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DYNAMIC MODELING OF INDUCTION MOTOR FOR EV

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Abstract: This paper addresses the impact of load modelling in particular induction motor. The paper proposes a methodology that is based on modelling capabilities, represented by dynamic modelling of induction motor. The objective is to analyze the dynamic charactertics of loads. The equivalent circuits for dynamic simulation proposed until now, are not able to obtain the transient response of the induction motor, because the lack of mechanical components representations. In this paper electrical analogy of mechanical system is integrated with d-q equivalent circuits from stator frame of reference to obtain a complete equivalent circuit for three phase induction motor which is suitable for dynamic simulations. This paper describes the modeling approach using d-q analysis of induction motor.

Keywords: Load modeling; d-q transformation; Dynamic model; induction motor; torque; flux; speed

I. INTRODUCTION

During the Past three decades the use of induction motor both in industry and daily life has increased due to its low maintenance cost, robustness and reliable operation. Induction motor modelling has a continuously attracted the attentions of researchers as they have varied modes of operation both under steady state and dynamic state. The control methods for induction motor are divided into two parts: scalar control and vector control method. The purpose of the scalar control technique is to control the magnitude of the chosen quantities whereas the vector control is more complex technique than scalar control. Vector controls technique works with vector quantities. 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. The basic purpose of using d-q model approach to control the motor parameters independently i.e. torque and flux of the induction motor. State of the art control, such as vector control and direct torque control (DTC) use the method of varying the frequency in order to control the synchronous speed of the induction motor. The core loss components mentioned earlier are functions of frequency. Thus any change in frequency will change the value of the core loss exhibited by the machine. The higher the frequency the more will be the core loss of the machine. Also, the efficiency of an induction motor decreases under light loads due to the imbalance between copper and core losses. Selection of proper flux level is very important to ensure that the induction motor is operating at maximum efficiency.

II. INDUCTION MOTOR

Principle of induction motor

First, one of the most common electrical motor used in most applications which is known as induction motor. This motor is also called as asynchronous motor because it runs at a speed less than its synchronous speed. An Induction motor always runs at a speed less than synchronous speed because the rotating magnetic field which is produced in the stator will generate flux in the rotor which will make rotor to rotate, but the rotor will never reach to its rotating magnetic field speed which is the synchronous speed because of the lagging of flux current in the stator. There are basically two types of induction motor that depend upon the input supply: -

1)Single phase induction motor
- Split phase induction motor
- Capacitor start induction motor
- Capacitor start capacitor run induction motor
- Shaded pole induction motor

2)Three phase induction motor
- Squirrel cage induction motor
- Slip ring induction motor

Working Principle of Induction Motor

We consider a DC motor, as we need to give double excitation to make a machine to rotate. we will give one supply to the stator and another to the rotor through brush arrangement. But in induction motor we give only one supply and which goes to stator winding. Due to flow of current in the coil flux will be generated in the coil and the rotor winding is arranged in such a way that it becomes short circuited in the rotor circuited. Current will start flowing in the coil of the rotor according to Faradays law of electromagnetic induction. There will be another flux generated due to this current through the coil and therefore there are two flux, one is stator flux and another rotor flux. Due to this rotor will feel a torque which will make a rotor to rotate in the direction of rotating magnetic flux and the speed of the rotor will be depending upon the ac supply and the speed can be controlled by varying the input supply. This is the working principle of an induction motor.

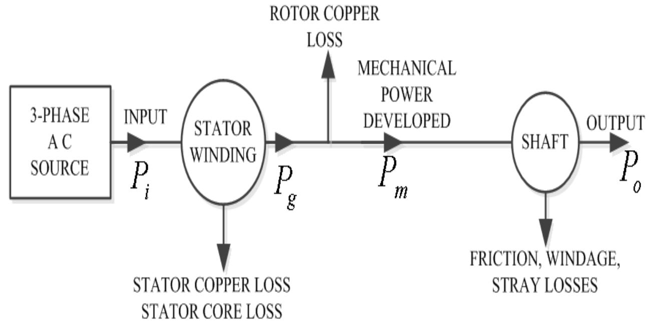
Induction Motor for Electric Vechicle

The threat of global warming and other environmental concerns have made the automobile industry shift its focus to hybridize and electrify the vehicles they manufacture. Electric vehicle (EVs) have been with us for a consideration time now. There has always been a debate over the motor best suited for electric vehicle (EV) propulsion. The requirements for drive systems of EVs are high torque and high power density combined with a wide range of speed and high efficiency. Other minor factors that should not be neglected are cost and ruggedness, augmented with reliability. Thus, for EV propulsion, the induction motors seem to be a good candidate that fulfills the above mentioned criteria.

