Chapter 6

NONLINEAR PHENOMENON IN ELECTRICAL MACHINES

6.1 General:

The study of bifurcation phenomenon for generalized machine as reported in the previous chapter can be used for the study of the same in other conventional machines and that can be validated. For its application, the equations of the dynamics of other machines have to be modified as per the existence of the coils. Similar process will be adopted to find out the route of the chaos. However, as mentioned earlier that the dynamic equation of the conventional machines as well as the generalized machine are similar to Lorenz like systems. Some of those systems are reported in the chapter 2 and their brief bifurcation phenomenon and the dynamics are outlined there so that those existing systems can be compared with the available equations of dynamics of the conventional machines[91].

6.2 Nonlinear Phenomenon in Permanent Magnet Synchronous Machines:

6.2.1 Mathematical Modeling:

The permanent magnet Synchronous machine is a machine containing two windings on the rotor. Along with the equation of motion of becomes 3. Hence dimension of the system is reduced and it is 3. No. of parameters also becomes fewer.

Detailed modeling of PM motor is required for proper simulation of the system. The d-q model has been developed [70]-[75]on rotor reference frame as shown in fig.6.1.At any time t, the rotating rotor d-axis makes and angle θr with the fixed stator phase axis and rotating stator mmf makes an angle α with the rotor d-axis. Stator mmf rotates at the same speed as that of the rotor.

The model of PMSM without damper winding has been developed on rotor reference frame using the following assumptions:

1) Saturation is neglected.

2) The induced EMF is sinusoidal.

3) Eddy currents and hysteresis losses are negligible.

4) There are no field current dynamics.

The dynamic d q modeling is used for the study of motor. It is done by converting the three phase voltages and currents to dqo variables by using Parks transformation.

Converting the phase voltages variables vabc to vdqo variables in rotor reference frame the following equations are obtained:

$$\begin{bmatrix} V_{ds} \\ V_{qs} \\ V_0 \end{bmatrix} = \frac{2}{3} \begin{bmatrix} \sin\theta_r & \sin(\theta_r - 120) & \sin(\theta_r + 120) \\ \cos\theta_r & \cos(\theta_r - 120) & \cos(\theta_r + 120) \\ 1/2 & 1/2 & 1/2 \end{bmatrix} \begin{bmatrix} Va \\ Vb \\ Vc \end{bmatrix} \tag{6.1}$$

It also can be converted to Vabc by using the transformation:

$$\begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix} = \begin{bmatrix} \sin\theta_r & \cos\theta_r & 1 \\ \sin(\theta_r - 120) & \cos(\theta_r - 120) & 1 \\ \sin(\theta_r + 120) & \cos(\theta_r + 120) & 1 \end{bmatrix} \begin{bmatrix} V_{ds} \\ V_{qs} \\ V_0 \end{bmatrix} \tag{6.2}$$

Voltage equations are given by:

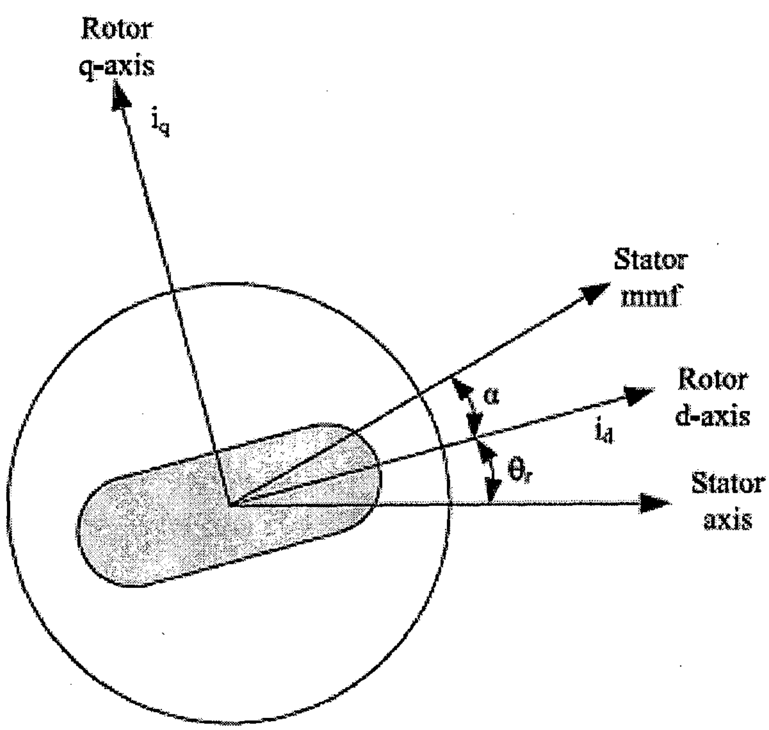


Fig. 6.1: d-q Phasors of permanent magnet Synchronous motor

Voltage equations are given by:

$$v_{ds} = L_{ds} \frac{di_{ds}}{dt} + R_1 i_{ds} - \omega L_{qs} i_{qs}$$

$$v_{qs} = L_{qs} \frac{di_{qs}}{dt} + R_1 i_{qs} + \omega L_{ds} i_{ds} + \omega \psi_r \tag{6.3}$$

And dynamic equation

$$J \frac{d\omega}{dt} = Te - T_L - B\omega \tag{6.4}$$

Where $T_e = n_p \psi_r i_{qs} + n_p (L_{ds} - L_{qs}) i_{ds} i_{qs}$

Here, V_{ds}, V_{qs} = Direct axis and Quadrature axis stator voltages

I_{ds}, I_{qs} = Direct axis and Quadrature axis stator currents

L_{ds}, L_{qs} = Direct axis and Quadrature axis stator inductances

ψ_r = permanent magnet flux

Np= no. of pole pair of the machine

J= moment of inertia of motor load combination

B= viscous damping

R1= stator winding resistances

6.2.2 Analytical Approach:

The analytical approach of studying nonlinear phenomenon in Generalized electrical machine discussed in chapter 5 is being adopted here for the study of the permanent magnet synchronous motor. It's mathematical model is already developed in previous section. As the rotor windings are replaced by a permanent magnet two state variables are eliminated and no. of state variables has been reduced to 3 [34],[35].

