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Fuzzy Logic Controller Based Sensorless BLDC Motor

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***Abstract* – The brushless dc motor has a permanent-magnet rotor, and the stator windings are wound such that the back electromotive force is trapezoidal. Therefore it requires rectangular-shaped stator phase currents to produce constant torque. The trapezoidal back EMF implies that the mutual inductance between the stator and rotor is non sinusoidal. Therefore, no particular advantage exists in transforming the machine equations into the well-known two-axis equations, which is done in the case of machines with sinusoidal back EMF'S. This paper develops a phase variable model of the BDCM and uses it to examine the performance of a BDCM speed servo drive system when fed by hysteresis and pulse width-modulated (PWM) current controllers. Transients similar to those applied to the permanent-magnet synchronous motor system are applied to this drive system to allow a comparative evaluation Particular attention is paid to the motor torque pulsations. The ac servo has established itself as a serious competitor to the brush-type dc servo for industrial applications. In the fractional-to-30-hp range, the available ac servos include the BLDC permanent-magnet synchronous, and brushless dc motors (BLDCM). The BLDCM has a trapezoidal back EMF, and rectangular stator currents are needed to produce a constant electric torque, as shown in Fig. 1. Typically, hysteresis or pulse width-modulated (PWM) current controllers are used to maintain the actual currents flowing into the motor as close as possible to the rectangular reference values.**

Keywords: **BLDC, PWM, Sensorless Control.**

I. Introduction

It is shown that, because of the trapezoidal back EMF and the consequent non sinusoidal variation of the motor inductances with rotor angle, a transformation of the machine equations to the well-known d, q model is not necessarily the best approach for modeling and simulation. Instead, the natural or phase variable approach offers many advantages. While this approach has already been proposed, the back EMF is not represented as a Fourier series. Instead, the back EMF is generated according to the position of the rotor using piecewise linear curves. This technique avoids the so-called Gibbs phenomenon that occurs due to the truncation of the higher order harmonics necessary when using the Fourier series approach. Using this model of the BDCM, a detailed simulation and analysis of a BDCM speed servo drive is given. The simulation includes the state variable model of the motor and speed controller and a real-time model of the inverter switches. Although the switches are assumed to be ideal devices, the software developed is flexible enough to incorporate their turn-on and turn-off times. Every instance of a power switch opening or closing is simulated to determine the current oscillations and consequent torque pulsations. The effects of the hysteresis window size on the motor torque pulsations is investigated, and the effects of hysteresis and PWM current controllers on the drive system performance are also examined. Similar transients that were applied to the permanent-magnet synchronous motor (PMSM) drive are applied here for comparative evaluation. In addition, both the small and large signal performances are investigated. The ac servo has established itself as a serious competitor to the brush-type dc servo for industrial applications. In the fractional-to-30-hp range, the available ac servos include the BLDC, permanent-magnet synchronous, and brushless dc motors (BLDCM).

II. BRUSHLESS DC MOTOR

A brushless DC motor (known as BLDC) is a permanent magnet synchronous electric motor which is driven by direct current (DC) electricity and it accomplishes electronically controlled commutation system (commutation is the process of producing rotational torque in the motor by changing phase currents through it at appropriate times) instead of a mechanically commutation system. BLDC motors are also referred as trapezoidal permanent magnet motors. Unlike conventional brushed type DC motor, wherein the brushes make the mechanical contact with commutator on the rotor so as to form an electric path between a DC electric source and rotor armature windings, BLDC motor employs electrical commutation with permanent magnet rotor and a stator with a sequence of coils. In this motor, permanent magnet (or field poles) rotates and current carrying conductors are fixed.

Fig 1. Brushless DC motor

The armature coils are switched electronically by transistors or silicon controlled rectifiers at the correct rotor position in such a way that armature field is in space quadrature with the rotor field poles. Hence the force acting on the rotor causes it to rotate. Hall sensors or rotary encoders are most commonly used to sense the position of the rotor and are positioned around the stator. The rotor position feedback from the sensor helps to determine when to switch the armature current.

III. MODELING OF BLDC MOTOR

The two names for the same type of motor, BLDC motor and asynchronous motor, describe the two characteristics in which this type of motor differs from DC motors and synchronous motors. BLDC refers to the fact that the field in the rotor is induced by the stator currents, and asynchronous refers to the fact that the rotor speed is not equal to the stator frequency. No sliding contacts and permanent magnets are needed to make an BLDC work, which makes it very simple and cheap to manufacture. As motors, they rugged and require very little maintenance. However, their speeds are not as easily controlled as with DC motors. They draw large starting currents, and operate with a poor lagging factor when lightly loaded.

