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Performance of Five Phase Induction Machine for Open Phase Faults using Harmonic Balance Technique

Dr. B. Jyothi, P. Bhavana

Abstract: In recent times, five phase Induction machines are extensively used in the industrial drive systems over the preceding three decades as a resource of converting electric power to mechanical power and in all realistic applications where capricious speed is required. This is because of its sturdiness adaptability and consistency. The imperative feature of machines with a high numeral of phases is their improved consistency, hence they can operate even one or two phases are missing. The paper primarily spotlight on the steady state and dynamic performance of five phase induction machine drive for open phase faults such as one phase, two phases (consecutive or non consecutive) and it is shown that, the five-phase machine can start and generate a high percentage of rated torque even one or two phases missing. In order to obtain the steady state and dynamic performance of five phase machine drive harmonic balance technique on the full-order differential equation model of the faulted machine in stationary reference frame is implemented. Simulation results are presented to calculate the harmonic components of speed and torque pulsations with MATLAB software.

Index Terms: Dynamic and steady state performance, Five Phase Machine drive, Harmonic Balance Technique, phase open faults.

I. INTRODUCTION

In broad-spectrum, the induction machine drives (IMD) with three-phases are used, since three phase power supply is standard. However, when it is fed by an inverter, there is no fixed count of phases, some other numbers of phases are possible and advantageous. A multiphase machine drives can operate in general after loss of either one or more phases. An increase in count of phases can effects increase in torque/ampere relation for the same machine, such that five-phase induction machine (FPIM) can develop torque using not only the fundamental, but also using higher harmonics of the air gap field. Another important aspect of machines with a higher number of phases is their improved reliability, since they can operate in their normal state even when one phase is missing. Multiphase machine drives (IM) are recently proposed in applications like Electric Vehicles and traction etc.

There are numerous key points of the proposed IM than conventional 3-Φ machines.

- Whenever stator excited from the supply in the enhanced phase number of the machine, then rotating field is developed with less harmonics;
- If anyone phase gets opened during running, motor continues to run only with the additional equipment in the classical motors but in the proposed motor it continues to run without any additional equipment.
- Multiphase machines are having the reduced torque ripples than the traditional motors.

The proposed Five phase induction machine designed based on the following literature survey.

H. A. Toliyat et al., [1] proposed in the year 1993, a Mathematical model based on complex voltage vectors for the theoretical studies of 5-Φ VSI PWM inverters. Complex vector representation is employed to help in visualizing the current regulation similar to the 3-Φ systems. 2-Φ based on transformation equations are presented for the proposed machines. Finally various PWM Controllers are described.

Huangsheng et al., [2] in the year 2001 proposed a new topology for a DSP based 5-Φ IM drive with two control techniques. The two control techniques are namely vector control and direct torque control. Fundamental and third harmonic currents are generated through vector control. Due to these currents, rectangular flux linkages are developed. It gives higher power density and resulting torque. Using direct torque control technique, stator ripple flux and torque are reduced. Hence the drive can be controlled precisely and it is beneficial.

G.K. Singh [3] in the year 2002 assessed the advantages of higher number of phases of the IM drive over conventional 3-Φ IM drives. These drives are very efficient for high power applications and also reduces the torque pulsations, harmonic currents of the rotor. In electric ship propulsion, electric/hybrid vehicles and aircrafts applications high reliability multiphase drives are applied. Hence, the author reviews the development of the proposed drive from its origination along with principles and comparisons of the existing drives.

Steve Williamson et al., [4] in the year 2003, analyzed the pulsating torque and losses of multiphase IM. Both the stator and rotor losses of the proposed motor with the conventional 3-Φ motor losses are compared. Due to fundamental component, phase-belt harmonic fields appear under excitation.

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By means of usual expressions harmonics of the proposed motor are analyzed. Through the enhanced phase number of the motor runs with any pulse width modulated inverter, the finally the author finds the sources of pulsating torque and determines them.

Emil Levi et al., [5] in the year 2007 proposed new techniques with two traditional motors which are connected in a sequence through a vector control. These two motors are have more than the conventional phase number as per the given application with one supply source. Here these two motors are ac motors which are IM and Synchronous motors. When motors are excited with the supply source, a magnetic field is obtained. Due to this magnetic field in vector control, the current and torque of the given set of drives is produced. Currently, the author restricted with only odd phase number rather than even phase due to some advantages compared with conventional 3-Φ system. Individual motors fundamental operation was discussed.

Multiphase IM drives were given by E. Levi et al., in the year 2007 [6]. A control strategy of the proposed drives includes the DTC, vector control and space vector PWM approach. Merits and demerits are listed out compared to the conventional 3-Φ motor drives. By means of collective information, the researcher analyzed the dynamic performance of the proposed drive.

Mario J. Duran et al., [7] in the year 2008, introduced a new technique 3rd harmonic inoculation for the adjustable speed drives which are having high number of phases than conventional speed drives. Using the introduced analysis that is bifurcation for the drive an amount of torque density and power gets increased compared to the existing drives and also gives the vigorous controllers for the proposed drive when the drive is employed for both concentrated and distributed windings. Current harmonics are inserted to the concentric windings of the motor to upgrade the performance of the drive compared to the existing speed drives

Martin Jones et al., [8] in the year 2009 proposed Multiphase IM Drives in Synchronous Current Control Scheme. Here MMF distributed sinusiodally in the windings of the proposed drive is developed. In general current controllers are considered in synchronous reference frame but it has some limitations. To overcome these limitations the conventional controllers are modified which eliminates the imbalances in the proposed drive and operates smoothly in all the conditions by two different connection schemes. Here, the obtained currents are in sinusoidal nature and hence it completely compensates the imbalances in the winding.

