DQ Modeling Of Induction Motor For Virtual Flux Measurement

Sushma.P Rajalakshmi Samaga.B.L Vittal.K.P,*Member*,IEEE

Department of Electrical and Electronics Engineering, National Institute of Technology Karnataka, Surathkal, Mangalore, India

***Abstract*— Three phase induction motors are continuing to remain as work horses in industrial applications. The accurate behavioral modeling of induction motor helps in designing controller for the machine and also useful in detection of faults in machines. Almost all faults in the induction motor affect the flux in the air gap. These fluxes can be measured virtually using dq model of induction motor by feeding voltage and current values extracted in real time and stored. In this paper, DQ model is developed in stator reference frame using MATLAB-SIMULINK platform and a data acquisition system supported with LabVIEW is used to obtain motor terminal voltage and current signals which are useful in estimation of flux in an actual machine.**

***Keywords-component;* DQ model, Data acquisition system, Induction motor, modeling.**

NOMENCLATURE:

v_{as}, v_{bs}, v_{cs} - Input Voltages for phase a, b and c respectively in Volts.

v_{qs}, v_{ds} - Stator q and d axis voltages in Stationary reference frame respectively in Volts.

v_{qr}, v_{dr} - Rotor q and d axis Voltages in Stationary reference frame respectively in Volts.

i_{qs}, i_{ds} -Stator q and d axis Currents in Stationary reference frame respectively in A.

i_{qr}, i_{dr} -Rotor q and d axis Currents in Stationary reference frame respectively in A.

R_s - Stator Resistance/phase in Ω.

L_s - Stator Self Inductance/phase in H.

L_m - Mutual Inductance in H.

R_r - Rotor Resistance/phase in Ω.

L_r - Rotor Self Inductance in H.

$\omega_c, \omega_r, \omega_s$ - Angular speed in arbitrary frame, rotor speed and synchronous speed respectively in rad/sec.

J -Inertia of Motor in kg-m^2.

T_e - Electrical Torque in N-m.

T_L - Load Torque in N-m.

p -Number of Poles

ω_{mech} - Mechanical speed in rad/sec.

I. INTRODUCTION

Conventionally vibration analysis is the most popular method used to detect the asymmetrical faults in induction motors in industries. It is reported that no industrial case histories have successfully predicted the number of broken rotor bars using vibration analysis [1]. Prof. Thomson in his paper [1], presents Motor Current Signature Analysis (MCSA) scheme for successful detection of the rotor and eccentricity faults. In reality any nonuniformity in the air gap results in nonuniform distribution of flux [2] and its effect is found on the line current. Hence it can be stated that change in the current signatures are the secondary effects of change in flux due to fault.

The signature analysis of flux is expected to give better results as it is the parameter which is affected by the abnormalities in the motor. Nandi et al [3] in their review paper mentioned the use of (i) Search coil, (ii) Large coil wound concentrically around the shaft of the machine, and (iii) The shorted stator turns used to measure the flux in the machine. These methods are invasive in nature.

Noninvasive method of fault detection is possible by virtual flux measurement technique. In paper [4], Electro motive force (Emf) based flux detecting algorithms are presented. Here the current is measured at machine supply terminal and then substituted in the space phase equivalent circuit of induction motor. In paper [5], rotor fluxes are estimated using signal processors TMS 320C32 and all the quantities are simulated in stationary reference frame. Dulce F. Pires et al [6] have used fault signatures in the current and virtual flux for rotor fault detection. In paper [7], the concept of flux equivalent with virtual winding currents is used to detect the faults. In paper [8], Moving horizon state estimator (MHSE) are used to estimate the flux in the machine.

In this paper, dq model of induction motor is used to estimate the flux in the machine based on real-time measurement of voltage and current at the terminal of the motor. The Dynamic dq model is developed using MATLAB and simulations are carried out to observe the speed, flux, torque and current waveforms. In order to enable estimation of the flux in an actual machine, the same model is developed in LabVIEW environment and the model is simulated with extracted line current and voltage values fed to the machine for one complete rotation of rotor through NI-DAQ data acquisition system. The proposed technique was evaluated using two induction motors available in the laboratory. Required tests were conducted on these induction motors to determine the machine parameters used in modeling. The experimentation and simulation results are presented in sections III. The efficacy of the proposed methodology is discussed in sections IV and V.