The BLDC can be operated directly from the mains, but variable speed and often better energy efficiency are achieved by means of a frequency converter between the mains and the motor. A typical frequency converter consists of a rectifier, a voltage-stiff DC link, and a pulse-width modulated (PWM) inverter. The inverter is controlled using a digital signal processor (DSP). The majority of BLDC are used in constant speed drives, but during the last decades the introduction of new semiconductor devices has made variable speed drives with BLDC available. Variable speed IMs are usually fed by open loop frequency inverters. The rotor speed of the machine is not measured and a change in load torque will result in the speed to change.

The control and speed sensorless estimation of BLDC drives is a vast subject. Traditionally, the BLDC has been used with constant frequency sources and normally the squirrel-cage machine is utilized in many industrial applications, from chemical plants and wind generation to locomotives and electric vehicles.

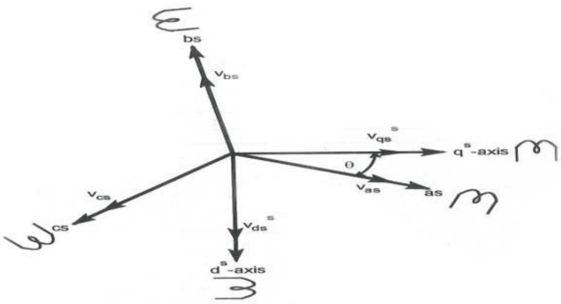

Fig 2. 3-ϕ to 2-ϕ Transformation

$$\begin{bmatrix} V_{as} \\ V_{bs} \\ V_{cs} \end{bmatrix} = \begin{bmatrix} \cos\theta & \sin\theta & 1 \\ \cos(\theta - 120^0) & \sin(\theta - 120^0) & 1 \\ \cos(\theta + 120^0) & \sin(\theta + 120^0) & 1 \end{bmatrix} \begin{bmatrix} V_{qs}{}^s \\ V_{ds}{}^s \\ V_{os}{}^s \end{bmatrix} \quad 3.1$$

The corresponding inverse relation is

$$\begin{bmatrix} V_{qs}{}^{s} \\ V_{ds}{}^{s} \\ V_{os}{}^{s} \end{bmatrix} = \frac{2}{3}\begin{bmatrix} Cos\theta & Cos(\theta - 120^{o}) & Cos(\theta + 120^{o}) \\ Sin\theta & Sin(\theta + 120^{o}) & Sin(\theta + 120^{o}) \\ 0.5 & 0.5 & 0.5 \end{bmatrix}\begin{bmatrix} V_{as} \\ V_{bs} \\ V_{cs} \end{bmatrix} \quad 3.2$$

Here $v_{os}{}^{s}$ is zero-sequence component, convenient to set θ = 0 so that q^s axis is aligned with as-axis. Therefore ignoring zero-sequence component, it can be simplified as-

$$V_{qs}{}^{s} = \frac{2}{3}v_{as} - \frac{1}{3}v_{bs} - \frac{1}{3}v_{cs} = v_{as} \quad 3.3$$

$$V_{ds}{}^{s} = \frac{-1}{\sqrt{3}}v_{bs} + \frac{1}{\sqrt{3}}v_{cs} \quad 3.4$$

Equations 3.3 & 3.4 consistively called as *Clark Transformation.*

Figure 3.1 (b) shows the synchronously rotating d^e-q^e axes, which rotate at synchronous speed w_e with respect to the d^s-q^s axes and the angle $\theta_y = \omega_e * t$. The two-phase d^s-q^s windings are transformed into the hypothetical windings mounted on the d^e-q^e axes. The voltages on the d^s-q^s axes can be transformed (or resolved) into the d^e-q^e frame as follows:

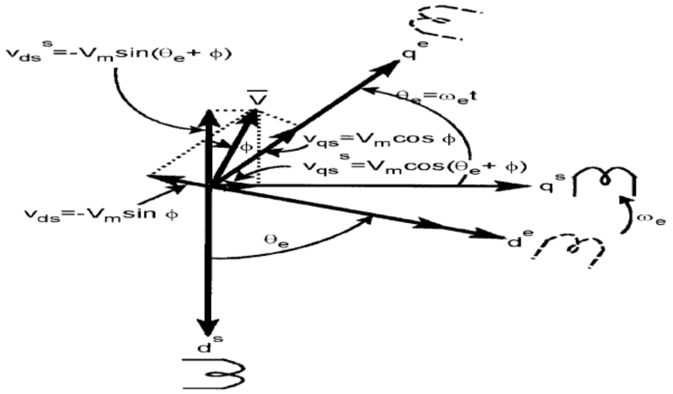

Fig 3. stationary frame d^s-q^s to dynchronously rotating frame d^e-q^e transformation