$[v]=\begin{bmatrix} v_{ds} \\ v_{qs} \end{bmatrix}$, states are given by $\begin{bmatrix} i_{ds} \\ i_{qs} \\ \omega \end{bmatrix}$, then states equations derived from voltage equations and equation of the motion and given by

$$L_{ds}\frac{di_{ds}}{dt}=v_{ds}-R_1 i_{ds}+\omega L_{qs} i_{qs}$$

$$L_{qs}\frac{di_{qs}}{dt}=v_{qs}-R_1 i_{qs}-\omega L_{ds} i_{ds}-\omega\psi_r$$

$$J\frac{d\omega}{dt}=n_p\psi_r i_{qs}+n_p(L_{ds}-L_{qs})i_{ds}i_{qs}-T_L-B\omega \tag{6.5}$$

The equilibrium of the system will be obtained by setting the LHS of the equation s zero. This gives

$$I_{qs}=\frac{T_L}{n_p\psi_r}+\frac{B}{n_p\psi_r}\omega$$

$$I_{ds}=\frac{V_d}{R_1}+\frac{\omega L_{qs}T_L}{n_p\psi_r R_1}+\frac{\omega^2 L_{qs}B}{n_p\psi_r R_1} \tag{6.6}$$

$$\varpi^3+\frac{T_L}{B}\varpi^2+\left(\frac{R_1^2}{L_{ds}L_{qs}}+\frac{\psi_r^2 n_p R_1}{L_{ds}L_{qs}B}+\frac{V_{ds}n_p\psi_r}{L_{ds}L_{qs}B}\right)\varpi+\left(\frac{R_1^2 T_L}{L_{ds}L_{qs}B}-\frac{V_{qs}n_p\psi_r R_1}{L_{ds}L_{qs}B}\right)=0 \tag{6.7}$$

with $a_2=\frac{T_L}{B}$

$$a_1=\left(\frac{R_1^2}{L_{ds}L_{qs}}+\frac{\psi_r^2 n_p R_1}{L_{ds}L_{qs}B}+\frac{V_{ds}n_p\psi_r}{L_{ds}L_{qs}B}\right)$$

$$a_0=\left(\frac{R_1^2 T}{L_{ds}L_{qs}B}-\frac{V_{qr}n_p\psi_r R_1}{L_{ds}L_{qs}B}\right) \tag{6.8}$$

The equilibrium point(I_{ds}, I_{qs}, ϖ) is described by the above equations. If the equilibrium is restricted in the real domain then D≤0 must hold.

Where $$D = \left(\frac{p}{3}\right)^3 + \left(\frac{q}{2}\right)^2$$

$$p \equiv \frac{3a_1 - a_2^2}{3}$$

$$q \equiv \frac{9a_1 a_2 - 27a_0 - 2a_2^3}{27}$$

If D=0, ϖ has 3 real roots where two of them are equal and reminder is negative. The condition D=0 can be achieved without loosing the generality where T_L and v_{qs} can take deterministic values and v_{ds} can be adjusted accordingly. Other corresponding values of the state variables can be obtained from Equation 6.2

If D<0 , all roots are real and unequal. That condition also can be achieved by adjusting the parameters and other corresponding values of state variables for those equilibrium points can be calculated.

A general case may be worked out here. It is assumed that $V_{ds} = V_{qs} = T_L = 0$

Then

$$\varpi^3 + \left(\frac{R_1^2}{L_{ds}L_{qs}} + \frac{\psi_r^2 n_p R_1}{L_{ds}L_{qs}B}\right)\varpi = 0$$

It gives $\varpi_1 = 0$ There fore from Equation (6.2)

$$I_{ds1} = I_{qs1} = 0$$

That is, the origin is an equilibrium point. For other two nontrivial equilibrium point,

$$\varpi^2 + \left(\frac{R_1^2}{L_{ds}L_{qs}} + \frac{\psi_r^2 n_p R_1}{L_{ds}L_{qs}B}\right) = 0$$

$$\text{or } \varpi_{2,3} = \pm\sqrt{-\left(\frac{R_1^2}{L_{ds}L_{qs}} + \frac{\psi_r^2 n_p R_1}{L_{ds}L_{qs}B}\right)} \tag{6.9}$$

For the existence of those values,

$$\left(\frac{R_1^2}{L_{ds}L_{qs}} + \frac{\psi_r^2 n_p R_1}{L_{ds}L_{qs}B}\right) \le 0 \tag{6.10}$$

Corresponding values of the other state variables:

$$I_{ds2,3} = \varpi_{2,3}^2 = -\left(\frac{R_1^2}{L_{ds}L_{qs}} + \frac{\psi_r^2 n_p R_1}{L_{ds}L_{qs}B}\right)$$

$$I_{qs2,3} = \varpi_{2,3} = \sqrt{-\left(\frac{R_1^2}{L_{ds}L_{qs}} + \frac{\psi_r^2 n_p R_1}{L_{ds}L_{qs}B}\right)}$$

Like the Lorenz equation, the system will remain stable at the origin till $\left(\frac{R_1^2}{L_{ds}L_{qs}} + \frac{\psi_r^2 n_p R_1}{L_{ds}L_{qs}B}\right) \prec 0$

However, at $\left(\frac{R_1^2}{L_{ds}L_{qs}} + \frac{\psi_r^2 n_p R_1}{L_{ds}L_{qs}B}\right) = 0$, the origin will loose the stability in a pitchfork bifurcation at that point creating two nontrivial equilibria which are initially stable. To determine the stability of these nontrivial equilibria the Jacobian matrix has to be formed.

