and ordinary vehicles with combustion engines Miller et al (2001) and Miller and Stefanovic (2002). The integrated idea replaced two electrical machines with a single machine and matches the goal of reducing the number of assemblies to have lighter vehicles.

The major types of electric motors adopted for EV/HEV includes DC motor, Induction motor, permanent magnet motor and Switched reluctance motor. A general review of the state of the art in EV/HEV shows that cage induction motors and the permannet magnet motors are highly dominant, whereas, study on the use of DC motors are going down.

6.1. Comparative study

6.1.1. Dc motor

DC motors have established presence in electric propulsion because their torque-speed characteristics suit traction requirement well and their speed controls are simple, Wildi (2004). However, dc motor drives have large assemblage, low efficiency, low reliability and continuous need of maintenance, mainly due to the presence of the mechanical commutator (brush).

Contrary to this, the continuous development of rugged solid-state power semiconductors has made it increasingly practicable to introduce AC induction and synchronous motor drives that are mature to replace dc motor drive in EV/HEV /traction applications.

The motors without commutator are attractive, as high reliability and maintenance-free operation are prime considerations for electric propulsion. Nevertheless, with regard to the cost of the inverter, ac drives are used generally just for higher power. At low power ratings, the dc motor is still more than an alternative (Zeraoulia, 2006).

6.1.2. Induction motor

Cage induction motors has wide acceptance as a potential candidate for the electric propulsion of EV/HEVs based on their reliability, ruggedness, low maintenance, low cost, and the ability to operate in a hostile environment. They are particularly well suited for the rigors of industrial and traction drive environments. Today, induction motor drive, Chris (2007) is the most mature technology among various commutatorless motor drives.

The introduction of, as well as the level of development in the HPO machines has further strengthened the position of Induction machine for electric propulsion in EV/HEV, particularly

Propulsion				
Characteristics				2
	DC	IM	PM	SRM
	DC	IM	PM	SRM
Power Density	2.5	3.5	5	3.5
Efficiency	2.5	3.5	5	3.5
Controllability	5	5	5	3
Reliability	3	5	4	5
Technology Maturity	5	5	4	4
Cost	4	5	3	4
	E.	50'33h		



Table 1. Evaluation of Electric Propulsion Systems (Zeraoulia, 2006)

because of the possibility of high power, high torque and high torque per ampere for same volume of machine.

Zeraoulia (2006) carried out an evaluation of electric propulsion systems based on the main characteristics EV/HEV's propulsion, table 6.1. It was consensually established that induction motor is the most adapted for the propulsion of urban HEV's. This report is pre-the recent developments in the design and control of HPO machines.

7. Conclusions

A study of *HPO* machine using six-phase squirrel cage induction machine as a case study has been presented in this chapter. An experimental 1.5 KW six phase induction machine with 220V, 50Hz supply has been used for the study. Three different methods have been applied for modelling and analysis of the study and the performance behaviours of the machine have been considered under no-load and loaded conditions for a healthy machine and a machine with faults.

The results obtained showed that in both healthy and unhealthy cases the machine is able to produce the starting torque. However, it has been observed that the torque produced by the healthy machine is greater in magnitude and produces fewer oscillations than the machine with faults at the stator phases. The significant observation is that the machine settles down to a new steady state with the fault, thus confirming fault tolerance, albeit the performance of the signal variables is compromised.

The steady state performance of real power, reactive power, power factor, electromagnetic torque, the stator currents and efficiency have been shown. In the steady state results, the performance characteristics obtained from the simulations were compared with the experimental results, while the dynamic ones were similarly compared. While good agreements were generally observed the generalized theory gave closer result to the experiment than the classical field and the finite element methods.

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