Drazen Du et al., [9] in the year 2010, introduced a new topology for Multiphase IM drives using various connection schemes of the polygon access with pulse width modulation schemes to analyzed the rms current ripples of the drive. To get the sinusoidal output voltage two PWM schemes are employed and analyzed the produced harmonics. Here sinusoidal and harmonic injected pulse width modulation techniques are introduced to analyze the proposed drive current ripples. By means of injected harmonics for the drive dc bus utilization gets picked up.

B. Kundrotas [10] proposed model of multiphase IM in the year 2011 and developed 6-Φ IM dynamic model. 3-Φ rotor winding and multiphase stator winding are in synchronous frame. For d and q axis of motor equivalent circuits per phase are discussed. Similar to the conventional 3-Φ drives, the parameters like speed, torque, starting transient currents were determined.

Emil Levi [11] in the year 2012 proposed a new topology of dual-inverter fed adjustable 3-Φ drives with open-end winding, for several applications, together with motors employed for traction systems. Conventional multilevel converters suffer voltage imbalance problems. These vanished by using enhancing the phase number and the switching states are increased accordingly. By means of simple SVM algorithm, analyze the proposed 5-Φ two-level drive. By using this technique motor develops a low harmonic content of output phase voltages and up to 17-level were presented.

Hussain et al., [12] in the year 2012 introduced a new topology 5-Φ IM to analyze the likely caused faults of the proposed motor. To decline the bearing faults there are many approaches but cost may be varied according to the equipment arrangements which are used to find out the faults. The author explained in his research mainly bearing faults of the proposed motor and compares the performance of the motor with existing motor. Due to these faults motor may breakdown. Hence to reducing the faults and improving the performance of the motor, a software program is developed and applied to the motor to get low voltage and bearing currents.

S. H. Asgari [13] proposed in the year 2014, a new technique for 3-Φ IM when it is operated in D-Q axis model. By using the proposed model, controllers are designed to identify the fault-tolerant drive system. Here the motors suffer with one and two phase loss. The researcher observed the speed and torque and compared the integrity between healthy operation and faulty operation of the motor.

Saifullah Payami et al., [14] 2015, introduced a new topology of 5-Φ IM drive to analyze the common mode voltage when it is fed back to 3-level neutral point clamped converter. Usually the existing drives suffered from the common mode voltage imbalances and hence severe fluctuations occur. These draw backs were eliminated by means of the proposed topology with space vector approach. The number of switching states controlled the common mode voltage; the same states were employed for dc link capacitor voltages and eliminate the imbalances and fluctuations with affected currents of common mode. The proposed drive analyzed with and without considering the common mode voltage effects.

Yongchang et al., [15] introduced in the year 2015 a MPTC technique for IM drives. For adequate function at various operating points, stator flux and weighing factors are varied accordingly. With the empirical formulae, weighing factors are analyzed for the proposed drive. While continually varying weighing factor, it became a serious drawback for the operation of the drive. Model predictive flux control (MPFC) was the best solution for the above said drawback; here control variable is a stator flux vector. As a result MPFC was more advantageous than traditional MPTC and it was appropriately suitable for practical application.

Avanish Tripathi et al., [16] in the year 2015, proposed an IM drives with low-order harmonic torques, operated at a low pulse number by means of synchronous reference frame (SRF) and frequency-domain (FD) methods.

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The FD technique is independent of the load and motor parameters where as in SRF; the low harmonic torques taken into account of the load and machine parameters. Both topologies ST and SHE pulse width modulations were employed for the proposed drive. Based on the results SRF technique gave the performance compared to frequency domain technique.

Yang Mei et al., [17] in the year 2016, proposed a new improved modulation technique for a 5-leg inverter to drive series connected IM. Here the proposed inverter operating with svpwm approach in order to balance the common mode voltage and 30 voltage switching vectors and two states are zero vectors. These two states are used for dc common link for the series connected motors. The series connected motors are controlled with different loads and varied speed individually with respect to the PWM inverter the performance of the motor was analyzed.

Vivek M. Sundaram et al., [18] in the year 2016, introduced a new 5-Φ IM drive for smooth operation by analyzing the stator in turn faults. Here the drive was operated with and without fundamental fault environment without interrupting the drive operation and investigated stator faults. DC voltages were injected to the drive to monitor and detect the in turn stator faults with a low cost operated drive. Using a simple logic the drive was operated from healthy operation to faulty operation without interrupting the other functionaries of the drive. Various fault detection methods were discussed.

II. OBJECTIVES

The objectives of the proposed work are

- o model five phase machine drive(IM) in stationary reference frame
- o model and analyze the performance of five phase machine drive (IM) for one phase and two phase open fault using harmonic balance technique.