II. DQ MODELLING

DQ model is extensively used in control applications as it has the capability to convert sinusoidal variable quantities to dc quantities using suitable reference theory. By having the voltage and current quantities in dq frame, it is possible to control the speed of the machine by controlling the flux and torque independently. It is also a method of sensor less flux measurement.

The direct and quadrature axis model (d-q model) based on the space phasor theory is widely used for simulation the dynamic behavior of three-phase induction motor. In this model 3 phase machine (abc) is transformed into two phase machine (dq0). The equivalence is based on the equality of the magneto motive force (mmf) produced in the two phase and three phase windings and equal current magnitudes. The relationship between dq0 and abc voltages is given by equation (1) [9][10][11][12]:

$$\begin{bmatrix} v_{qs} \\ v_{ds} \\ v_o \end{bmatrix} = \frac{2}{3}\begin{bmatrix} \cos\theta_c & \cos(\theta_c \ \ \frac{2\pi}{3}) & \cos(\theta_c + \frac{2\pi}{3}) \\ \sin\theta_c & \sin(\theta_c \ \ \frac{2\pi}{3}) & \sin(\theta_c + \frac{2\pi}{3}) \\ \frac{1}{2} & \frac{1}{2} & \frac{1}{2} \end{bmatrix}\begin{bmatrix} v_{as} \\ v_{bs} \\ v_{cs} \end{bmatrix} \quad (1)$$

For the purpose of control, there is a need to express sinusoidal system variables as dc quantities. This can be accomplished by selecting one of the three reference frames given below [2]

- **Stator reference frame:** $\omega_c=0$, the frame is fixed in stator
- **Rotor reference frame:** $\omega_c=\omega_r$, the frame is fixed in rotor
- **Synchronous reference frame:** $\omega_c=\omega s$, the frame is fixed in synchronously rotating frame

The dynamic model of an induction machine is developed using equations (2),(3),(4),(5)[10]

$$v_{qs} = R_s i_{qs} + L_s\frac{di_{qs}}{dt} + \omega_c L_s i_{ds} + L_m\frac{di_{qr}}{dt} + \omega_c L_m i_{dr} \quad (2)$$

$$v_{ds} = \omega_c L_s i_{qs} + R_s i_{ds} + L_s\frac{di_{ds}}{dt} \ \ \omega_c L_m i_{qr} + L_m\frac{di_{dr}}{dt} \quad (3)$$

$$v_{qr} = L_m\frac{di_{qs}}{dt} + (\omega_c - \omega_r) L_m i_{ds} + R_r i_{qr} + L_r\frac{di_{qr}}{dt} + (\omega_c - \omega_r) L_r i_{dr} \quad (4)$$

$$v_{dr} = (\omega_c - \omega_r) L_m i_{qs} + L_m\frac{di_{ds}}{dt} + R_r i_{dr} + (\omega_c \ \ \omega_r) L_r i_{qr} + L_r\frac{di_{dr}}{dt} \quad (5)$$

The advantage of this method is virtual flux measurement can be done using flux linkage equations using equations (6), (7), (8), (9)[10]:

$$\lambda_{qs} = L_s i_{qs} + L_m i_{qr} \quad (6)$$

$$\lambda_{ds} = L_s i_{ds} + L_m i_{dr} \quad (7)$$

$$\lambda_{qr} = L_r i_{qr} + L_m i_{qs} \quad (8)$$

$$\lambda_{dr} = L_r i_{dr} + L_m i_{ds} \quad (9)$$

Dynamic torque and speed can be calculated by Mechanical system equations (10), (11), (12)[10]

$$T_e = \frac{3}{2}\frac{p}{2} L_m (i_{qs} i_{dr} \quad i_{ds} i_{qr}) \quad (10)$$

$$T_e = J\frac{d\omega_{mech}}{dt} + T_L \quad (11)$$

$$\omega_{mech} = \frac{2}{p}\omega_r \quad (12)$$

III. SIMULATION RESULTS

Dynamic model of squirrel cage induction motor is developed by using the equations from (1) to (12) in MATLAB / SIMULINK platform. The simulations are carried out using the motor data obtained from the No load test, Short circuit test, Retardation test and stator resistance measurement test on the motors. Test results are shown in Table1. Obtained Simulation results of machine 1 are shown in Figures 1-2.