The torque produced by three phase induction motor depends upon the following three factors. Firstly, the magnitude of rotor current, secondly the flux which interact with the rotor of three phase induction motor and is responsible for producing emf in the rotor part of induction motor and lastly the power factor of rotor of the three phase induction motor. Therefore, the torque equation is given as-

$$T \propto \emptyset I cos\theta$$

Power Flow Diagram for the three phase Induction Motor



(electric4u.com)

Power flow Diagram of induction motor explains the input given to the motor, the losses occurring and the output of the m motor. The input power given to an Induction motor is in the form of three phase voltage and currents.

The power flow is given by the equation shown below:-

$P_{is} = \sqrt{3} V_L I_L cos\Phi_i = 3V_{SP} I_{SP} cos\Phi_i$

Where, $\cos\Phi_I$ is the input power factor

The losses in the stator are I^2R losses in the stator winding resistances. It is also known as Stator copper losses.

$P_{SCL} = 3I^2_{sp}R_{SP}$

Hysteresis and Eddy current losses in the stator core and they are known as Stator core losses which is given as:-

$P_{s(h+e)}$

The output power of the stator is given as

$P_{OS} = P_{iS} – P_{SC} – P_{s(h+e)}$

The losses in the rotor are as follow:-

$P_{rc} = 3I^2_2R$

If the rotor copper losses are subtracted from rotor input power P_g, the remaning power is converted from electrical to mechanical form and its know as Developed Mechanical Power P_{md}.

Developed Mechanical power = Rotor input – Rotor copper loss

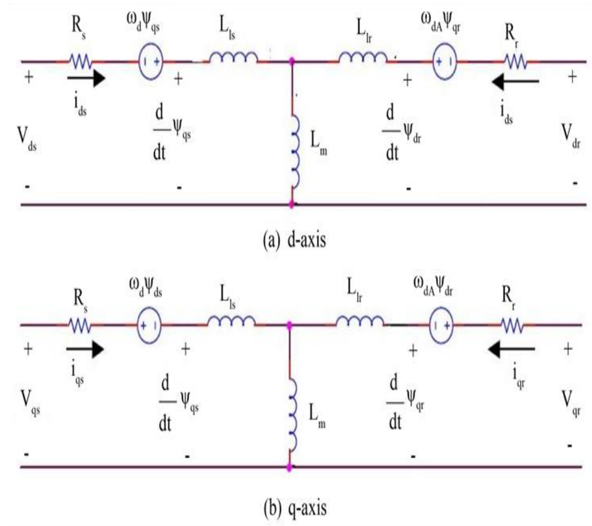
$P_{md} = P_{ir} - P_{rc}$

The output of the motor is given by the equation given below:-

$P_O = P_{md} – P_{fw} - P_{misc}$

Dynamic Modelling of Induction Motor using D-Q Transformation:-

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). The induction machine d-q are dynamic equivalent circuit shown. Direct quadrature transformation is a mathematical transformation used to simplify the analysis of three phase circuits, application of d-q transformation reduces the tree AC. The d-q transformations applied to three phase voltages are shown below



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Flux linkage equations:

For Stator

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

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

For Rotor

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

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

Current Equations:

Stator Current

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

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

Rotor Current

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

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

Voltage Equations:
Stator voltage

$$Vsd = Rs \times isd + (d \div dt) \times \lambda sd - \omega d \times \lambda sq$$

$$Vsq = Rs \times isq + (d \div dt) \times (\lambda sq) - \omega d \times \lambda sd$$

Rotor voltage:

$$Vrd = Rs \times ird + (d \div dt) \times \lambda rd - \omega d \times \lambda rq$$

$$Vrq = Rs \times irq + (d \div dt) \times (\lambda rq) - \omega d \times \lambda rd$$

Electromagnetic Torque:

$$T_{em} = \frac{\rho}{2} \times L_m \left(i_{sq} \times i_{rd} - i_{sd} \times i_{rq} \right)$$

Where,
d: direct axis
q: quadrature axis
s: stator variable
r: rotor variable
λ: flux linkage
V_{qs}, V_{ds}: axis stator voltages
V_{qr}, V_{dr}: axis rotor voltages
λ_{mq}, λ_{md}: magnetizing flux linkages
Rs: stator resistance
Rr: rotor resistance
X_{ls}: stator leakage reactance
X_{lr}: rotor leakage reactance
i_{qs}, ids: axis stator currents