III. PRODUCTION OF REVOLVING FIELD FOR THE PROPOSED FPIM

The stator winding of FPIM is fed from the five phase supply, a revolving field will be developed due to the currents produced in the stator. The total flux is analyzed at various instants in terms of maximum flux at different instants.Here, φ_a, φ_b, φ_c, ϕ_d, ϕ_e is flux produced by the respective phases a, b, c, d, e etc., and shown in Figure 1 with a phase delay of 72^0 as the developed stator currents are also in phase delay of 72^0. In the conventional supply, the total flux produced by three phases is 1.5 times of the maximum flux. But this should be varied in the case of the proposed motor, analyzed by the produced flux in all the five phases at several instants which are shown below in five modes.

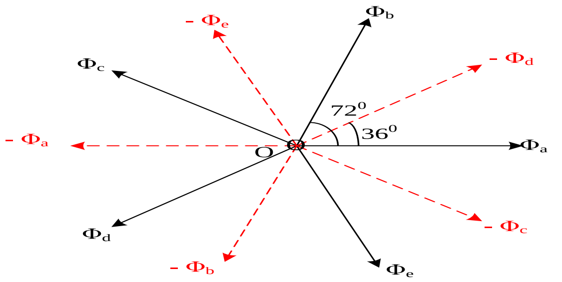

Figure 1 Flux Produced in Five Phases by FPIM

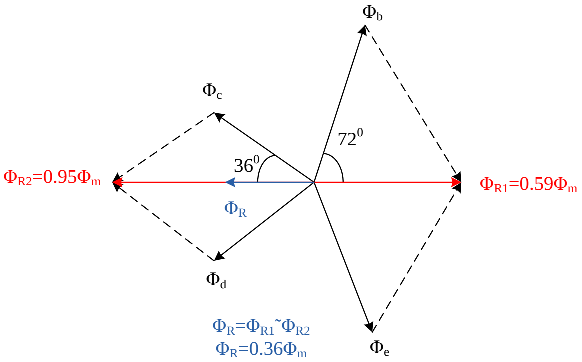

Figure 2 Resultant Flux Analyzed in Mode 1

The revolving flux rotates at constant speed around the air gap of the proposed FPIM. In this mode I, the resultant flux is analyzed in terms of maximum flux from phasor diagram shown in Figure 2.

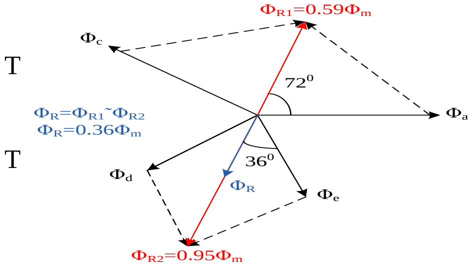

Figure 3 Resultant Flux Analyzed in Mode 2

In this mode 2, the resultant flux is analyzed in terms of maximum flux from phasor diagram shown in Figure 3.

At $\omega t = 72^0$,

$$\varphi_a = 0.95,\ \varphi_b = 0,\ \varphi_c = 0.95\varphi_m \qquad (1)$$

$$\varphi_d = 0.59\varphi_m,\ \varphi_e = 0.95\varphi_m$$

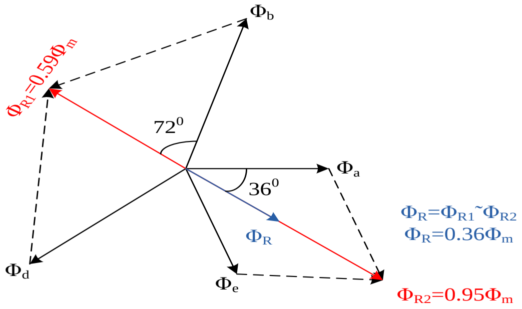

Figure 4 Resultant Flux Analyzed in Mode 3

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In this mode 3, the resultant flux is analyzed in terms of maximum flux from phasor diagram shown in Figure 4.

At $\omega t = 144^0$,

$$\varphi_a = 0.59\varphi_m\ ,\ \varphi_b = 0.95\varphi_m,\ \varphi_c = 0 \qquad (2)$$

$$\varphi_d = 0.95\varphi_m,\ \varphi_e = 0.59\varphi_m$$

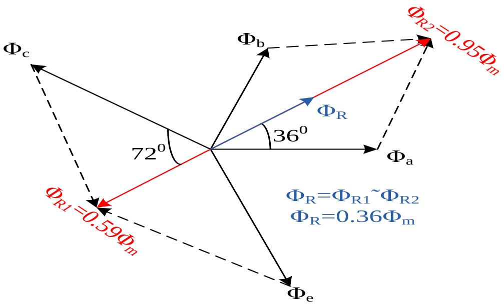

Figure 5 Resultant Flux Analyzed in Mode 4

In this mode 4, the resultant flux is analyzed in terms of maximum flux from phasor diagram shown in Figure 5.

At $\omega t = 216^0$,

$$\varphi_a = 0.59\varphi_m\ ,\ \varphi_b = 0.59\varphi_m\ ,\ \varphi_c = 0.95\varphi_m \qquad (3)$$

$$\varphi_d = 0,\ \varphi_e = 0.95\varphi_m$$

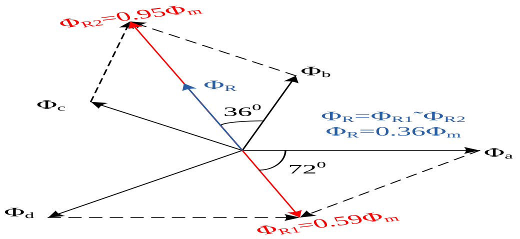

Figure 6 Resultant Flux Analyzed in Mode 5

In this mode 5, the resultant fluxes are analyzed in terms of maximum flux from phasor diagram shown in Figure 6..