$$v_{qs} = v_{qs}^{s}\cos\theta_e - v_{ds}^{s}\sin\theta_e \ldots\ldots 3.5$$

$$v_{ds} = v_{qs}^{s}\sin\theta_e + v_{ds}^{s}\cos\theta_e \ldots\ldots 3.6$$

Constitutively eq 3.5 and 3.6 are known as *Park Transformation.*

For convenience, the superscript 'e' has been dropped from now on from the synchronously rotating frame parameters. Again, resolving the rotaing frame parameters into a stationary frame, the relations are

$$v_{qs}^{s} = v_{qs}\cos\theta_e + v_{ds}\sin\theta_e \ldots\ldots 3.7$$

$$v_{ds}^{s} = -v_{qs}\sin\theta_e + v_{ds}\cos\theta_e \ldots\ldots 3.8$$

Constitutively eq 3.7 and 3.8 are known as *Inverse Park Transformation*

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IV. VECTOR CONTROL

The various control strategies for the control of the inverter-fed BLDC motor have provided good steady state but poor dynamic response. From the traces of the dynamic responses, the cause of such poor dynamic response is found to be that their air gap flux linkages deviate from their set values. The deviation is not only in magnitude but also in phase. The variations in the flux linkages have to be controlled by the magnitude and frequency of the stator and rotor phase currents and instantaneous phases.

The oscillations in the air gap flux linkages result in oscillations in electromagnetic torque and, if left unchecked, reflect as speed oscillations. This is undesirable in many high-performance applications. Air gap flux variations result in large excursions of stator currents, requiring large peak converter and inverter ratings to meet the dynamics. An enhancement of peak inverter rating increases cost and reduces the competitive edge of ac drives over dc drives.

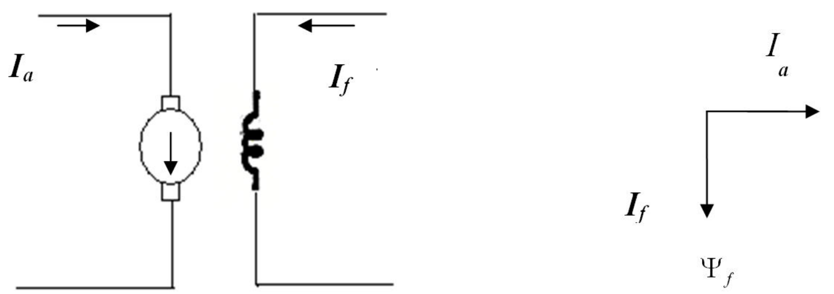

Fig 4. Separately excited motor

$$T_e = K_t \Psi_f \Psi_a = K_t^{'} i_a i_f \qquad 4.2$$

Where I_a = torque component & I_f = field component.

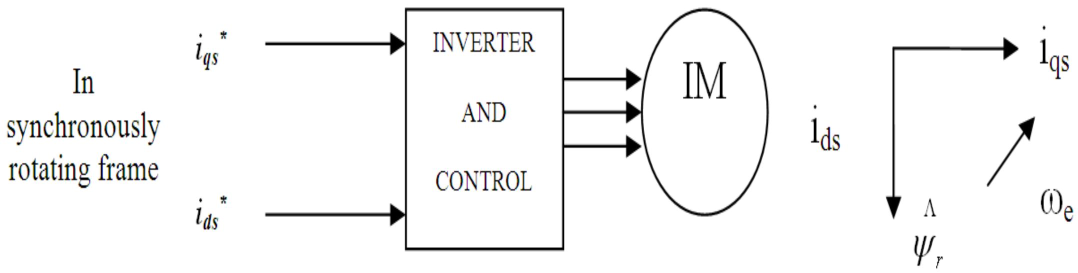

Fig 5. Vector controlled BLDC motor

$$T_e = K_t \hat{\Psi}_r i_{qs} = K_t^{'} i_{qs} i_{ds} \qquad 4.3$$

Where i_{qs} = torque component & i_{ds} = field component

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$\hat{\Psi}_r$ = Absolute $\overline{\psi_r}$ is the peak value of the sinusoidal space vector

