Direct Quadrate (D-Q) Modeling of 3-Phase Induction Motor Using MatLab / Simulink

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Abstract
This paper addresses the impact of load modeling in particular induction motor. The paper proposes a methodology that is based on advanced modeling capabilities, represented by dynamic modeling of induction motor. The objective is to analyze the dynamic characteristics of loads. The paper describes the modeling approach using d-q analysis of induction motor.
Key words: load modeling, d-q transformation, induction motor, torque, flux, speed

Introduction:
In recent years the control of high-performance induction motor drives for general industry applications and area of production has received a lot of research interests. Induction machine modeling has a continuously attracted the attentions of researchers not only because such machines are made and used in larger numbers i.e. (80% of all the loads), but also due to their varied modes of operation both under steady state and dynamic state.[1] Load characteristics have been known to have a sufficient effect on the system performance and transient stability. Because of the uncertainty of the actual load characteristics, utilities use the dynamic models for accurate and precise result. Several efforts have been made to develop method for constructing improved load models. One of the modes used for this paper demonstrate the validity of a load modeling process based on the components that make up the dynamic load model. The basic purpose of using d-q model approach to control the motor parameters independently i.e. torque and flux of the induction motor. In this paper, a modular Simulink implementation of an induction machine model is described in step by step

Approach. With the modular system, each block solves one of the model equations. Because of

This approach, all of the machine parameters are assessable for control and verification purposes.[2] As long as equations are known, any drive or control algorithm can b modeled in Simulink. However, the equations by themselves are not always enough; some experience with differential equation solving is required.
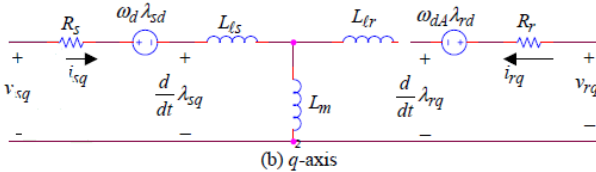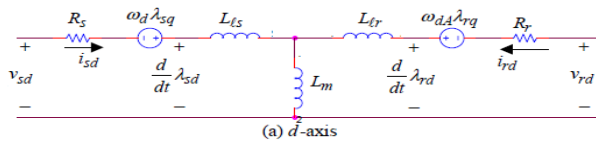
Induction Motor Model:
The induction machine d-q are dynamic equivalent circuit is shown in figure 1.

D-q transformation:
Direct Quadrature (d-q) transformation is a mathematical transformation used to simplify the analysis of three phase circuit. In the case of balanced three phase circuits, application of d-q transformation reduces the tree AC quantities to 2 quantities. Simplified calculations can then b carried out on these imaginary quantities before performing the inverse transformation to recover the actual three phase ac results.[3] The d-q transformations applied to three phase voltages are shown below.

$$V_{sd} = \sqrt{\frac{2}{3}} * [(\cos\theta_{da} * V_a) + (\cos\theta_{da} * \frac{2\pi}{3} * V_b) + (\cos\theta_{da} * \frac{4\pi}{3} * V_c)]$$

$$V_{sq} = -\sqrt{\frac{2}{3}} * [(\sin\theta_{da} * V_a) + (\sin\theta_{da} - \frac{2\pi}{3} * V_b) + (\sin\theta_{da} - \frac{4\pi}{3} * V_c)]$$

(a) d-axis

(b) q-axis

Flux linkage equations:

Stator

$$\lambda_{sd} = L_s * i_{sd} + L_m * i_{rd}$$

$$\lambda_{sq} = L_s * i_{sq} + L_m * i_{rq}$$

Rotor

$$\lambda_{rd} = L_r * i_{rd} + L_m * i_{sd}$$

$$\lambda_{rq} = L_r * i_{rq} + L_m * i_{sd}$$

Current equation:

Stator

$$i_{ds} = \frac{1}{Xls}(\lambda_{ds} - \lambda_{md})$$

$$i_{qs} = \frac{1}{Xls}(\lambda_{qs} - \lambda_{mq})$$

Rotor

$$i_{dr} = \frac{1}{Xls}(\lambda_{dr} - \lambda_{md})$$

$$i_{qr} = \frac{1}{Xls}(\lambda_{qr} - \lambda_{mq})$$

Voltage Equations:

Stator

$$V_{sd} = R_s * i_{sd} + \frac{d}{dt}(\lambda_{sd}) - \omega_d * \lambda_{sq}$$

$$V_{sq} = R_s * i_{sq} + \frac{d}{dt}(\lambda_{sq}) - \omega_d * \lambda_{sd}$$

Rotor

$$V_{rd} = R_r * i_{rd} + \frac{d}{dt}(\lambda_{rd}) - \omega_{dA} * \lambda_{rq}$$

$$V_{rq} = R_r * i_{rq} + \frac{d}{dt}(\lambda_{rd}) - \omega_{dA} * \lambda_{rd}$$

Electromagnetic Torque:

$$T_{em} = \frac{p}{2} * L_m(i_{sq} * i_{rd} - i_{sd} * i_{rq})$$

Where,

d:direct axis

q:quadrature axis

s:stator variable

r:rotor variable

λ: flux linkage

V_{qs}, V_{ds}: q and d − axis stator voltages

V_{qr}, V_{dr}: q and d − axis rotor voltages

$\lambda_{mq}, \lambda_{md}$: q and d axis magnetizing flux linkages

R_s: stator resistance

R_r: rotor resistance

X_{ls}: stator leakage reactance

X_{lr}: rotor leakage reactance

i_{qs}, i_{ds}: q and d – axis stator currents

i_{qr}, i_{dr}: q and d – axis rotor currents

p:number of poles

T_{em}: Electrical output torque

Description of Power System Block set:

Matlab/Simulink is a systems simulator and unable to direct simulate electrical circuits. Therefore for simulation of electric circuits power system block set is used which is incorporates libraries of electrical blocks and analysis tools which are used to convert electrical circuits into Simulink diagrams.[4] The electrical blocks or electrical models such as electrical machines ,current and voltage sources, different electric elements , power electronics switches , conductors and sensors for measurement purpose. When the simulation starts Simulink use the PM block set and transfer the electrical circuit into a state space representation with the initial conditions of state variables.[5] The actual simulation starts after this initial conversion. This allows the use of wide variety of fixed step and variable step algorithms available in Simulink. As variable time step algorithms are faster than fixed time step method because the number of steps are less so these algorithms are used for small and medium size systems, and for large systems containing a more number of stages and/or power switches, a fixed time step algorithm is used. A Simulink scope can b used to display the simulation results or these results can be send to workspace during the simulation.
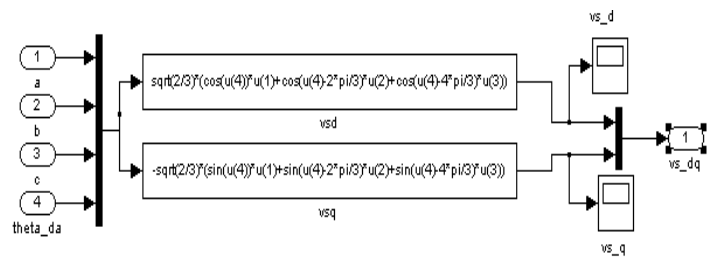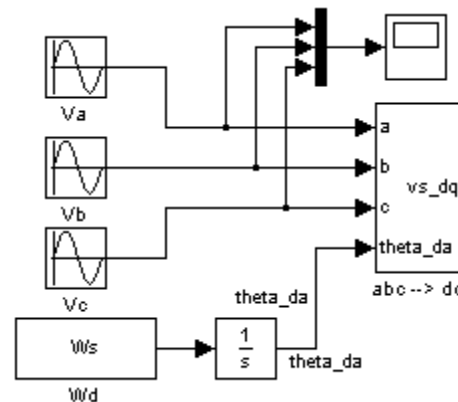
The variety of Matlab functions and tool boxes are present for processing and plotting of wave forms from store data.
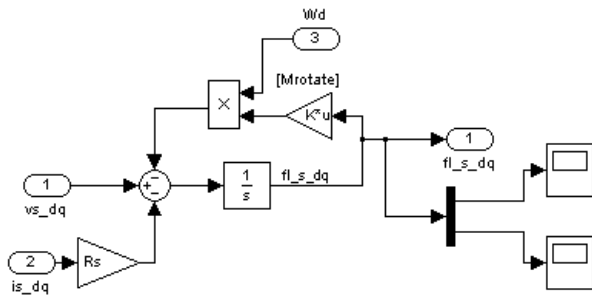
Induction Motor model in Matlab/Simulink:

A generalized dynamic model of the induction motor consists of an electrical sub-model to implement the three-axis to two-axis (3/2) transformation of stator voltage and current calculation a torque sum-model to calculate the developed electromagnetic torque (Tem), and mechanical sub-model to yield the rotor speed (ω). Electrical sub-model of the induction motor the three-axis to two-axis voltage transformation to achieved using the following equations.

$$V_{sd} = \sqrt{\frac{2}{3}} \cdot \left[(\cos \theta_{da} \cdot V_a) + \left(\cos \theta_{da} \cdot \frac{2\pi}{3} \cdot V_b \right) + \left(\cos \theta_{da} \cdot \frac{4\pi}{3} \cdot V_c \right) \right]$$

$$V_{sq} = -\sqrt{\frac{2}{3}} \cdot \left[(\sin \theta_{da} \cdot V_a) + \left(\sin \theta_{da} \cdot \frac{2\pi}{3} \cdot V_b \right) + \left(\sin \theta_{da} \cdot \frac{4\pi}{3} \cdot V_c \right) \right]$$
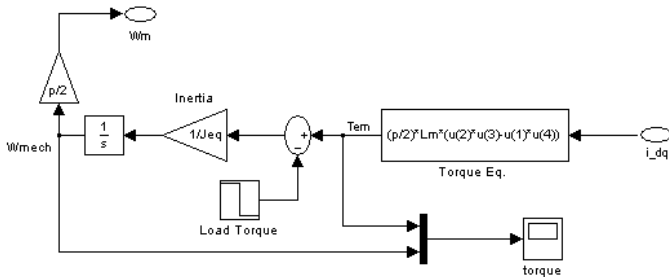
Where Va ,Vb and Vc are three-phase stator voltages, while Vsd and Vsq are the two-axis components of the stator voltage vector.[6]
Fig shows torque sub-model of induction motor in the two-axis stator reference frame, the electromagnetic Tem is given by

$$T_{em} = \frac{P}{2} * L_m (i_{sq} * i_{rd} - i_{sd} * i_{rq})$$

Also mechanical sub-model of induction motor from the torque balance equations and neglecting viscous friction, the rotor speed is also shown in the above figure [7]

The generalized load model of induction motor made in Matlab/Simulink is given below:
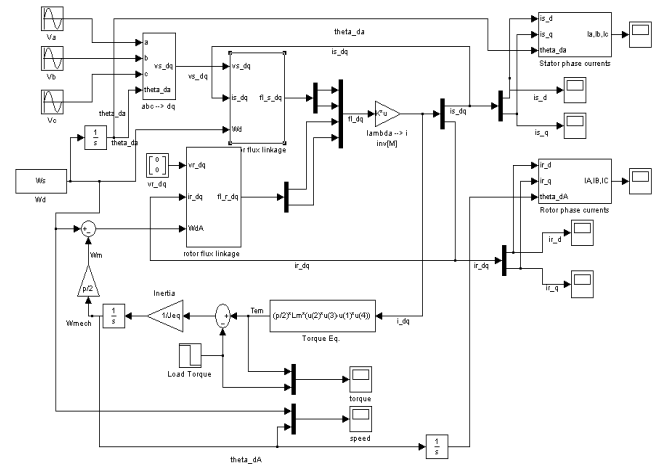
Simulation and results:
The induction motor chosen for the simulation studies has the following parameters:

$$R_r = 1.34\ \Omega$$

$$R_s = 1.77\ \Omega$$

$$L_r = 0.3808\ H$$

$$L_s = 0.3826\ H$$

$$L_m = 0.4425\ H$$

$$P = 4$$

$$E_{ma} = 3.5200e^{+02} - 1.756e^{+01i}$$

$$I_{dq0} = [5.5112; -6.4376; -5.5564; 0.2024]$$

$$I_a = 4.3633 - 3.0212i\ A$$

$$I_{r0} = -6.7344 + 0.7331i\ A$$

$$I_{rd} = -5.5564\ A$$

$$I_{rq} = 0.2024\ A$$

$$I_{sd} = 5.5122\ A$$

$$I_{sq} = -6.4376\ A$$

$$T_L = 25.5545\ Nm$$

$$T_{em} = 25.5545\ Nm$$

$$V_\alpha = 375.5884\ V$$

$$V_{s0} = 563.3826\ V$$

$$V_{sd} = 460\ V$$

$$V_{sq} = 0\ V$$

$$X_{lr} = 4.57$$

$$X_{ls} = 5.25$$

$$X_m = 139$$

$$Z_{eq} = 58.1844 + 0.2873i$$

$$Z_m = 0 + 1.39e^{+012}$$

$$Z_{rotor} = 77.9070 + 4.57i$$

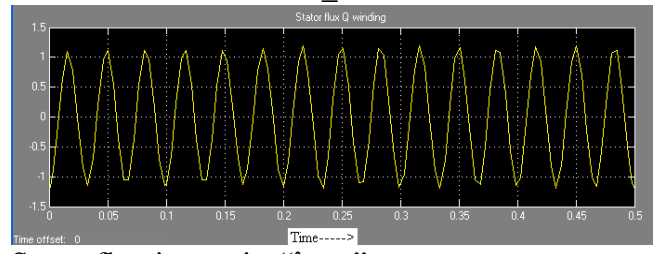The simulation results are as follows in the form of graph:
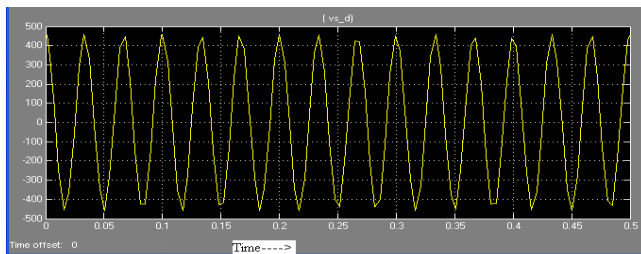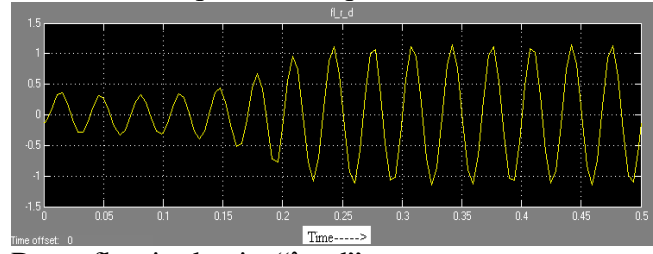

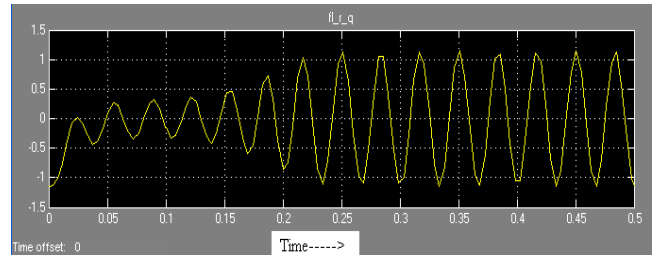Stator voltages in d axis "Vs_d"
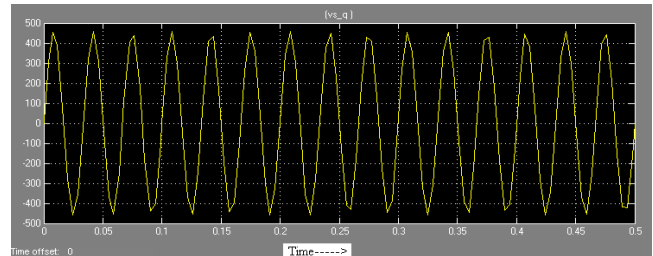
Stator voltages in q axis "Vs_q"
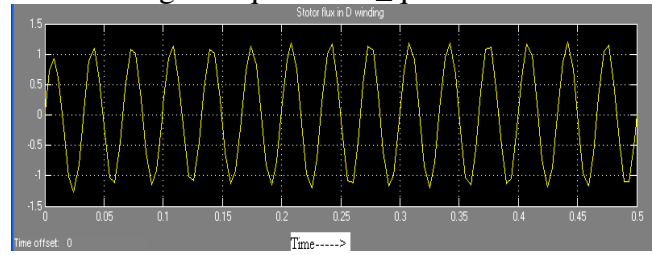
Stator flux in d axis "λs_d"

