Emotional Controller (BELBIC) based DTC for Encoderless Synchronous Reluctance Motor Drives

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Abstract— **In this paper, a direct torque control (DTC) of encoderless Synchronous Reluctance Motor (SynRM) drives is proposed based on emotional controller and space vector modulation. The proposed modern controller is called brain emotional learning based intelligent controller (BELBIC). The utilization of BELBIC is based on the emotion processing mechanism in brain, and is essentially an action, which is based on sensory inputs and emotional cues. This intelligent control is inspired by the limbic system of mammalian brain. In this work, a BELBIC controller is designed for torque and flux control in stator flux reference frame, respectively. The proposed controller is able to reduce the torque, flux, current and speed pulsations during steady-state behavior while the fast response and robustness merits of the classic DTC are preserved. In addition, in order to achieve a maximum torque per Ampere (MTPA) strategy at any operating condition, a search algorithm changes the stator flux magnitude. The proposed controller is successfully implemented in real-time through a PC-based three-phase, 0.5 Hp SynRM. The obtained results show superior proposed control characteristics, especially very fast response, simple implementation and robustness with respect to disturbances and parameter variations. So the proposed encoderless MTPA emotional controller for SynRM drives with minimized number of dependent parameters presents excellent promise for industrial scale utilization**

Keywords-component; medial brain, emotional intelligent controller, model-free, SynRM, DTC, stator flux reference, MTPA

I. INTRODUCTION

In recent years, the synchronous reluctance motor (SynRM) received much attention for many applications due to its cold rotor, simple and rugged construction [1]. A multitude of solutions for control of SynRM drives have been proposed [1]–[6]. Among them, the direct torque and stator flux control for SynRM drives has been developed as direct torque control (DTC) [3-6]. The DTC strategy was an induction motor control technique that has been successful because it explicitly considers the variable structure nature of the voltage source inverter and uses few machine parameters, while being more robust to parameter uncertainty than field-oriented control (FOC) [7]. The DTC features fast responses, structural simplicity and robustness to modeling uncertainty and disturbances. However, it still has some disadvantages that can be summarized in the following points: high torque, flux and current ripples; variable switching frequency behavior and difficulty to control torque and flux at very low speed. To overcome the above drawbacks, some researchers have tried to propose some different DTC space vector modulation (SVM) techniques or to improve switching state patterns [5, 6].

Variable structure control (VSC) is one of the robust control methods applicable to electromechanical systems [8]. Recently, several solutions that integrate the VSC and DTC principles (VS-DTC) within high performance drives have been proposed [9, 10]. The uncertainties, parameter variations and/or disturbances can be rejected for VSC when the boundaries of the system and lumped uncertainties are known.

The Artificial Intelligence (AI) techniques, such as expert system (ES), fuzzy logic (FL), artificial neural network (ANN or NNW), biologically-inspired (BI) and genetic algorithm (GA) have recently been applied widely in power electronics and motor drives. The goal of AI is to model human or natural intelligence in a computer so that a computer can think intelligently like a human being [11]. In [12], it has been claimed the fuzzy-neural network hybrid requires less control effort in compared to sliding mode.

Despite the versatility of bio-inspired and intelligent systems, many practical applications require large computational power to overcome complexity and real-time constraints of these systems. In addition, dedicated systems are need in many industrial applications to meet lower power and space requirements [11], also without any previous learning can't do the control process, and some of them are based on rule [13].

Similar to AI techniques, other well-known nonlinear control strategies such as adaptive input-output feedback linearization [14] and adaptive backstepping methods [15] are complex to implement and are costly; therefore, it is important to design a controller that requires less cost with good performance.

Several attempts have been made to model the emotional behavior of human brain [16, 17]. Based on the cognitively motivated open loop model, brain emotional learning based intelligent controller (BELBIC) was introduced for the first time by Lucas et al. [18], and during the past few years this controller has been used, with minimal modifications, in control devices for several industrial applications. In [19], a BELBIC was designed and implemented on field-programmable gate arrays (FPGA), and applied for controlling a laboratorial overhead traveling crane in model-free and embedded manner. For the first time, implementation of the BELBIC method for electrical drive control was presented by Rahman et al. [20]. The results show superior control characteristics, especially very fast response, simple implementation and robustness with respect to disturbances and parameter variations. In [21], the controller was used for first time to control an IM drive and investigated its independent of the parameters variations, especially rotor resistance. Also the controller was implemented for some other electric drives successfully [22-24]. Based on the above mentioned evidence of the emotional control approaches in computer and control engineering, it can be concluded that the application of emotion in systems could by its simple and unique control design, overcome the problems of non-linear system, manufacturing imperfections, acceptably.

In this paper, it is proposed to use emotional intelligent controller for encoderless DTC (BELBIC-DTC) of SynRM drives. The proposed system drive does not require position sensor due to using stator flux reference frame instead of rotor reference frame. In addition, continues change to stator flux reference is applied for the purpose of searching a maximum torque per Ampere operating point.