V. SENSORLESS CONTROL

Estimation can be defined as the determination of constants or variables for any system, according to a performance level and based in the measurements taken from the process. Speed sensorless estimation as its name implies, is the determination of speed signal from an IM drive system without using rotational sensors. It makes use the dynamic equations of the IM to estimate the rotor speed component for control purposes. Estimation is carried out using the terminal voltages and currents which are readily available using sensors. There are various rotor speed estimation schemes available in the market [9][30]. These schemes were based on different algorithms with the purpose to improve the performance of the speed estimation process. The schemes range from open loop basis to closed loop basis with its own advantages and disadvantages. To estimate the speed of the IM, type of scheme chosen is a factor to consider which at the end will determine the design complexity, feasibility and performance of the selected scheme. In this section, an overview of the speed sensorless estimation schemes available will be discussed. Sensor less vector control BLDC motor drive essentially means vector control without any speed sensor. An incremental shaft mounted speed encoder, usually an optical type is required for closed loop speed or position control in both vector control and scalar controlled drives. A speed signal is also required in indirect vector control in the whole speed range and in direct vector control for the low speed range, including the zero speed start up operation. Speed encoders undesirable in a drive because it adds cost and reliability problems. Controlled bldc motor drives without mechanical speed sensors at the motor shaft have the attractions of low cost and high reliability. To reduce total hardware complexity, costs and to increase mechanical robustness, it is desirable to eliminate speed and position sensors in vector-controlled drives. Drives operating in hostile environments or in high speed drives speed sensors can't be mounted.

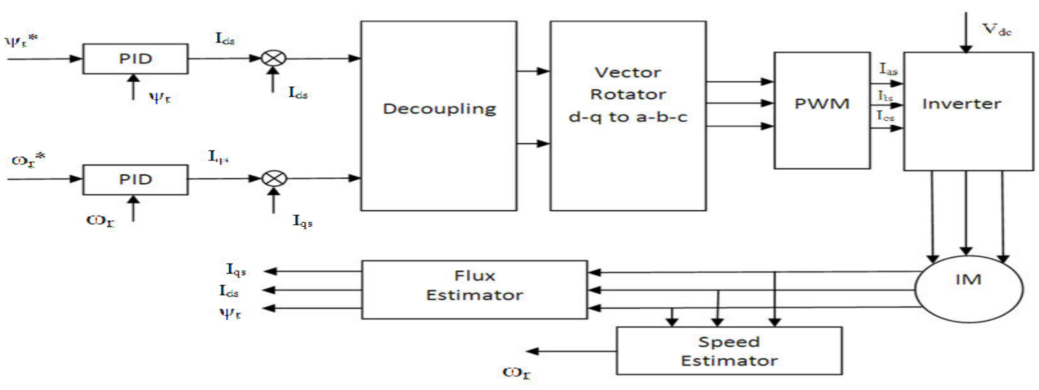

Fig 6. Block Diagram of Sensorless Control of Bldc Motor

VI. Fuzzy Logic Controllers

The logic of an approximate reasoning continues to grow in importance, as it provides an in expensive solution for controlling know complex systems. Fuzzy logic controllers are already used in appliances washing machine, refrigerator, vacuum cleaner etc. Computer subsystems (disk drive controller, power management) consumer electronics (video, camera, battery charger) C.D. Player etc. and so on in last decade, fuzzy controllers have convert adequate attention in motion control systems. As the later possess non-linear characteristics and a precise model is most often unknown. Remote controllers are increasingly being used to control a system from a distant place due to inaccessibility of the system or for comfort reasons. In this work a fuzzy remote controllers is developed for speed control of a converter fed dc motor. The performance of the fuzzy controller is compared with conventional P-I controller.