Table1. Induction Motor Parameters from Conventional Tests.

	Machine1	Machine2
L_s (H)	0.04599	0.07353
L_r (H)	0.00766	0.00311
L_m (H)	0.012	0.012
R_s (Ω)	4.163	6.168
R_r (Ω)	5.470	4.855
J (kg.m^2)	0.0161	0.02379

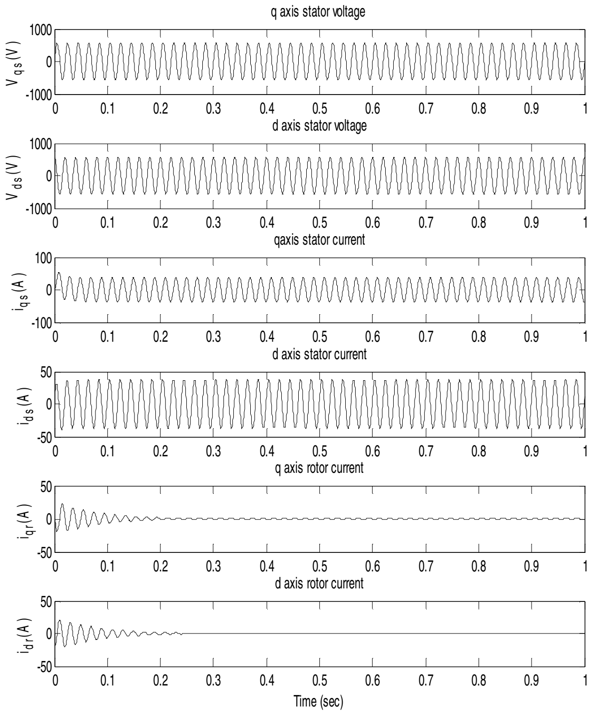

Fig. 1 q axis Stator voltage, d axis Stator voltage, q axis Stator current, d axis Stator current, q axis Rotor current and d axis Rotor current at free acceleration (no load) conditions

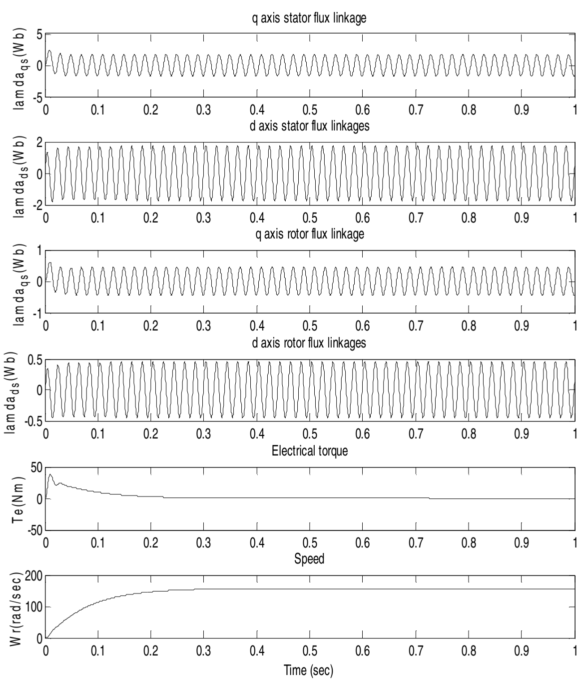

Fig.2 q axis Stator Flux Linkages, d axis Stator Flux Linkages, q axis Rotor Flux Linkages, d axis Rotor Flux Linkages, Electrical torque and Rotor Speed at free acceleration (no load) condition.