For nontrivial equilibria, Jacobian matrix is given by

$$J_{2,3} = \begin{bmatrix} \dfrac{-R_1}{L_{dr}} & \dfrac{\varpi_{2,3}L_{qr}}{L_{dr}} & \dfrac{L_{qr}I_{qr2,3}}{L_{dr}} \\ -\dfrac{\varpi_{2,3}L_{dr}}{L_{qr}} & \dfrac{-R_1}{L_{qr}} & \dfrac{-L_{dr}I_{dr2,3} - \Psi_r}{L_{qr}} \\ 0 & \dfrac{n_p\Psi_r}{J} & \dfrac{-B}{J} \end{bmatrix} \tag{6.11}$$

For eigen values,

$$\begin{vmatrix} \frac{-R_1}{L_{ds}}-\lambda & \frac{\varpi_{2,3}L_{qs}}{L_{ds}} & \frac{L_{qs}I_{qs2,3}}{L_{ds}} \\ -\frac{\varpi_{2,3}L_{ds}}{L_{qs}} & \frac{-R_1}{L_{qs}}-\lambda & \frac{-L_{ds}I_{ds2,3}-\psi_r}{L_{qs}} \\ 0 & \frac{n_p\psi_r}{J} & \frac{-B}{J}-\lambda \end{vmatrix} = 0$$

It gives

$$\lambda^3+\lambda^2\left(\frac{B}{J}+\frac{R_1}{L_{ds}}+\frac{R_1}{L_{qs}}\right)+\lambda\left(\frac{-\psi_r n_p R_1}{BL_{ds}L_{qs}J}+\frac{R_1B}{L_{qs}J}+\frac{R_1B}{L_{ds}J}\right)+\left(\frac{-n_p\psi_r L_{ds}I_{ds2,3}-n_p\psi_r^2}{L_{ds}L_{qs}J}+\frac{n_p\psi_r\varpi_{2,3}^2}{J}\right)$$

$$=0 \qquad (6.12)$$

Since two nontrival equilibria are symmetric, their stability must be same. Hopf Bifurcation[19] occurs when the corresponding Jacobian matrix has a pair of purely imaginary eigenvalues, with the remaining eigenvalues having nonzero real parts. For the bifurcation of two nontrival equilibria, i.e., values of the parameters for which either $\lambda=0$ or $\lambda=j\omega$ is the solution of the eigen value equation.

Setting $\lambda=0$, $\left(\frac{R_1^2}{L_{ds}L_{qs}}+\frac{\psi_r^2 n_p R_1}{L_{ds}L_{qs}B}\right)=0$ it gives pitchfork bifurcation which is already known.

For Hopf Bifurcation, putting $\lambda=j\omega$ in equation and equating real and imaginary parts:

$$\omega^2=\frac{\left(\frac{-n_p\psi_r L_{ds}I_{ds2,3}-n_p\psi_r^2}{L_{ds}L_{qs}J}+\frac{n_p\psi_r\varpi_{2,3}^2}{J}\right)}{\left(\frac{B}{J}+\frac{R_1}{L_{ds}}+\frac{R_1}{L_{qs}}\right)}=\left(\frac{-\psi_r n_p R_1}{BL_{ds}L_{qs}J}+\frac{R_1B}{L_{qs}J}+\frac{R_1B}{L_{ds}J}\right) \qquad (6.13)$$

Rearranging this relation the critical values of different parameters responsible for Hopf Bifurcation will be available. At that critical value corresponding to Hopf Bifurcation, the equilibria will be surrounded by the limit cycle. At a value of the parameter greater than the critical value, all three equilibria will become unstable.

The analytical results are similar to those obtained in case of Generalized machine as described in chapter 5. However, due to less no. of dimension analysis becomes easier to some extent and able to find the significant results like hopf bifurcation point analytically which was not possible for earlier case.

6.2.3 Numerical Approach:

The mathematical model of permanent magnet synchronous motor developed earlier is simulated to nonlinear dynamics of the machine[33].

Simulation is done for the following values of the parameters:

$$
\begin{aligned}
&\mathrm{np} = 1 \\
&\mathrm{R1} = 0.9\Omega \\
&\mathrm{Lds} = 15m\mathrm{H}, \\
&\mathrm{Lqs} = 15mH \\
&\mathrm{J} = 0.00005, \mathrm{Kgm}^2 \\
&\mathrm{B} = 0.017\mathrm{N/rad/s} \\
&\psi_r = 0.03 \\
&\mathrm{np} = 1 \\
&\mathrm{T_L} = 0
\end{aligned}
$$

Vds and Vqs are chosen as variable parameters. However, during experiment, they will not be readily available but phase voltages will be obtained.

Here the values of the parameters are chosen same as those are having for the motor under test to be described in the next section. This is done so that the results obtained from numerical analysis can be compared with the experimental results. However, during numerical analysis, the transformed dq0 state variables are used as it is done conventionally however, for experimental study only the real and actual state variables are available. Therefore, only rotor speed is considered for comparison while simulation results are being compared with the experimental results.