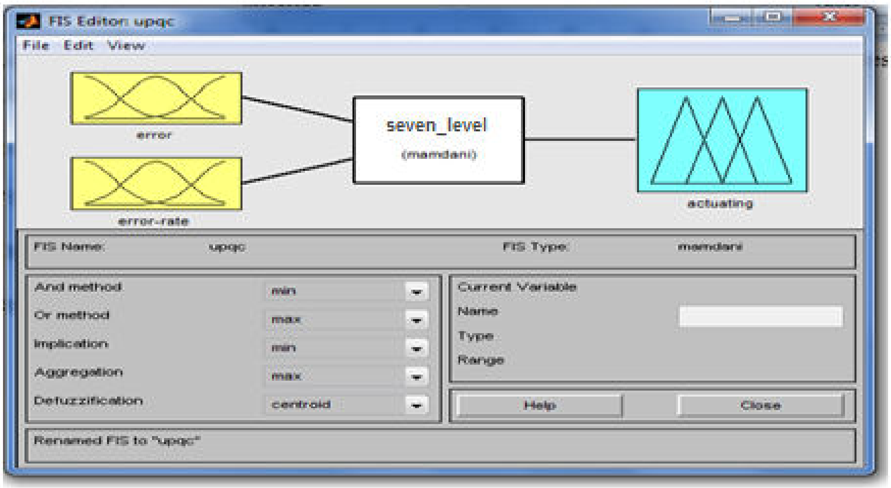

Fig.7. -fuzzy interface system

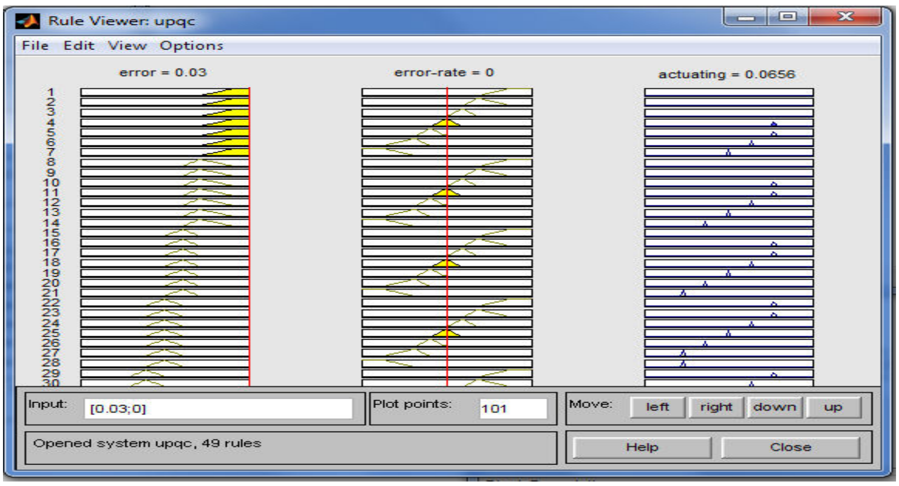

Fig.8. fuzzy Rule Viewer

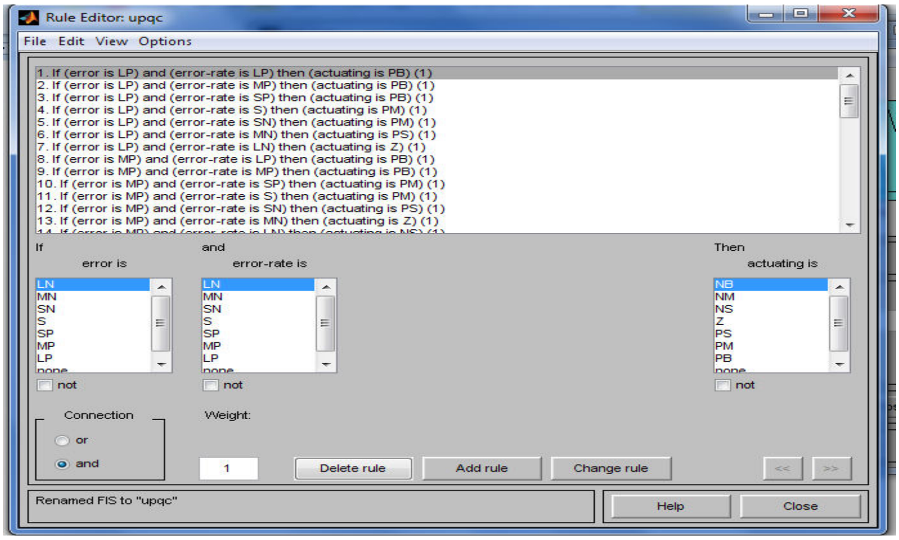

Fig 9.-fuzzy Rule Editor

VII. Simulink Block Diagrams

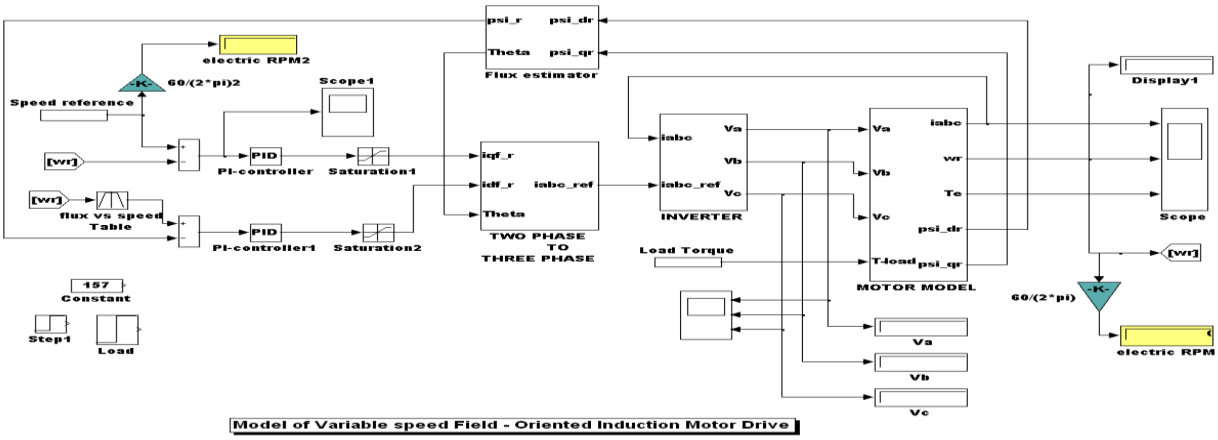