At $\omega t = 288^0$,

$$\varphi_a = 0.95\varphi_m\ ,\ \varphi_b = 0.59\varphi_m,\ \varphi_c = 0.59\varphi_m \qquad (4)$$

$$\varphi_d = 0.95\varphi_m,\ \varphi_e = 0$$

3.1 PRODUCTION OF TORQUE FOR THE PROPOSED FPMD

Let us suppose that conductor A of the stationary rotor is lying under the influence of North Pole and the developed field flux is rotating in clock wise direction.

In this case the relative motion of the rotor conductor as compared to stator is anti clock wise as shown by dotted arrow in Figure 7.By applying Fleming's right hand rule, the induced current is found to be outward. If the current is allowed to complete its path, it will produce a magnetic field around the conductor which is anti clock wise as determined by applying cork screw rule. As these two field fluxes are acting in the same space, the total field will be the resultant of the two conductors is shown in Figure 7. From this Figure 7, it is clear that the field on the L.H.S is less. Hence clockwise torque will act on the rotor causing rotary motion of the rotor towards the direction of the revolving magnetic field.

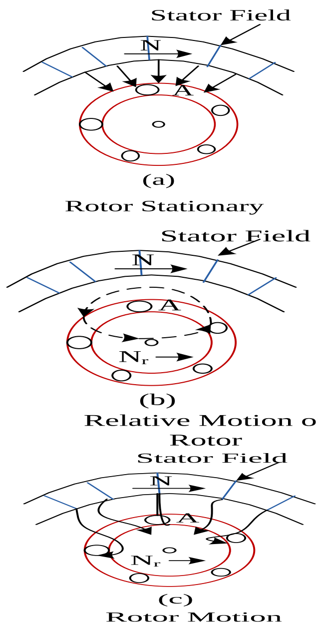

Figure 7 Production of Torque in FPIM

3.2 LINEAR TRANSFORMATION IN ELECTRICAL MACHINES

Several transformations are applied in series which convert the quantities to continuous equation with unvarying coefficients. Normally the conversion is used in the ac machine analysis, which converts the 3-Φ to 2-Φ with zero sequence system.

Another transformation is applied to obtain the constant coefficients independent of rotation. The inductance becomes independent of rotation if the transformation can be developed in this method there is no comparative motion among the stator and rotor coils in transformed system. The resulting matrix contains constant coefficients. If the air gap is uniform, in the proposed motor the reference frame is fixed to stator. It can be fixed to the rotating magnetic field; advantages are depending upon the type of solution and excitation used for the machine. IM voltage and torque equations of time-varying in nature, illustrates the dynamic behavior of the motor.

The dynamic Equations for the FPIM will be rewritten as follows.

For the stator winding, the voltage Equations are expressed as

$$v_{as} = r_s i_{as} + p\lambda_{as} \qquad (5)$$

$$v_{bs} = r_s i_{bs} + p\lambda_{bs} \qquad (6)$$

$$v_{cs} = r_s i_{cs} + p\lambda_{cs} \qquad (7)$$

$$v_{ds}^a = r_s i_{ds}^a + p\lambda_{ds}^a \qquad (8)$$

$$v_{es} = r_s i_{es} + p\lambda_{es} \qquad (9)$$

where v_{as}, v_{bs}, v_{cs}, v_{ds}^{a} and v_{es} are the voltages of stator phases, i_{as}, i_{bs}, i_{cs}, i_{ds}^{a} and i_{es} are the currents of stator phases, and λ_{as}, λ_{bs}, λ_{cs}, λ_{ds}^{a} and λ_{es} are the flux linkages of stator phases, respectively; r_s is the resistance of stator phase. The superscript 'a' on phase'd' variables are the d-axis variables.

For the rotor winding, the voltage Equations are expressed as

$$v_{ar} = r_r i_{ar} + p\lambda_{ar} \quad (10)$$

$$v_{br} = r_r i_{br} + p\lambda_{br} \quad (11)$$

$$v_{cr} = r_r i_{cr} + p\lambda_{cr} \quad (12)$$

$$v_{dr}^{a} = r_r i_{dr}^{a} + p\lambda_{dr}^{a} \quad (13)$$

$$v_{er} = r_r i_{er} + p\lambda_{er} \quad (14)$$

where v_{ar}, v_{br}, v_{cr}, v_{dr}^{a} and v_{er} are the phase rotor voltages, i_{ar}, i_{br}, i_{cr}, i_{dr}^{a} and i_{er} are the phase rotor currents, and λ_{ar}, λ_{br}, λ_{cr}, λ_{dr}^{a} and λ_{er} are the phase rotor flux linkages, respectively; r_r is the rotor phase resistance.