Stator flux in q axis "λs_q"

Rotor flux in d axis "λr_d"
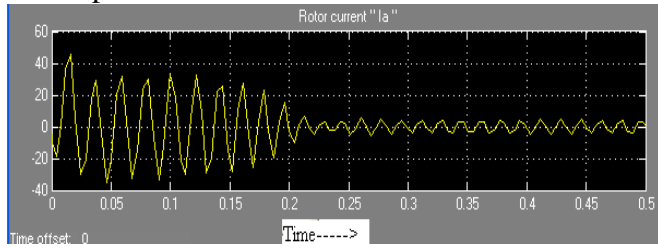

Rotor flux in q axis "λr_d"
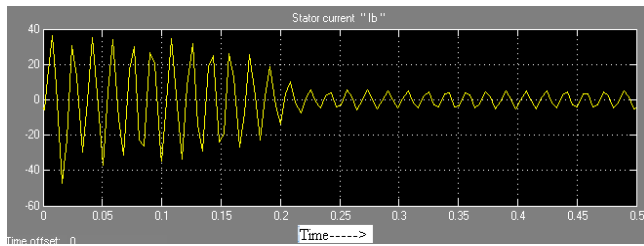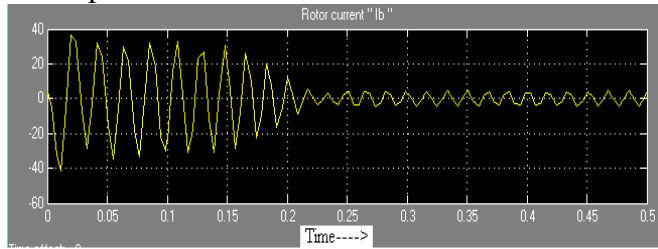
Stator phase current "Ia"
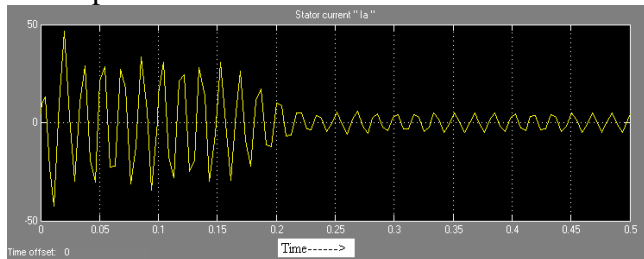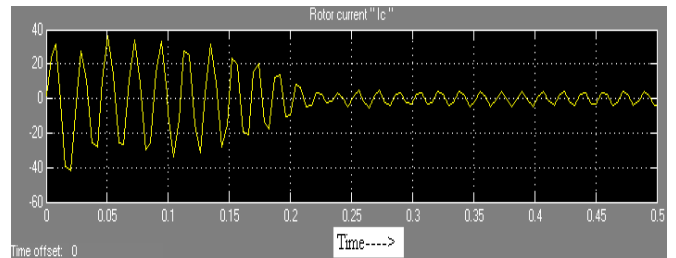