Fig 10. Simulink Model of Vector Controlled Bldc motor

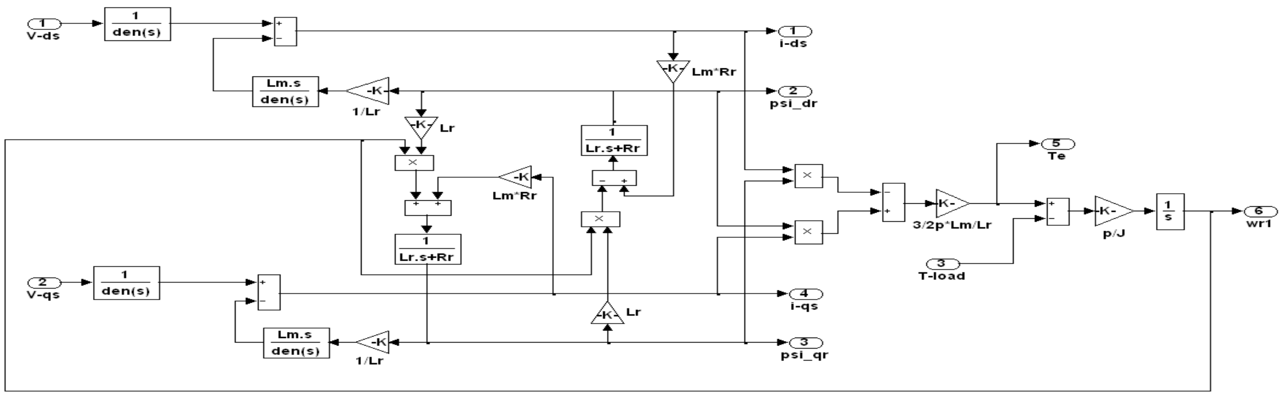

Fig.11: Simulink block diagram for bldc motor model

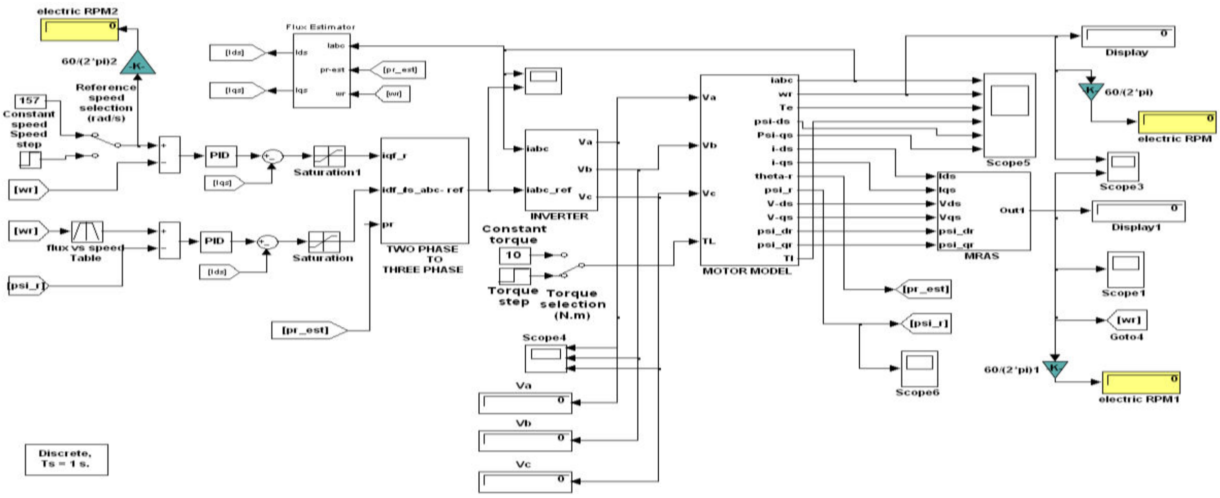

Fig 12. Simulink root block diagram of Sensorless control of bldc motor using MRAS