Results obtained for machine 2 also showed similar results.

IV. HARDWARE DAQ IMPLEMENTATION

The DAQ system developed runs on a desktop computer with National Instruments (NI) 6024-E DAQ card. The DAQ system was implemented as a virtual instrument (VI), whereby programming and user interface was developed using the NI LabVIEW software. The Block diagram of the data acquisition system and hardware setup for acquiring currents and voltages of the three phase squirrel induction machine is shown in Figures 3-4. The measured analog signals undergo signal conditioning, before getting digitized and finally fed to the computer for processing. The software consists of two main programs, which are for data acquisition and data analysis. Data acquisition program is used to perform real time current and voltage monitoring, detection and data recording whereas data analysis program is for post acquisition data analysis.

(i).Stator Voltage monitoring system:

The line voltages of the three phase induction motor, are extracted by high voltage terminal box TBX1316 and they are sent to the signal conditioner SCXI 1125 and then to the PC through Data Acquisition Card 6024-E.

(ii)Stator current monitoring system:

The purpose of the monitoring system is to measure three-phase stator currents fed to the induction motor. The currents are sensed by a set of three Hall Effect Current Transducers and are converted into equivalent voltages in SCXI 1338 and conditioned in SCXI 1125 and are processed on PC. The digitalized current and voltage signal is applied to the low pass filter to remove the undesirable high frequency components that produce aliasing of the sampled signal.

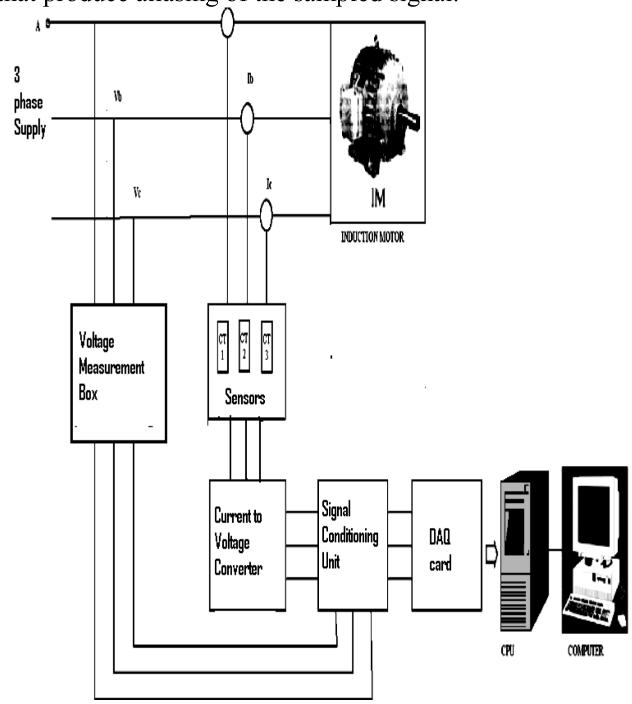

Fig. 3 Block diagram of data acquisition system

The selected sampling frequency is 10k samples/sec. The sampled data for 1 complete rotation of rotor (in this case 2 periods) are stored in the spread sheets. The continuous sinusoidal waves are generated using these extracted data and are fed to the model developed in LabVIEW for offline study.

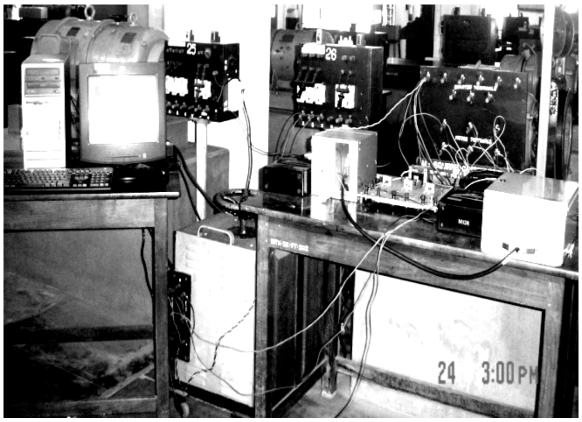

Fig. 4 Experimental set up

V. RESULTS AND DISCUSSIONS

Using the offline data values, continuous sinusoidal voltage and currents are generated and fed to the model. The simulation parameters chosen are Runge Kutta 4, fixed step, step size 0.0001. The simulated waveforms are as shown in Figures 5-9. The model developed in LabVIEW is as shown in Figure 10 in the Appendix