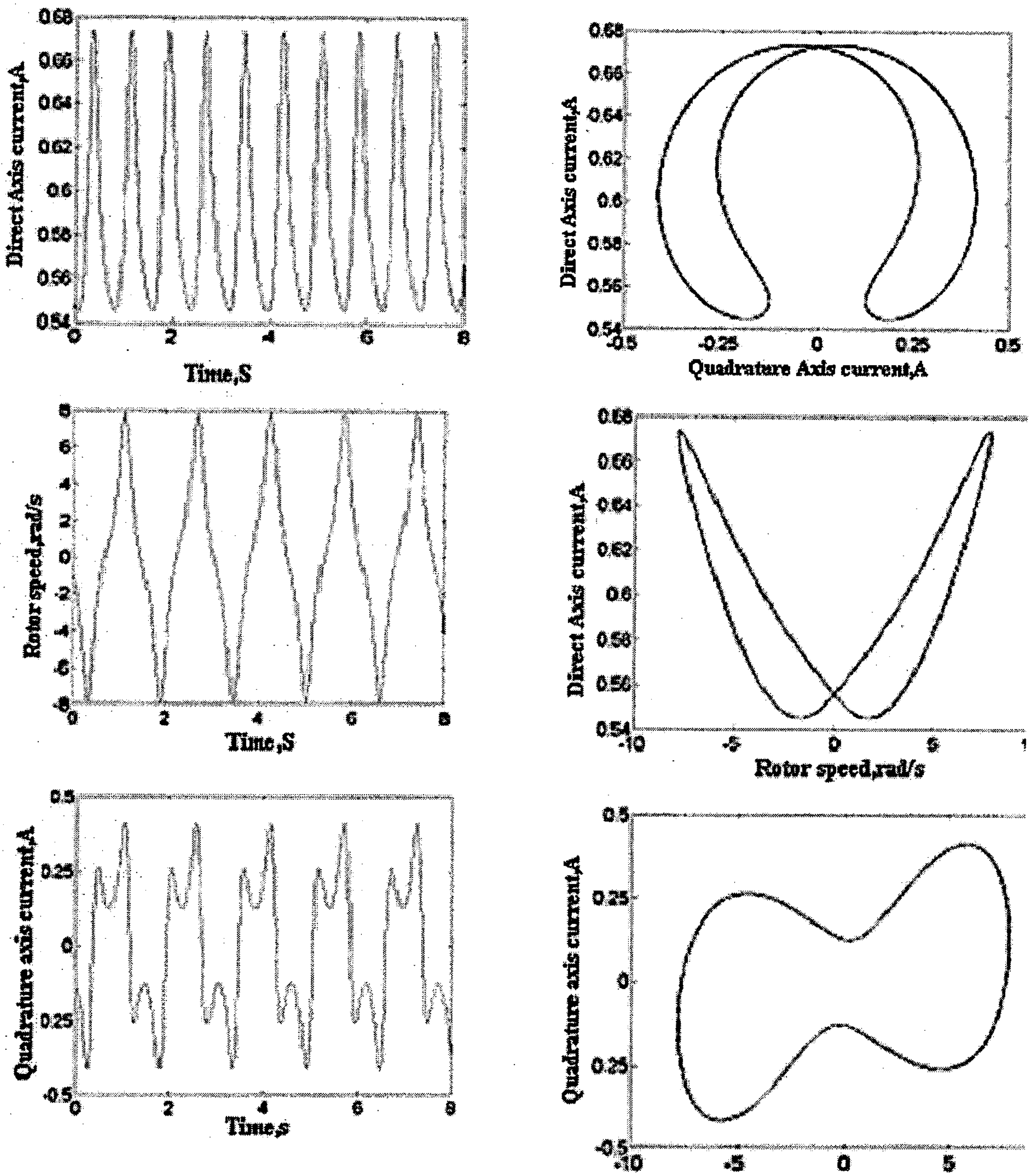


Fig6.2: Periodic waveforms and phase portraits of permanent magnet synchronous motor with the parameters as mentioned above and Vds=67V and Vqs=67V with TL=0