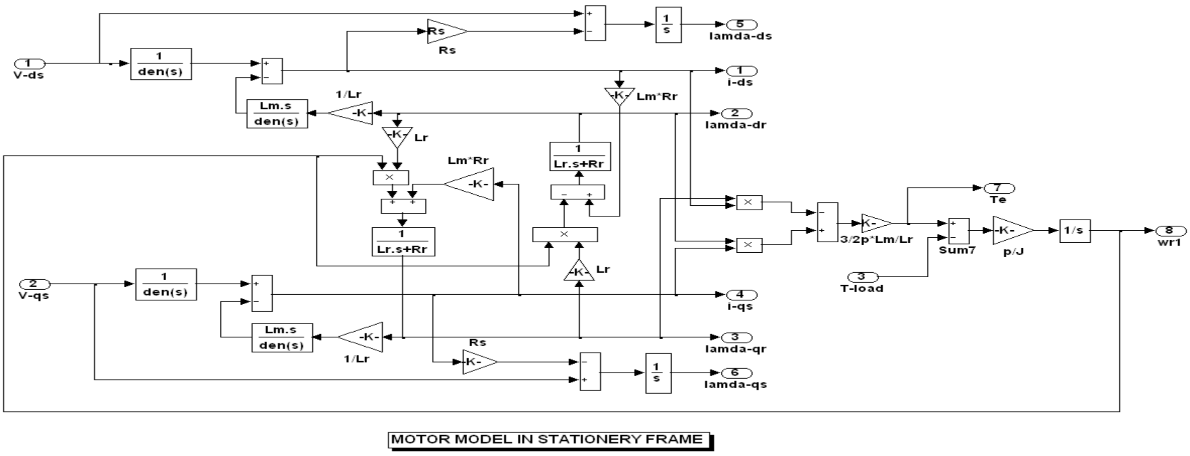

Fig 13. Simulink block diagram for bldc motor model

The simulation of Vector Control of bldc is done by using MATLAB®/SIMULINK. The results for different cases are given below.

Reference speed = 100 rad/sec and on no-load

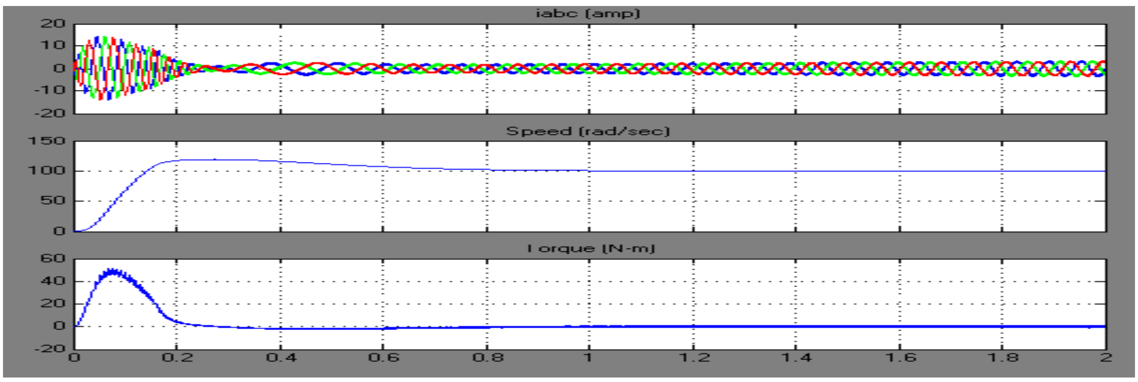

Fig 14: 3-ϕ currents, Speed, and Torque for no-load reference speed of 100 rad/sec