III. SIMULATION OF THREE PHASE INDUCTION MOTOR

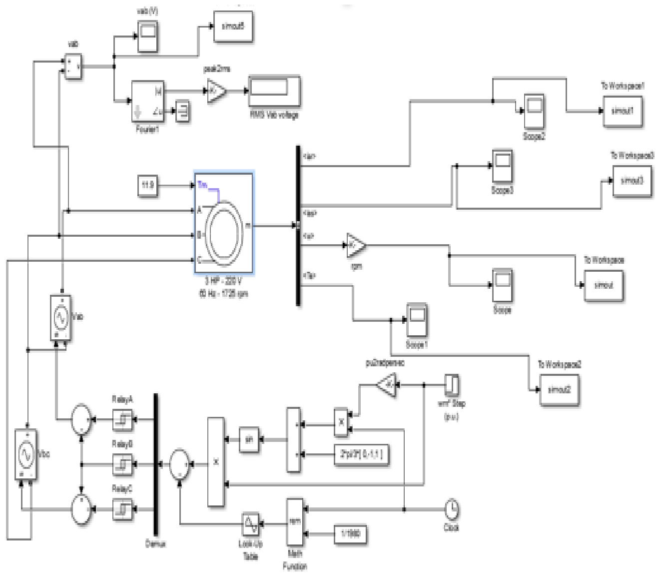

Fig 1. Matlab Model of Induction Motor

% Parameters of a typical induction machine.
rs=0.435; %Stator resistance
rr=0.816; %Rotor resistance
Ls=2*2.0e-3 ;%Stator inductance
Lr=2.0e-3 ;%Rotor inductance
M=69.31e-3; % Mutual inductance
P=3; %Poles
J=0.00488;%Inertia
sigma=(Ls*Lr)-(M*M);
B=0.000;
sls=sigma/Lr;
tr=Lr/rr;
sigma1=sigma/(Lr*Ls);
c1=(Lr/M);
c2=(Ls*Lr-M*M)/(M);lst=sigma/Lr;

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). The induction machine d-q are dynamic equivalent circuit shown. Direct quadrature transformation is a mathematical transformation used to simplify the analysis of three phase circuits, application of d-q transformation reduces the tree AC.

IV. PWM Inverter for three phase Induction Motor

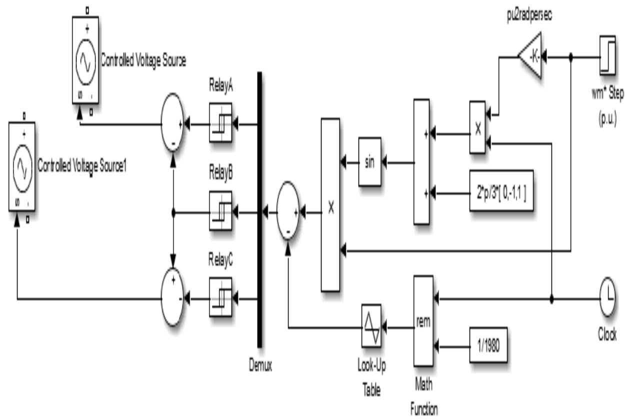

Fig 2. PWM Inverter

The Machine rotor is short circuited and stator is fed by the PWM inverter, built with Simulink blocks and interfaced to the asynchronous machine block through the controlled voltage source block. The inverter uses sinusoidal pulse width modulation. The base frequency of the sinusoidal reference wave is set at 60Hz and the triangular carrier wave frequency is set at 1980 Hz. This frequency corresponds to a frequency modulation factor m of 33(60Hz * 33 = 1980). Sinusoidal PWM is a type of "carrier-based" pulse width modulation. Carrier based PWM uses pre-defined modulation signals to determine output voltages. In sinusoidal PWM, the modulation signal is sinusoidal, with the peak of the modulating signal always less than the peak of the carrier signal. Sinusoidal PWM inverter leg and line-line voltages are illustrated below.