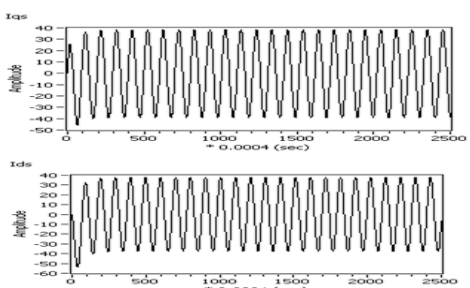

Fig. 5 Stator currents in q and d axis.

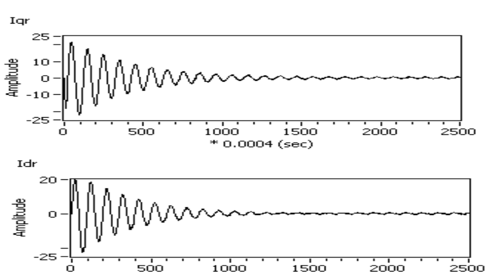

Fig. 6. Rotor currents in q and d axis.

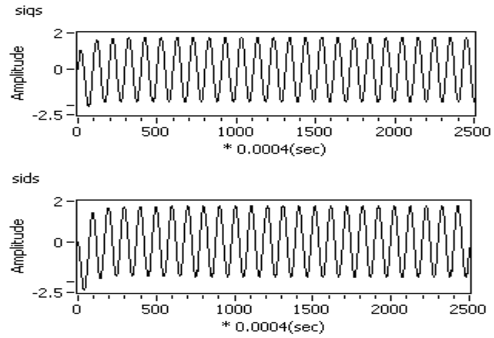

Fig. 7. Stator flux linkages in q and d axis.

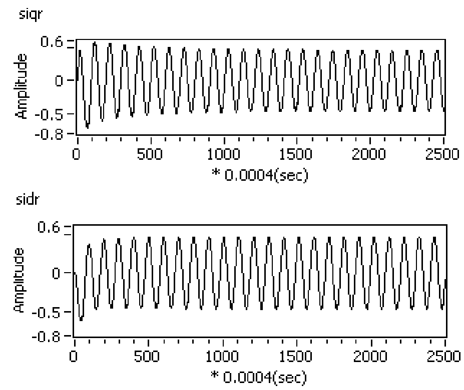

Fig. 8 Rotor flux linkages in q and d axis

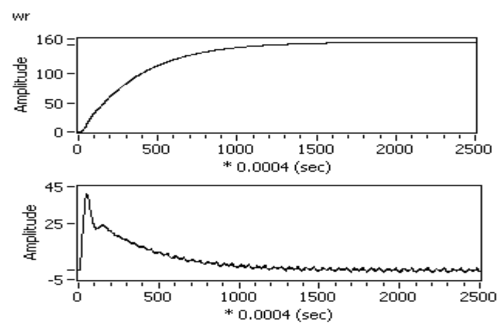

Fig. 9 Torque and speed of machine1

VI. CONCLUSION

The dq modeling of the induction motor has been developed specially to estimate virtual flux. In case of noninvasive method of fault detection scheme for eccentricity detection, this model can be adopted to estimate the flux, as flux is the primary parameter to get affected by air gap eccentricity. Any asymmetry in the air gap gives rise to nonuniform distribution of the flux and harmonics are induced in the stator current. Using these stator currents, fluxes can be estimated after simulating the model. The model developed also can be used to estimate the dynamic torque as this is another parameter to get affected by air gap asymmetry in the machine. This model can also be used to study the effect of variable frequency converters on the performance of machine.