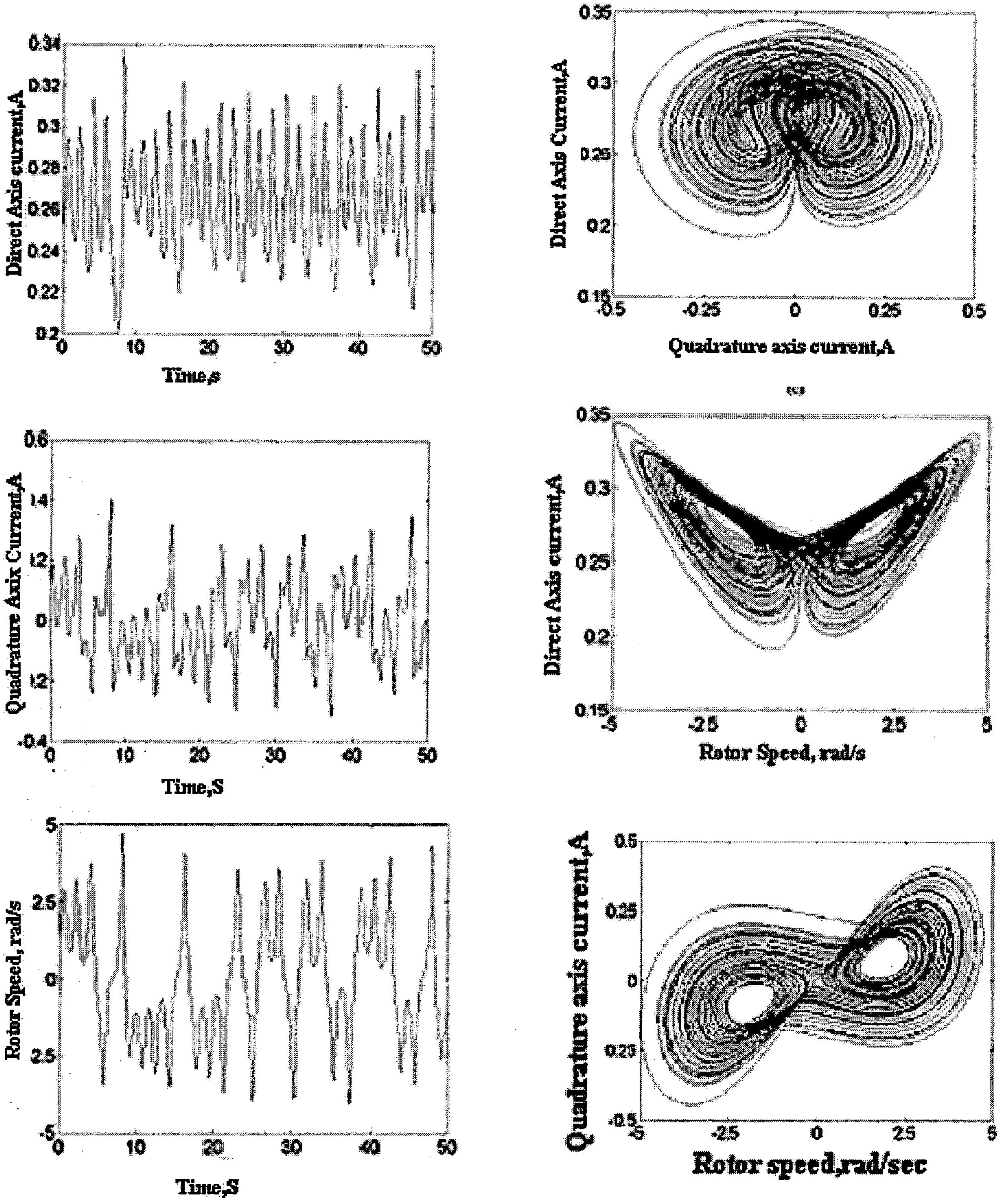


Fig6.3: Chaotic waveforms and phase portraits of permanent magnet synchronous motor with the parameters as mentioned above and Vds=115V and Vqs=115V with TL=0

6.2.3 Experimental Results:

Rating from the Nameplate:

C.Stall Torque=1.5Nm 2.4A

Max rpm = 6000

V =380Volt12 2A

IP =64/65 IC-400

Machine under test has the following parameter value:

$np = 1$

$R1 = 0.9\Omega$

$Lds = 15mH,$

$Lqs = 15mH$

$J = 0.00005, Kgm^2$

$B = 0.017N/rad/s$

$\psi_r = 0.03$

$T_L = 0$

Supply voltage are taken as variable parameters during the experiment. The dq variables, Vds and Vqs can be calculated using their measured value.

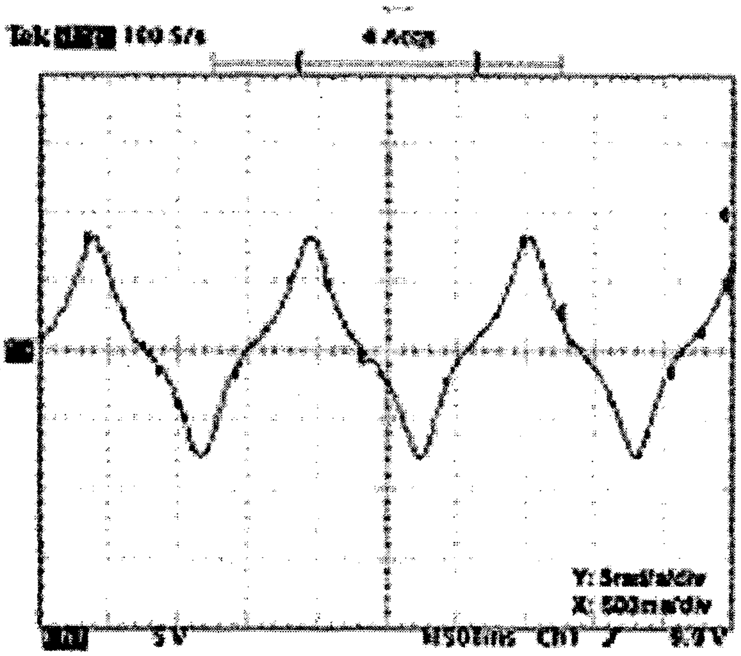


Fig6.4: Periodic waveforms and phase portraits of permanent magnet synchronous motor with the parameters as mentioned above and supply voltages are balanced with rms value of 67V i.e., Vds= Vqs= 67V with TL=0

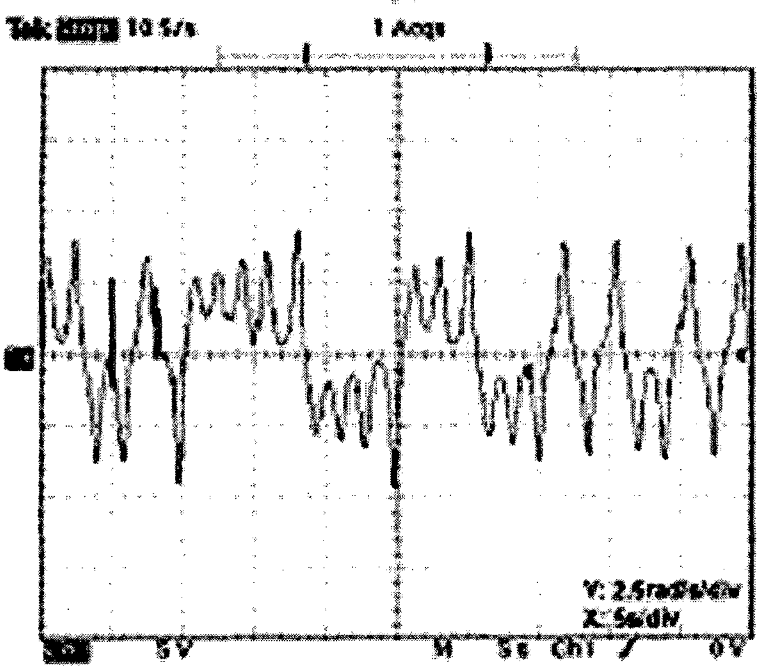


Fig6.5: chaotic waveform of permanent magnet synchronous motor with the parameters as mentioned above and supply voltages are balanced with rms value of 115V i.e., Vds= Vqs= 115V with TL=0

As mentioned earlier, only directly measurable state variable i.e., rotor's speed as obtained from experiment and numerical study are readily available for comparison. Comparison clearly reveals that they are fairly same and hence it not only shows that the performance of the numerical analysis is satisfactory , it also validates that the approach adopted for the study of hypothetical generalized machine in chapter 5 is fairly general and can be adopted for other conventional electrical machines.