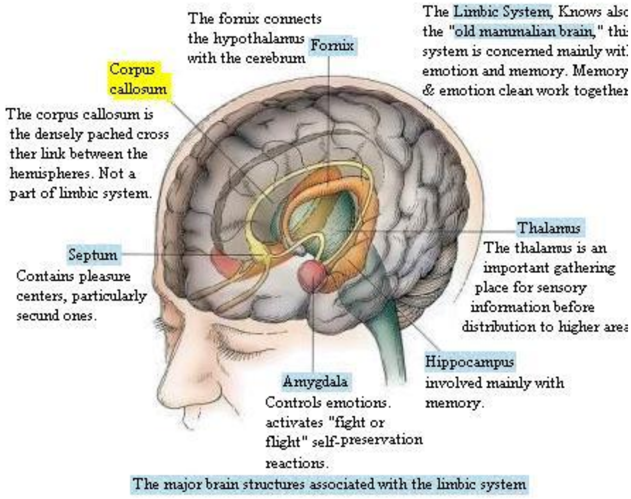
II. Computational Model of Limbic System

The main purpose of this paper is to use a structural model based on the limbic system of mammalian brain and emotional learning based action selection, for decision making and control engineering applications. Fig. 1 (a) shows the pertinent pictures of the human brain, and Fig. 1(b) provides a graphical depiction of the modified sensory signal and learning network connection model inside the brain [18]. For sake of simplicity, the BELBIC term is called emotional controller in this paper.

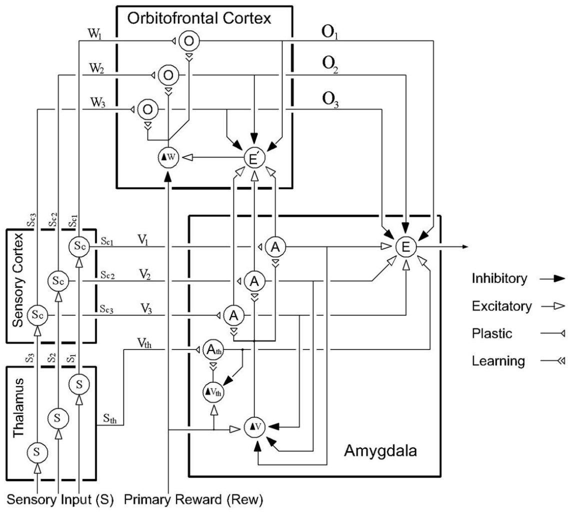
The model of the proposed BELBIC structure is illustrated in Fig. 1(b). The BELBIC technique is essentially an action generation mechanism based on sensory inputs and emotional cues. In any given application, the choice of the sensory inputs (feedback signals) is informed by control engineering judgment whereas the choice of emotional cues depends on the performance objectives in that application. In general, these can be vector valued quantities. For the sake of illustration, one sensory input and one emotional signal (stress) have been considered in this paper [24]. In Fig. 1(b), there are some nods in different part of the model, that each of them is model by same mathematical equations. The abstract structure of the computational model mimicking some parts of mammalian brain is shown in Fig.2.

By entry, the sensory input and emotional case (reward) signal and processing them, the result is the output from the model. In other words, E can be obtained from:

$$E = \sum_j A_j + A_{th} - \sum_j O_j \tag{1}$$



(a)



(b)

Fig. 1. a) Sectional view of the human brain for emotion processing.b) Graphical depiction of the developed computational model of brain emotional learning process (BELBIC).

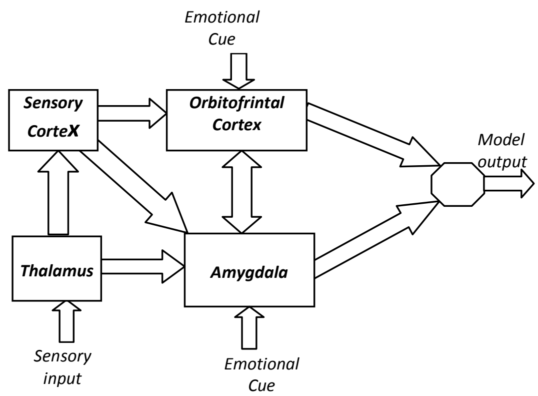


Fig. 2. Basic block structure of the emotional controller

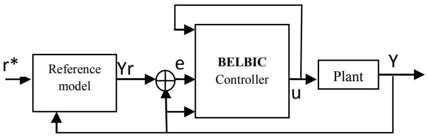


Fig. 4. Control system configuration using BELBIC.