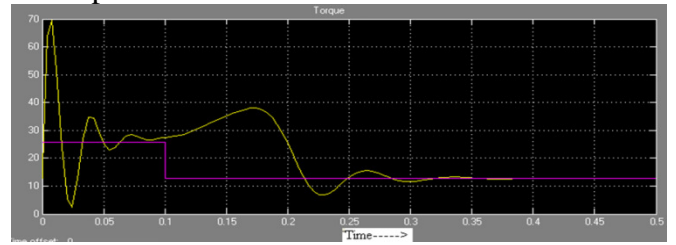Stator phase current "Ib"
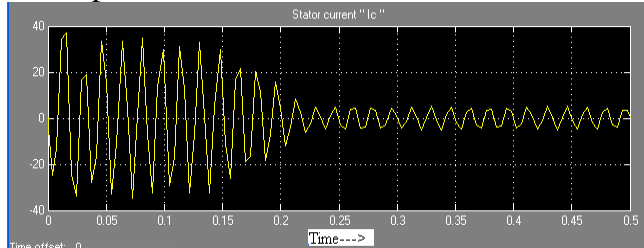
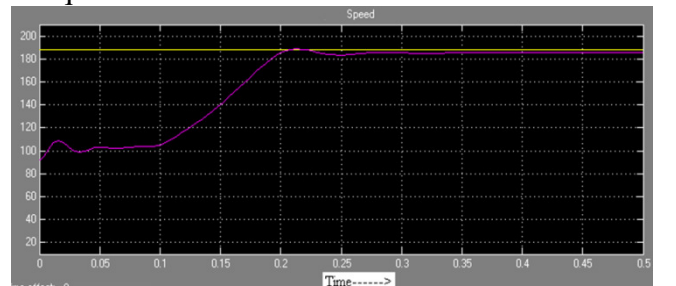Stator phase current "Ic"

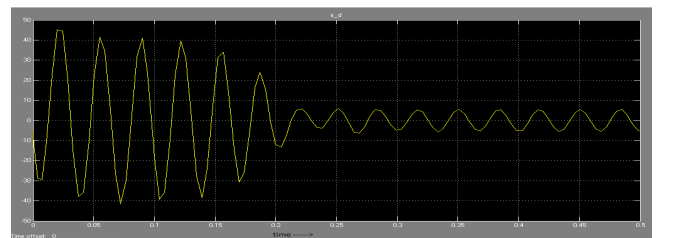Rotor phase current "IA"
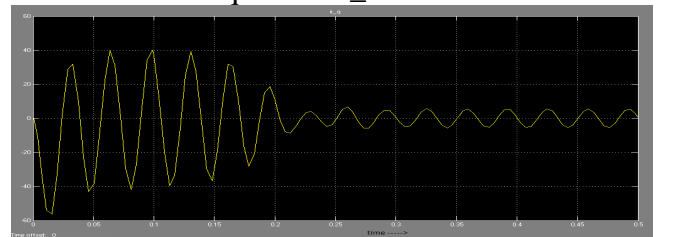

Rotor phase current "IB"

Rotor phase current "IC"

Load torque "Tload" and Electromagnetic Torque"Tem"
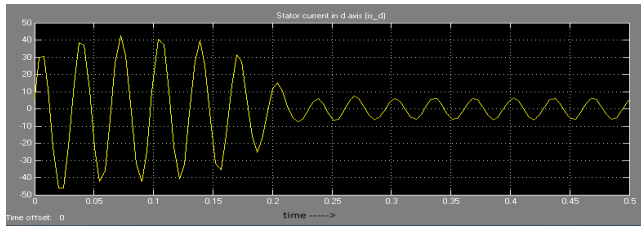

synchronous angular "ωsyn" speed and rotor angular speed "ωmech"
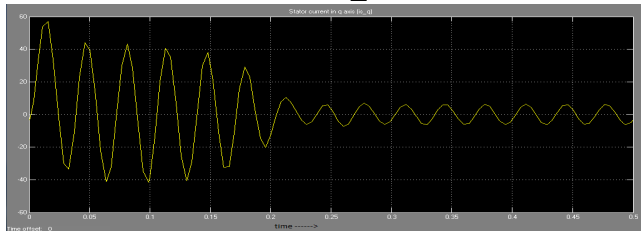

Rotor current in q axis "Ir_d"

Rotor current in q axis "Ir_q"

Stator current in d axis "Is_d"

Stator current in q axis "Is_q"

Conclusions:

In this paper, implementation of modular Simulink model for induction machine simulation has been introduced. Unlike most other induction machine model implementations, with this model, the user has asses to all the internal variables for getting an insight into the machine operation. Any machine control algorithm can be simulated in the Simulink environment with this model without actually using estimators. Individual parameter equations are solved in each block. Finally, the operation of the model is to simulate dynamic model of induction motor with torque and flux as independent quantities. The author believes that the Simulink will soon become an indispensable tool for the teaching and research of electrical machine drives.

References:

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