The transformation matrix of arbitrary reference frame is given by

$$T(x) = \frac{2}{5}\begin{bmatrix} \cos(x) & \cos(x-\alpha) & \cos(x-2\alpha) & \cos(x+2\alpha) & \cos(x+\alpha) \\ \sin(x) & \sin(x-\alpha) & \sin(x-2\alpha) & \sin(x+2\alpha) & \sin(x+\alpha) \\ \cos(x) & \cos(x-2\alpha) & \cos(x+\alpha) & \cos(x-\alpha) & \cos(x+2\alpha) \\ \sin(x) & \sin(x-2\alpha) & \sin(x+\alpha) & \sin(x-\alpha) & \sin(x+2\alpha) \\ \frac{1}{2} & \frac{1}{2} & \frac{1}{2} & \frac{1}{2} & \frac{1}{2} \end{bmatrix}$$

where $\alpha = \frac{2\pi}{5}$, $x = \theta - \theta_x$, θ is the transformation angle of arbitrary reference frame. $\theta_x = 0^0$ is for the stator stationary reference variable transformation and $\theta_x = \theta_r$ is for the corresponding rotor variable transformation, where θ_r is the electrical rotor angle.

Therefore, the variables of machine can be transformed to qdxyoz variables as

$$f_{qdxyoz} = T(x) f_{abcdez}$$

Where

$f_{qdxyoz} = \left[f_{qz} \quad f_{dz} \quad f_{xz} \quad f_{yz} \quad f_{oz}\right]^T$ is the variable matrix consisting of voltages, fluxes and currents in $qdxyo$ reference frame and $f_{abcdez} = \left[f_{az} \quad f_{bz} \quad f_{cz} \quad f_{dz} \quad f_{ez}\right]^T$ is the variable matrix consisting of voltages, fluxes and currents in frame of natural reference z can respectively be replaced with s and r for stator and rotor variables respectively.

The electromagnetic torque T_e, is given by

$$T_e = \frac{mP}{4}\frac{L_m}{L_r}(\lambda_{dr}^{'} i_{qs} - \lambda_{qr}^{'} i_{ds}) \quad (15)$$

The rotor speed is given by

$$\frac{2J}{P} p\omega_r = T_e - T_L \quad (16)$$

Where m is the number of phases, P is the number of poles, J represents moment of inertia, and T_L represents load torque.

4.1 HARMONIC BALANCE TECHNIQUE FOR ONE STATOR OPEN PHASE FAULT

For calculating steady state and harmonic quantities, equations are derived using the harmonic balance technique. The state variables are presumed to be the structure of the supply voltages. Representing the supply voltages as

$$v_{bs} = \mathrm{Re}(v_{bss} e^{j\theta_e}) \quad (17)$$

$$v_{bss} = V_m e^{-j\alpha} \quad (18)$$

$$v_{cs} = \mathrm{Re}(v_{css} e^{j\theta_e}) \quad (19)$$

$$v_{css} = V_m e^{-j2\alpha} \quad (20)$$

$$v_{ds}^{a} = \mathrm{Re}(v_{dss}^{a} e^{j\theta_e}) \quad (21)$$

$$v_{dss}^{a} = V_m e^{j2\alpha} \quad (10) \quad (22)$$

$$v_{es} = \mathrm{Re}(v_{ess} e^{j\theta_e}) \quad (23)$$

$$v_{bss} = V_m e^{-j\alpha} \quad (24)$$

where V_m represents peak value of the phase voltage. In view of the form of the supply phase voltages, the state variables and the input voltages are therefore defined. In attaining the model equations based on the harmonic balance technique, the following relation has been used and only second order harmonics are considered.

$$\mathrm{Re}(x)\mathrm{Re}(y) = \frac{1}{2}\left[\mathrm{Re}(xy^*) + \mathrm{Re}(xy)\right] \quad (25)$$

The model obtained by harmonic balance technique can be used to analyze the steady state performance of the faulted machine. State variables peaks are considered to be constant and their derivatives becomes zero. To study the dynamics of the faulted system, small signal model is derived from the harmonic balance technique model by causing small changes in the state and control variables.

(11)

IV.MODELING OF FPMD FOR OPEN PHASE FAULT

Consider the configuration of Figure 1 with a switch connected in series with phase 'a' of the stator winding. Open phase fault occurs when the switch is open such that the supply voltage is disconnected from the machine's phase 'a'.

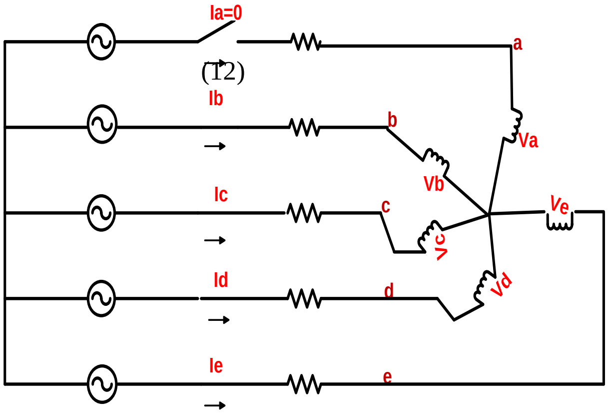

Figure 8 Open stator phase 'a' for the FPIM

(13)

From the transformation relationships of equation (12), where subscript z is replaced with s
for stator variables, it can be deduced that

(14)