Electromagnetic Torque based on Flux linkage
Rotor flux linkage:

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

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

Stator flux linkage:

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

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

Torque equation:

$$T_{em} = \frac{\rho}{2} \times L_m \left(i_{sq} \times i_{rd} - i_{sd} \times i_{rq} \right)$$

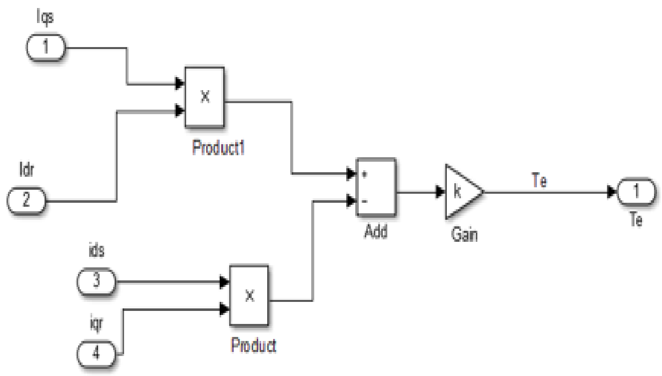

Fig 3. Torque Equation based on Flux linkage

V. MECHANICAL OUTPUT FOR THREE PHASE INDUCTION MOTOR

This is the mechanical sub-model of induction motor from the balance equations and neglecting viscous friction, the rotor speed is shown in the below figure along with T_e as the input.

$$T_{em} = \frac{\rho}{2} \times L_m \left(i_{sq} \times i_{rd} - i_{sd} \times i_{rq} \right)$$

$$W_m = \frac{(Lm * Iq)}{(Tr * Flux)} \text{ rad/s}$$

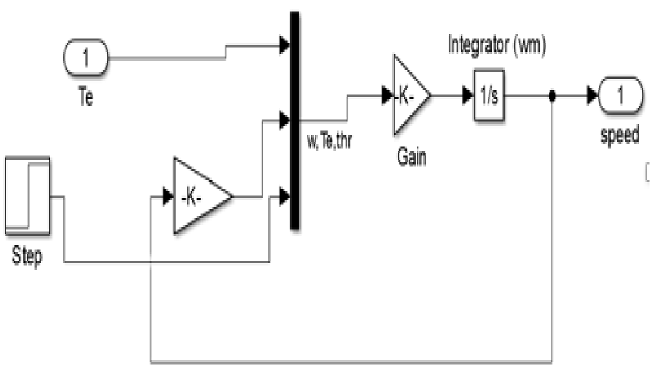

Fig 4. Mechanical Output

The block gives the theta (θ), required for dq to abc and abc to dq transformation. By using the integration block for integration of rotor frequency we can calculate theta (θ).

Theta (θ) = $\int (Wr + Wm)$

Equation for rotor frequency (Wr) is given as,

$$Wr = \frac{(Lm * Iq)}{(Tr * Flux)} \text{ rad/s}$$

Wm= Rotor mechanical speed.
Lm= 34.7mh
Lr=35.5mh
Rr= rotor resistance referred to stator, = 0.228 ohms

Tr= Time constant= $\left(\frac{Lm}{Rr}\right)$ sec.

ABC to DQ transformation

The three phase currents are controlling the PWM inverter. The latter is then generating the three phase voltages to be connected to the model of induction motor. The d-q current that i_d and i_q is transformed back to three phase current using the d-q to abc transformation.

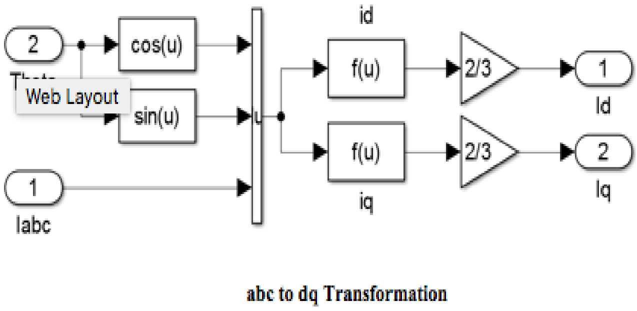

Fig 5. ABC to DQ transformation

This block is used to transform the Iabc to Id and Iq i.e ABC to dq transformation.

The equations used are,

Id= (2/3)*[(Ia*Cos θ) + (Ib* Cos (θ-2π/3)) + (Ic* Cos (θ+2π/3))]

Iq= (2/3)*[(Ia*Sin θ) + (Ib* Sin (θ-2π/3)) + (Ic* Sin (θ+2π/3))]

These Id and Iq are used for flux calculation and theta Calculation respectively

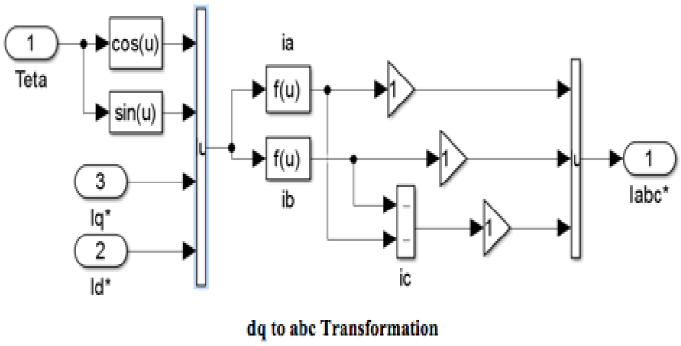

Fig 6. DQ to abc Transformation

The equations used in function blocks are given as,

Ia= (Id*) * Cosθ – (Iq*) *Sinθ
Ib= (Id*) *Cos (θ-2π/3) – (Iq*) *Sin (θ-2π/3)
Ic = (Id*)*Cos (θ+2π/3) – (Iq*) *Sin (θ+2π/3)