APPENDIX

Table2. Machine details

MACHINE 1	MACHINE 2
3Φ,400V,50 HZ	3Φ,440V,50 HZ
3.73 KW(5 HP)	3.73 KW(5HP)
1440 RPM	1440 RPM
7.5 A	7.0 A

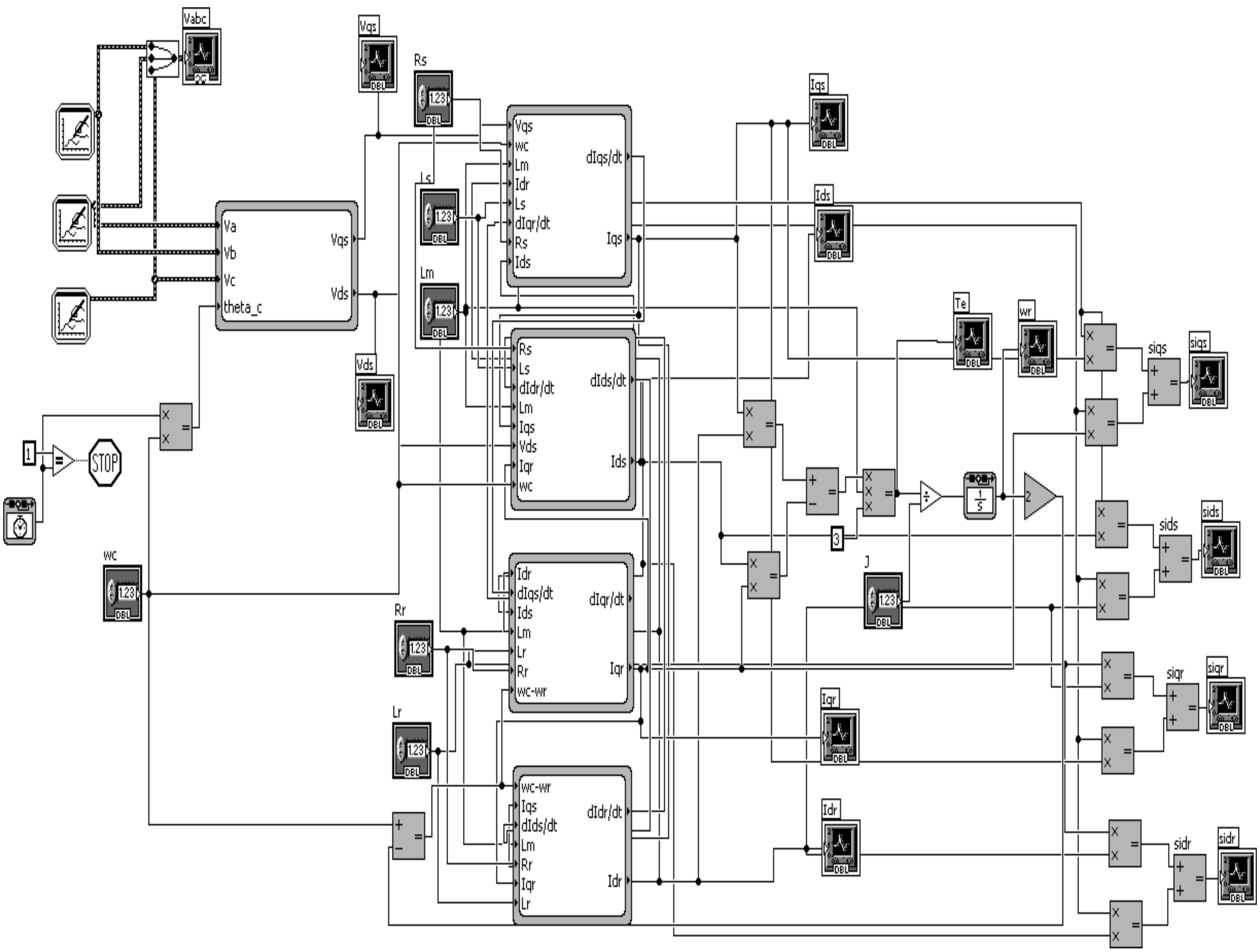

Fig. 10 Model developed in LabVIEW

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