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$$f_{qs}=\frac{2}{5}\left[f_{as}+f_{bs}\cos(\alpha)+f_{cs}\cos(2\alpha)+f_{ds}^{a}\cos(2\alpha)+f_{es}\cos(\alpha)\right]$$

$$f_{ds}=\frac{2}{5}\left[-f_{bs}\sin(\alpha)-f_{cs}\sin(2\alpha)+f_{ds}^{a}\sin(2\alpha)+f_{es}sn(\alpha)\right]$$

$$f_{xs}=\frac{2}{5}\left[f_{as}+f_{bs}\cos(2\alpha)+f_{cs}\cos(\alpha)+f_{ds}^{a}\cos(\alpha)+f_{es}\cos(2\alpha)\right]$$

$$f_{ys}=\frac{2}{5}\left[-f_{bs}\sin(2\alpha)+f_{cs}\sin(\alpha)-f_{ds}^{a}\sin(\alpha)+f_{es}\sin(2\alpha)\right]$$

$$f_{os}=\frac{1}{5}\left[f_{as}+f_{bs}+f_{cs}+f_{ds}^{a}+f_{es}\right] \tag{26}$$

When the stator phase ‘a’ is open, the machine voltages become unbalanced. Since phase ‘a’ voltage becomes unknown, then the q- x- and o-axis voltages become unknown.

The relationship between the q-axis and the x-axis stator variables can be given as

$$f_{qs}-f_{xs}=C$$

$$f_{qs}+f_{xs}=\frac{4}{5}f_{as}+\varepsilon_2\left[f_{bs}+f_{cs}+f_{ds}^{a}+f_{es}\right] \tag{27}$$

When the variable f is replaced with the stator phase voltages and currents, Equation (20) is used to eliminate the unknown phase ‘a’ voltage. Also Equation (21) is used to get the relationship between the q-axis and x-axis stator currents. Thus, (20) and (21) turn into

$$v_{qs}-v_{xs}=C$$

$$pi_{qs}=\frac{1}{L_{ls}L_r^{'}+L_sL_r^{'}-L_m^2}\left(L_r^{'}C-2r_sL_r^{'}i_{qs}-L_mp\lambda_{qr}^{'}\right) \tag{28}$$

$$pi_{ds}=\frac{1}{L_sL_r^{'}-L_m^2}\left(L_r^{'}v_{sd}-r_sL_r^{'}i_{qs}-L_mp\lambda_{dr}^{'}\right) \tag{29}$$

$$p\lambda_{qr}^{'}=v_{qr}^{'}-\frac{r_r^{'}}{L_r^{'}}\left(\lambda_{qr}^{'}-L_mi_{qs}\right)+\omega_r\lambda_{dr}^{'} \tag{30}$$

$$p\lambda_{dr}^{'}=v_{dr}^{'}-\frac{r_r^{'}}{L_r^{'}}\left(\lambda_{dr}^{'}-L_mi_{ds}\right)-\omega_r\lambda_{qr}^{'} \tag{31}$$

The phase ‘a’ voltage is given by

$$v_{as}=\frac{5}{2}v_{qs}-\left[v_{bs}+v_{es}\right]\cos(\alpha)-\left[v_{cs}+v_{ds}^{a}\right]\cos(2\alpha) \tag{32}$$

Equations (15), (16), (28), (29), (30), (31) and (32) defines dynamic Equations for the faulted machine and are used to determine the circuit based model of the open phase faulted five phase induction machine. They are used to simulate the machine for this faulted condition.

Similarly, the operation with two adjacent phases (‘a’ and ‘b’) open on fault is depicted in Figure 5.15. When the two phases are open, the phase voltages across the machine phase windings ‘a’ and ‘b’ become unknown. Under this condition, all the qdxyos transformed voltages become unknown.

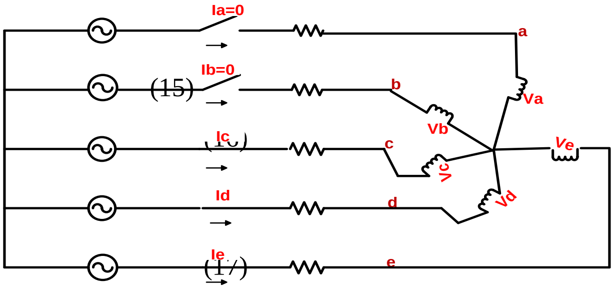

Figure 9 open stator phases ‘a’ and ‘b’ of the stator for the five phase induction machine

At steady state, the derivatives of the peaks are zero. When the speed harmonic component is taken into account, then the Equations have to be separate into their real and imaginary parts. The resulting systems of steady-state Equations will be solved by iteration to obtain the results.

V. RESULTS

The validity of the models presented in section 5.4 - 5.4.2 has been investigated through the computer simulation of the full-order model of the machine with stator phases ‘*a*’ and ‘*b*’ open-circuited. The steady-state model is used to calculate the state variables and then the results are compared.