These Iabc* and Iabc are combined with the help of vector method and hysteresis is generated using relay combinations to generate a pulse for gate.

VI. RESULTS

Rotor and Stator Current:-

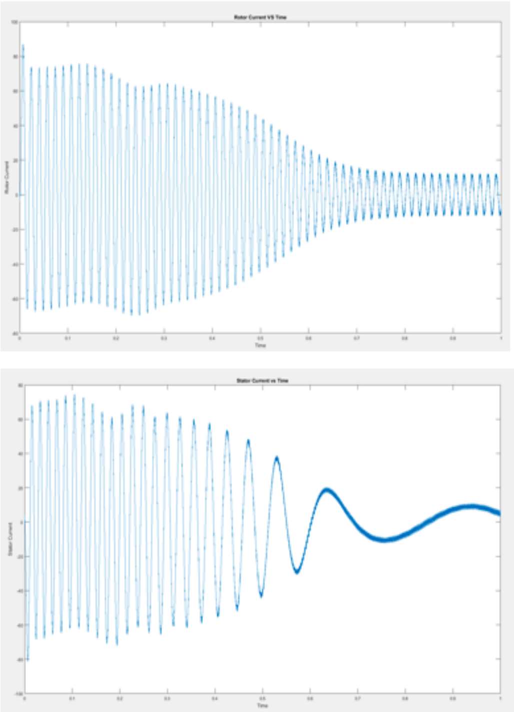

Fig 7. Rotor and Stator Currents

Speed and Torque Output:-

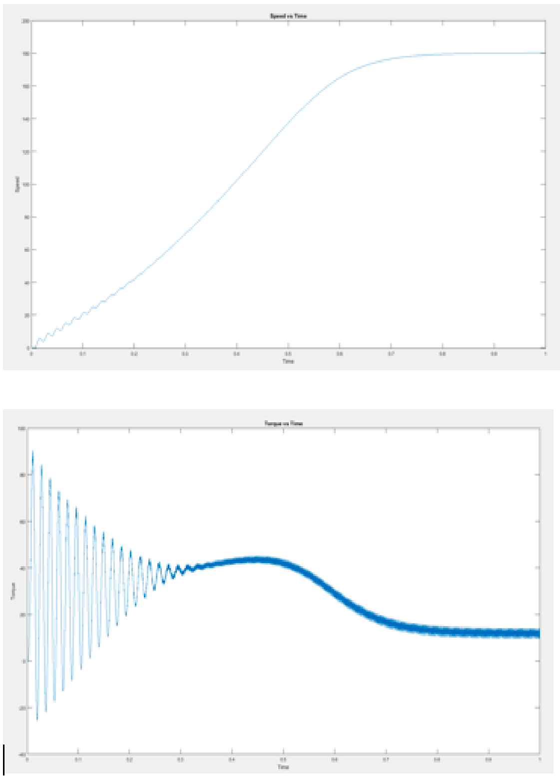

Fig 8. Torque and Speed

The first graph shows the machine's speed going from 0 to 1725 rpm (1.0 pu). The second graph shows the electromagnetic torque developed by the machine. Because the stator is fed by a PWM inverter, a noisy torque is observed. However, this noise is not visible in the speed because it is filtered out by the machine's inertia, but it can be seen in the stator and rotor currents.

VII. CONCLUSION

In this paper, implementation of dynamic model of induction motor with torque and flux as independent quantities. Individual parameter equations are solved in each block. Using the dynamic modelling of induction motor in Simulink we calculated stator and rotor current. The model developed also can be used to estimate the dynamic Torque and speed of the induction motor. Thus measuring the currents from only two phases serves the purpose as the current in flowing in the third phase can easily be calculated. Having made these measurements, the phase currents can now be easily transformed into their corresponding direct- and quadrature-axis values. The novel vector control block then generates the three-phase reference voltages required for ensuring loss minimized rotor- flux oriented control performance and sends them to the pulse width generation (PWM) block which eventually generates the switching pulses of the six inverter devices.

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