6.3 Nonlinear Phenomenon in Single Phase Induction Motor:

The Shaded pole induction motor is widely accepted for domestic appliances, especially cooling fans. It offers the definite advantages of simple structure, low cost as well as highly rugged and reliable. Its uniqueness is the use of the auxiliary winding, also called the shading winding, to produce a starting torque. As shown in Fig.6.6, a shaded-pole motor uses no starting switch. The stator poles are equipped with an additional winding in each corner, that is, the shade winding.

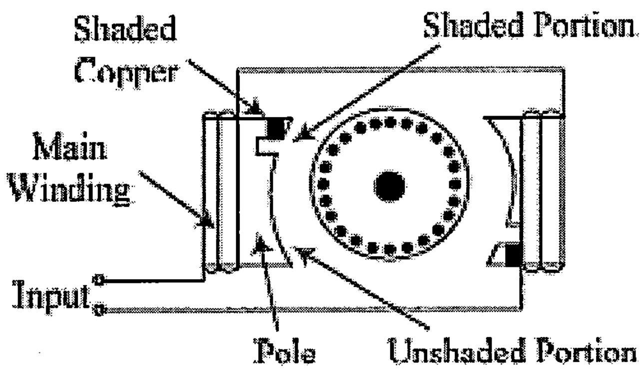


Fig.6.7: Shaded pole induction motor

These windings have no electrical connection for starting but use induced current to make a rotating magnetic field. The shaded pole structure of the SPIM enables the development of a rotating magnetic field by delaying the buildup of magnetic flux. A copper conductor isolates the shaded portion of the pole forming a complete turn around it. In the shaded portion, magnetic flux increases but is delayed by the current induced in the copper shield. Magnetic flux in the unshaded portion increases with the winding current forming a rotating field. The interaction of these two magnetic fields generates the starting torque for the motor. Normally, the effect of the shading winding is negligible when the motor reaches speed.

6.3.1 Mathematical Modeling:

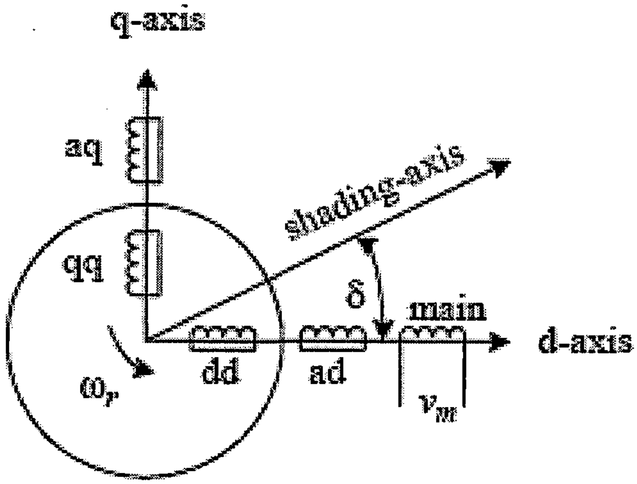


Fig.6.8: d-q model of Shaded pole induction motor

The d-q model of shaded pole induction motor[5],[6] is shown in fig.6.8.

When it is connected to supply,

$v_m = V\sin(2\pi ft + \theta)$

V= amplitude of the supply voltage

θ= initial phase angle

f= supply frequency

Then d-q model of the machine will be given by,

$$\begin{bmatrix} v_m \\ 0 \\ 0 \\ 0 \end{bmatrix} = \begin{bmatrix} L_{mm} & L_{ma} & L_{md} & 0 \\ L_{ma} & L_{aa} & L_{ar}\cos\delta & -L_{ar}\sin\delta \\ L_{md} & L_{ar}\cos\delta & L_{dd} & 0 \\ 0 & -L_{ar}\sin\delta & 0 & L_{qq} \end{bmatrix} p \begin{bmatrix} i_{ms} \\ i_{as} \\ i_{dr} \\ i_{qr} \end{bmatrix} + \begin{bmatrix} R_m & 0 & 0 & 0 \\ 0 & R_a & 0 & 0 \\ 0 & 0 & R_r & 0 \\ 0 & 0 & 0 & R_r \end{bmatrix} \begin{bmatrix} i_{ms} \\ i_{as} \\ i_{dr} \\ i_{qr} \end{bmatrix}$$

$$+\omega \begin{bmatrix} 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & n_p L_{ar}\sin\delta & 0 & -n_p L_{qq} \\ n_p L_{md} & n_p L_{ar}\cos\delta & n_p L_{dd} & 0 \end{bmatrix} \begin{bmatrix} i_{ms} \\ i_{as} \\ i_{dr} \\ i_{qr} \end{bmatrix} \tag{6.14}$$

i_{ms}= current in the main winding of stator

i_{as} =current in the shaded pole winding of stator

i_{dr} = current in the direct axis winding of rotor

i_{qr} = current in the quadrature axis winding of rotor

L_{mm} = self inductance of the main winding

L_{ma} =mutual inductance between main winding and shaded pole winding

L_{md} = mutual inductance between main winding and direct axis winding of rotor

L_{aa} = self inductance of the shaded pole winding

L_{ar} = mutual inductance between shaded pole winding and the rotor when the rotor is aligned with the shaded pole winding