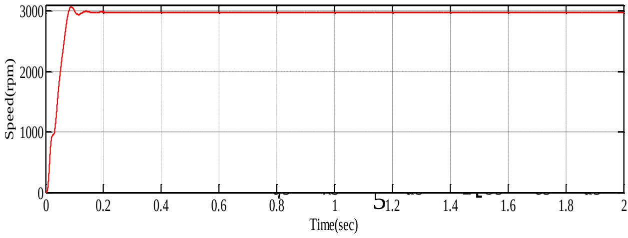

Figure 10 Speed of FPIM under Balanced Condition

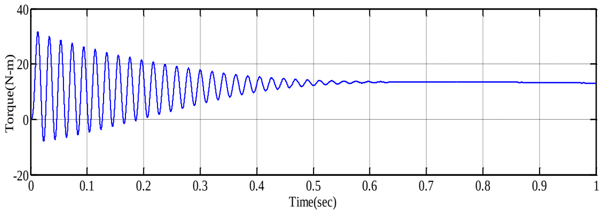

Figure 11 Torque of FPIM under Balanced Condition

Observe the Figure 10 and 11 the rotor speed and starting torque of the FPIM are 2985 rpm, 32N-m respectively. The experimental values are also tabulated. The settling time of the torque will be 0.6Sec and the magnitude of torque13.8 N-m. Both simulated and experimental results of speed and torque are approximately equal as shown.

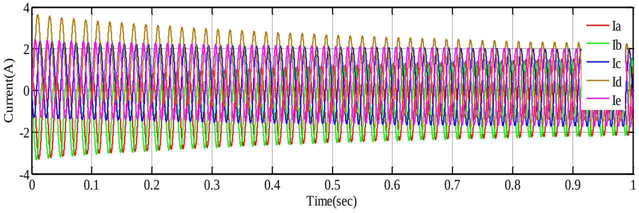

Figure 12 Starting Currents of FPIM under Balanced Condition

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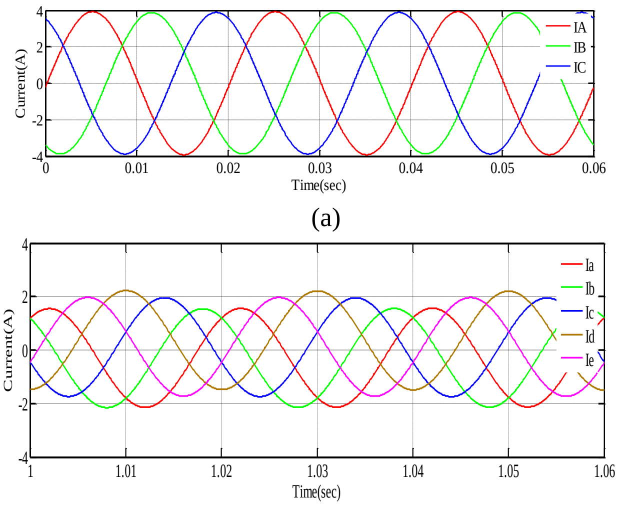
Observe the Fig.4.13 the five phase starting currents are 8A of FPIM. Clearly the waveforms are visible for three cycles as shown in Fig.ure 13.



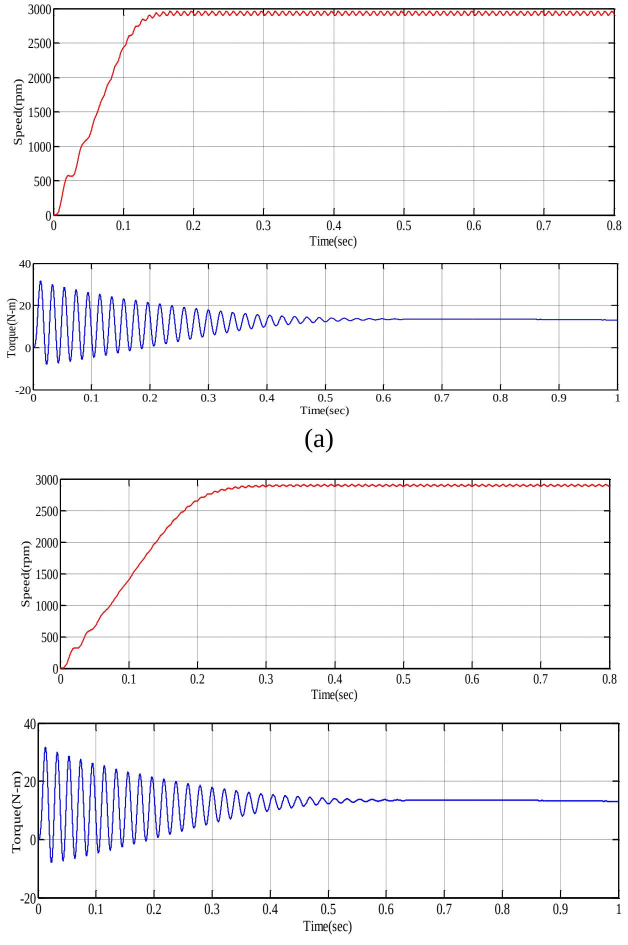
(a)

(b)

Figure 13 Stator Currents of FPIM under Balanced Condition (a) input current (b) output current

Observe the Fig.4.14 the input and output currents are 4A and 2.1 A during a period of three cycles with FPIM respectively.

During the phase loss environment of FPIM, there is no change in the input and output voltages. But if the speed and torque are changed slightly, the results are shown both simulated using MATLAB/SIMULINK and through experimental setup. Also practical values are tabulated.