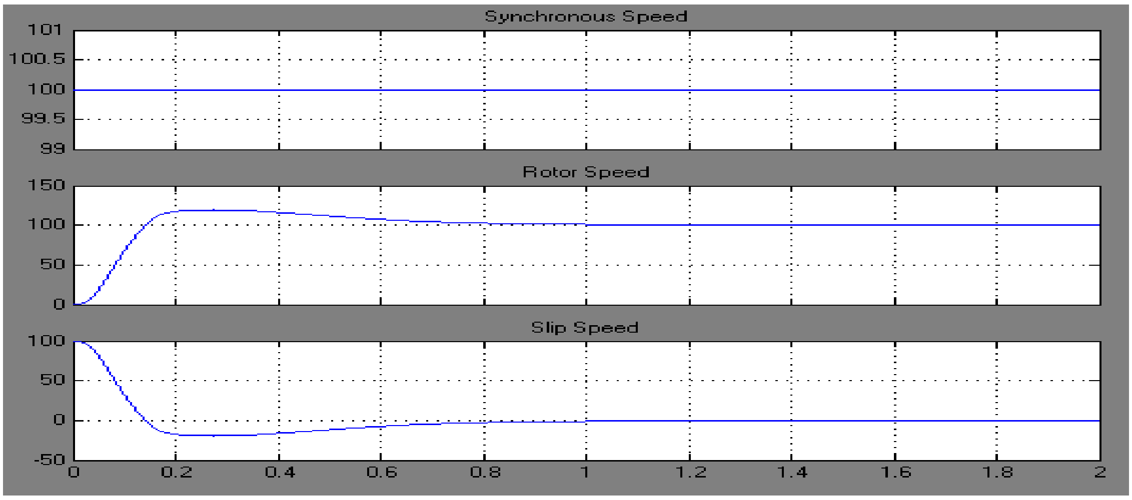

Fig 15: Reference speed, Rotor Speed, Slip Speed Respectively Reference speed = 100 rad/sec; Load torque of 15 N-m is applied at t = 1.5 sec

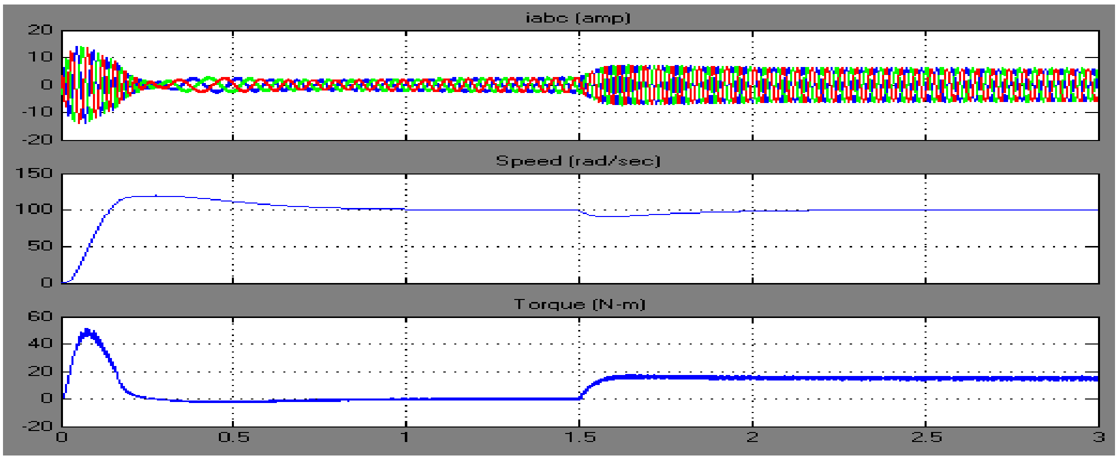

Fig 16: 3-ϕ currents, Speed, and Torque for no-load reference speed of 100 rad/sec

VIII. Conclusion

In this paper, Sensorless control of BLDC motor using Model Reference Adaptive System (MRAS) technique has been proposed. Sensorless control gives the benefits of Vector control without using any shaft encoder. In this thesis the principle of vector control and Sensorless control of BLDC motor is given elaborately. The mathematical model of the drive system has been developed and results have been simulated. Simulation results of Vector Control and Sensorless Control of BLDC motor using MRAS technique were carried out by using Matlab/Simulink and from the analysis of the simulation results, the transient and steady state performance of the drive have been presented and analyzed.

From the simulation results, it can be observed that, in steady state there are ripples in torque wave and also the starting current is high. The main results obtained from the Simulation, the following observations are made.

i) The transient response of the drive is fast, i.e. we are attaining steady state very quickly.

ii) The speed response is same for both vector control and Sensorless control.
iii) By using MRAS we are estimating the speed, which is same as that of actual speed of BLDC motor.

Thus by using sensorless control we can get the same results as that of vector control without shaft encoder. Hence by using this proposed technique, we can reduce the cost of drive i.e. shaft encoder's cost, we can also increase the ruggedness of the motor as well as fast dynamic response can be achieved

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