L_{dd} = self inductance of the direct axis winding of rotor

L_{qq} = self inductance of the quadrature axis winding of rotor

R_m = resistance of the main winding of stator

R_a = resistance of the shaded pole winding of stator

R_r = resistance of the direct and quadrature axis winding of rotor

δ = angle between main winding and shaded pole winding

T_L =Load torque

B = viscous damping

n_p =no. of pole pair

J = moment of inertia

In matrix form,

$$[v]=\begin{bmatrix} v_m \\ 0 \\ 0 \\ 0 \end{bmatrix} \quad [i]=\begin{bmatrix} i_{ms} \\ i_{as} \\ i_{dr} \\ i_{qr} \end{bmatrix}$$

$$[L]=\begin{bmatrix} L_{mm} & L_{ma} & L_{md} & 0 \\ L_{ma} & L_{aa} & L_{ar}\cos\delta & -L_{ar}\sin\delta \\ L_{md} & L_{ar}\cos\delta & L_{dd} & 0 \\ 0 & -L_{ar}\sin\delta & 0 & L_{qq} \end{bmatrix}$$

$$[G]=\begin{bmatrix} 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & n_p L_{ar}\sin\delta & 0 & -n_p L_{qq} \\ n_p L_{md} & n_p L_{ar}\cos\delta & n_p L_{dd} & 0 \end{bmatrix} \quad (6.15)$$

Therefore,

$$[v]=[L]p[i]+[R][i]+[G][i] \quad (6.16)$$

It is same to that used in chapter 5.

The equations can be rearranged in the form of state equations,

$$p[i]=[L]^{-1}([v]-[R][i]-\omega[G][i]) \quad (6.17)$$

Electromagnetic torque of the motor is given by,

$$T_e = n_p[L_{md}i_{ms}i_{qr} + L_{ar}i_{as}i_{dr}\sin\delta + L_{ar}i_{as}i_{qr}\cos\delta + (L_{dd}-L_{qq})i_{dr}i_{qr}] \quad (6.18)$$

Equation ofmotion is given by,

$$J\frac{d\omega}{dt}=T_e - B\omega - T_l$$

Thus total no. of state variables associated with the motor is 5. These are

$$[x]=\begin{bmatrix} i_{ms} \\ i_{as} \\ i_{dr} \\ i_{qr} \\ \omega \end{bmatrix}$$

The state equations can be expressed as,

$$p[x]=\left|[L]^{-1}([v]-[R][i]-\omega[G][i]);(T_e-B\omega-T_L)/J\right| \quad (6.19)$$

As no. of state variables is as good as that of Generalized electrical machines, it is very difficult to get fruitful result by adopting analytical approach. Therefore, numerical and experimental study are the only effective tools for the study of the dynamical behavior of the machine. As no. of state variable is more than 3, it is indicating that the machine under consideration is having a rich source of nonlinear phenomenon.

6.3.2 Numerical study:

Numerical study will be done to study the nonlinear phenomenon of the machine. Simulation of the system is done here with the parameters as they those are having to the motor under experimental study. This is done so that the simulation results can be compared with the experimental results.

However, all state variables used for simulations will not be available for measurement during experimental study. Then, the commonly available state variables will be compared. It does not affect the study because when a system becomes periodic or chaotic all state variables pass through similar states. Therefore, even comparison of only one state variable is sufficient.

Data used for simulation are given below:

np=01

Lmm=0.4H

Ldd=0.4H

Lqq=0.38H

Lmd=0.35H

Lmq=0.34H

Lma=15mH

Lar=17mH

Rm=5.6 ohm

Ra=0.2 ohm

Rr= 25 ohm

Laa=11mH

δ =28 degree

J=2.130×10^{-5}Kg.m^2

B=1.47×10^{-4}Nms

Tl=0 (6.20)

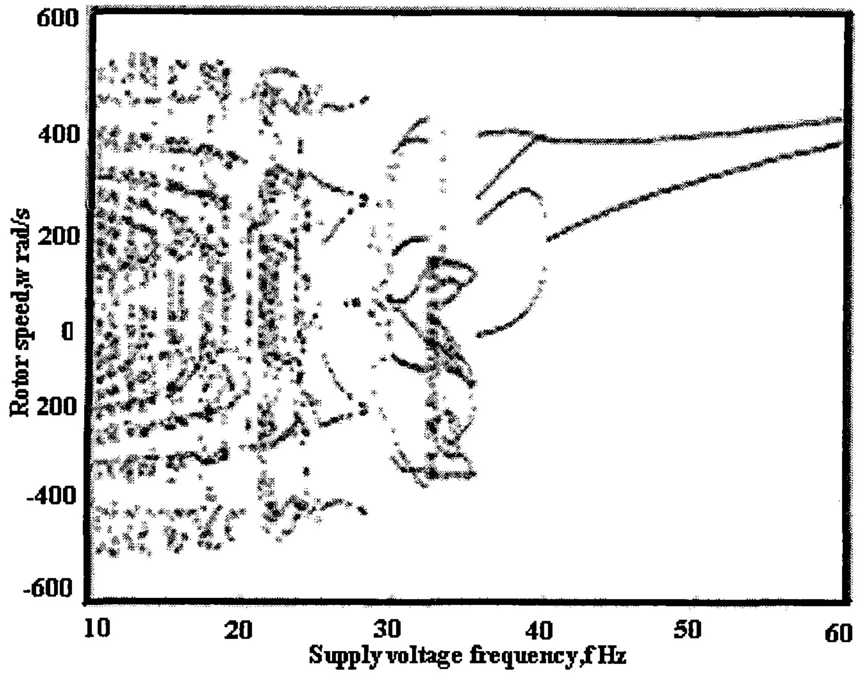


Fig: 6.9 Bifurcation diagram of single phase shaded pole induction motor with supply voltage=220V and supply frequency,f as Bifurcation parameter

From bifurcation diagram it is clear that frequency at about 60 Hz is almost periodicity becomes almost one. At frequency about3 8Hz, periodicity becomes four and at about 22Hz the motor becomes chaotic. The diagram also confirms that with certain sets of parameter values motor becomes chaotic. This was also expected as per the conclusion taken in chapter 5. Thus the simulation result validates the process described in chapter 5.