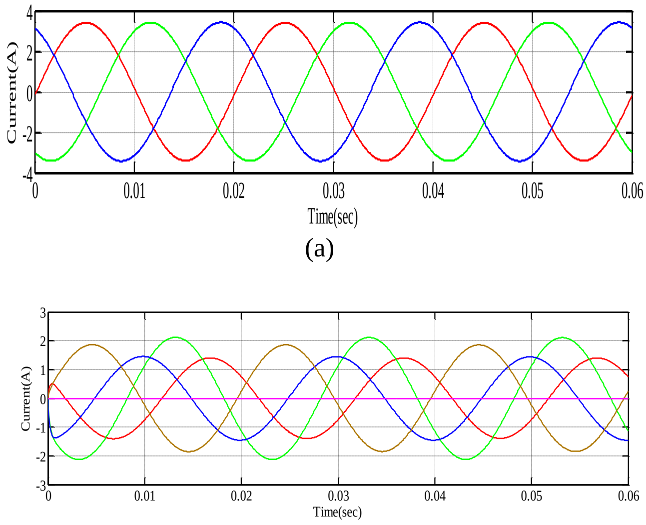


(a)

(b)

Figure14. Speed and Torque of FPIM under (a) One Phase (b) Two Phase

Observe the Figure 14 of speed and torque under phase loss condition; there is a small difference even at phase loss of FPIM and the values are tabulated. Torque is approximately constant in all the phase loss conditions for the proposed FPIM.



(a)

(b)

Figure 15 Stator Currents of FPIM under one phase loss condition (a) input current (b) ouput current

Observe the Figure 15 output currents are increased, without increasing the voltage under phase loss condition; when one phase loss condition i.e. stator current $I_e = 0$, now the magnitude of input and output currents are 3.6A and 2.6A during a period of three cycles with FPIMD.

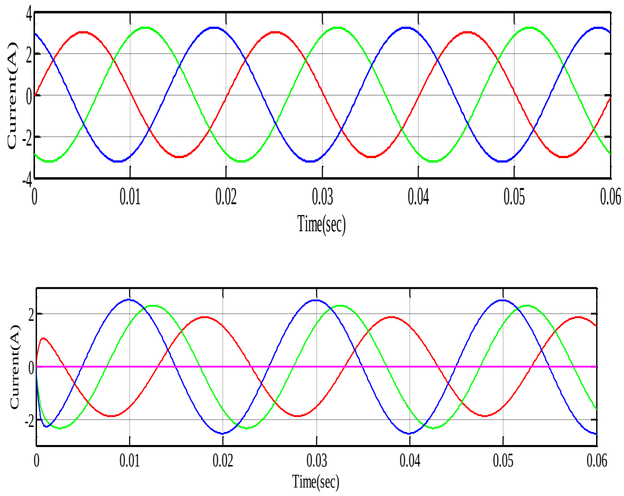


Figure 16 Stator Currents of FPIM under Two Phase Loss Condition (a) Input Current (b) Ouput Current

Observe the Figure 16 under two phase loss condition i.e. stator currents $I_e = I_d = 0$, the magnitude of input and output currents are 3.1A and 2.6A during a period of three cycles of with FPIM.

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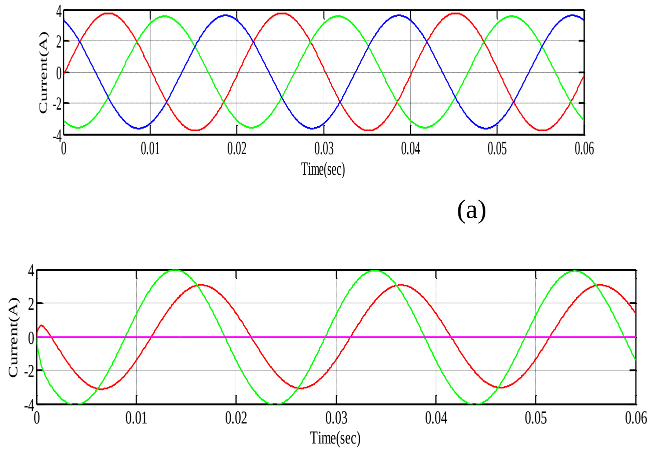

(a)

Figure 17 Stator Currents of FPIM under Three Phase Loss Condition (a) Input Current (b) Ouput Current

Observe the Fig.4.18 under three phase loss condition i.e. stator current $I_e = I_d = I_c = 0$, the magnitude of input and output currents are 4A and 4.1A during a period of three cycles of with FPIM.

Under phase loss condition; the performance of FPIM does not degrade much. The stator currents are increased when phase loss condition, therefore the advantages of the proposed drive, without increasing the voltage, the stator currents are increased with minimum torque ripple in the drive. Hence the reliability of the drive, gets enhanced.

VI. CONCLUSION

This paper offers a steady state and dynamic model of the open phase faults for a five phase induction machine drive for one phase and any two phases(either consecutive or non consecutive) out of five phases. The proposed circuit based models predicts not only the starting transients but also the steady-state of the faulted machine. Steady state and dynamic performance of the faulted machine can be obtained with the help of harmonic balance technique for full-order differential equation model in stationary reference frame under open-phase faults. Simulation results for starting transients and steady state results have been presented, in which it has been possible to calculate the speed harmonic components as well as the torque pulsations. Due to rotor flux linkages the machine show signs of instability at low rotor speeds.

The analysis has been presented in this work shows that , the five-phase machine drive is competent to start and generate a high percentage of rated torque even if one or two phases are misplaced. The diagnostic methodologies accessible in this work have great assure in the study of the transient, steady state and dynamic responses of various faults of multi-phase electric machinery.

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