6.3.3 Experimental study:

The Name plate rating of the motor on which test is done, is given below:

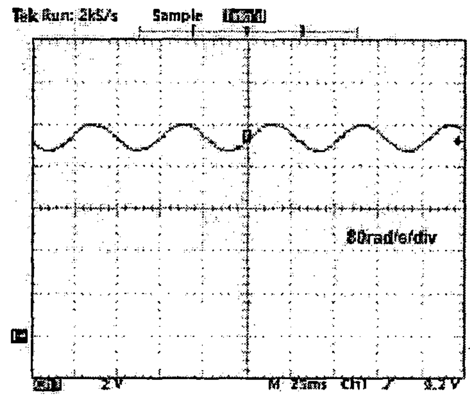
Hp =1.0 5.0A,

Volt =230V

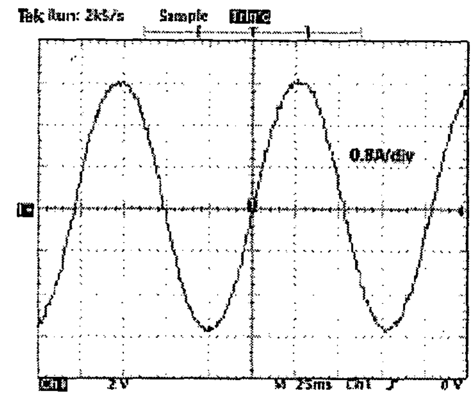
Hz =50

Shaded pole angle=28 degree

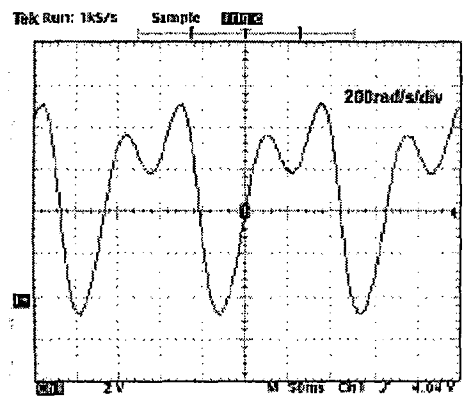
The values of the parameters for the machine used in the experiment are same to those used for simulation i.e., as given in(6.20). Actually those values are used for simulation so that the simulation results and experimental results can be compared. The state variables which can be observed directly during the experiments are rotors speed and the main winding currents on the stator. Those two state variables are observed from simulation and experimental results and compared.



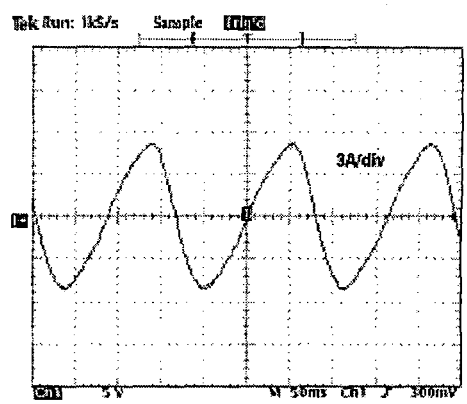
(a) rotor speed, ω with f=60 Hz



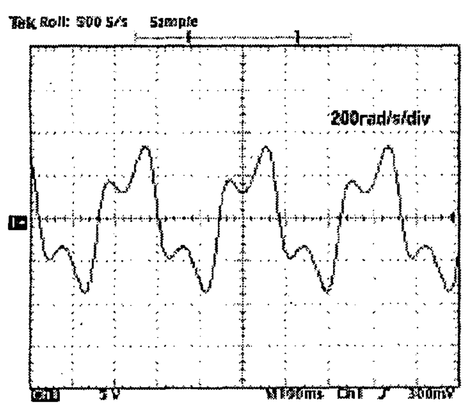
(b) stator main winding current, i_{ms} with f=60 Hz



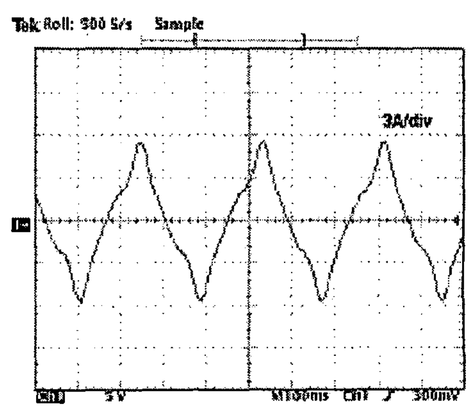
(c) rotor speed, ω with f=38 Hz



(d) stator main winding current, i_{ms} with f=38 Hz



(e) rotor speed, ω with f=22 Hz



(f) stator main winding current, i_{ms} with f=22 Hz

Fig: 6.10 periodic waveforms of single phase shaded pole induction motor with supply voltage=220V with different supply frequencies

Experimental results as found in Fig.6.10 clearly indicates the following thing:

- At frequency, f = 60Hz the motor operates with a periodicity equals to nearly one.
- At frequency, f= 38Hz the motor show period four operation
- At frequency, f=22Hz the operation of the motor is chaotic.

Hence, the experimental results reiterates the facts what was found during the simulation. It not only validates the simulation results but also reassures the effectiveness of the method described in the chapter 5 for generalized electrical machine.

6.4 Conclusion:

The process outlined in previous chapter is used to study the nonlinear phenomenon of some conventional machines. It is found that the method is effective for the machines it have been studied. The nonlinear phenomenon have been studied for two machines both by simulations and experiments. It is observed that similar results are obtained from simulation and experiments and the results are so as expected in chapter 5. This validates the proposed method of chapter 5. Also it has been found that for certain sets of parameters machines show that they may show the dynamics with one, two or more or even chaos. This not only confirms the effectiveness of the proposed method of chapter 5 to study the nonlinear phenomenon of generalized electrical machine but also approves that the method is general and can be adopted to study the nonlinear dynamical behavior of other conventional machines with minimum effort.