The internal areas output are computed pursuant to (2)-(3).

$$A_{th} = V_{th} \cdot \{\max(S_j) = S_{th} \} \quad (2)$$

$$A_j = S_j V_j \quad \& \quad O_j = S_j W_j \quad (3)$$

where A_j and O_j are the values of amygdala output and output of orbitofrontal cortex at each time, V_j is the gain in amygdala connection, W_j is the gain in orbitofrontal connection S_j is sensory output respectively and j is the j^{th} input. Variations of V_j and W_j can be obtained as:

$$\Delta V_i = \alpha \left(\max \left(0, Sc_i (R - \sum_i A_i) \right) \right) \quad (4)$$

$$\Delta V_{th} = \alpha_{th} \left(\max \left(0, S_{th} (R - A_{th}) \right) \right) \quad (5)$$

The E' node sums the outputs from A except A_{th}, and then subtracts from inhibitory outputs from the O nodes.

$$E' = \sum_j A_j - \sum_j O_j \quad (6)$$

$$\Delta W_i = \beta \left(Sc_i \left(E' - R \right) \right) \quad (7)$$

Where (α, α_{th}) and β are the learning steps in amygdala and orbitofrontal cortex, respectively. R is the value of emotional cue function at each time. The learning rule of amygdala is given in (4, 5) which cannot decrease.

Fig. 3 shows the BELBIC controller configuration. The used functions in emotional cue R and sensory input S blocks can be given by the following relations:

$$R = f(J, e, y, u) \ \& \ S = g(y, u, e) \quad (8)$$

Where e, u, y and J are system error, controller output, system output and an arbitrary object function respectively. Eventually, initial values for α and β in O and A and functions R and S should be selected for emotional signal generation.

III. BELBIC-DTC OF SENSORLESS SYNRM DRIVES

The classic DTC uses bang-bang torque and flux controllers, without decoupling [7]. A simple switching logic (switching table) employs the output signals of these controllers to select the most appropriate voltage vector, i.e., the one which rapidly reduces the torque and flux errors. Due to the fact that the voltage vector is maintained for the whole duration of the control period, the classic approach causes large torque, flux and current ripple, accompanied by acoustical noise. The switching frequency of the power devices is variable and uncontrollable. One way to decrease the ripple is to apply SVM techniques.

To preserve DTC transient and robustness merits, an emotional controller is designed for torque and flux control respectively. Block diagram of the proposed MTPA DTC for sensorless SynRM drives based on BELBIC is shown in Fig. 4. This drive is stator-flux oriented and stator-flux controlled. Control quantities are the torque T_e and the stator flux magnitude λ_s. Torque reference T_e^* is produced by an outer speed control loop, with a PI speed controller. The inner loop includes VS-DTC controller which calculates the most appropriate stator voltage vectors to drive the torque and flux to track their references. The control stator voltage signals have been limited before proceeding to SVM block, providing a solution for high resolution control and constant inverter switching frequency. The flux reference λ_s^* is set in accordance with the search algorithm. The flux estimator block is implemented by integrating the stator-induced voltage and then estimated torque is calculated. Stator flux and torque control can be achieved taking into account the SynRM stator equation in stator flux reference frame

$$\overline{V}_s = R_s \bar{i}_s + \frac{d}{dt} \overline{\lambda}_s + j \hat{\omega}_{\lambda s} \overline{\lambda}_s \quad (9)$$

where $\overline{V}_s$ and $\bar{i}_s$ are the stator voltage and current, R_s is the stator resistance, and $\hat{\omega}_{\lambda s}$ is the estimated stator flux angular speed. The direct and quadrature components of (9) are

$$V_{sx} = R_s i_{sx} + \frac{d}{dt} \lambda_s \quad (10)$$

$$V_{sy} = R_s i_{sy} + \hat{\omega}_{\lambda s} \lambda_s \quad (11)$$

Under the assumed orientation, the develop torque is

$$T_e = 1.5 P \lambda_s i_{sy} \quad (12)$$

If the stator flux is constant, it is evident that torque can be controlled by the imaginary component V_{sy}, the torque component of the voltage vector

$$V_{sy} = \frac{2 R_s}{3 P \lambda_s} T_e + \hat{\omega}_{\lambda s} \lambda_s \quad (13)$$

The estimated stator flux speed $\hat{\omega}_{\lambda s}$ is calculated in a stationary reference frame as follows

$$\hat{\omega}_{\lambda s} = \frac{d}{dt} \left(\tan^{-1} \frac{\lambda_{Qs}}{\lambda_{Ds}} \right) = \frac{\left(\lambda_{Ds} * \dot{\lambda}_{Qs} - \lambda_{Qs} * \dot{\lambda}_{Ds} \right)}{\lambda_s^2} = \frac{\left(\lambda_{Ds} * \left(v_{Qs} - R_s i_{Qs} \right) - \lambda_{Qs} * \left(v_{Ds} - R_s i_{Ds} \right) \right)}{\lambda_s^2} \quad (14)$$

where v_{Ds}, v_{Qs}, i_{Ds} and i_{Qs} are the voltage and currents values in stationary reference frame as well as λ_{Ds} and λ_{Qs} are the estimated direct and quadrature components of stator flux (λ_s) in stationary reference frame, and are calculated as

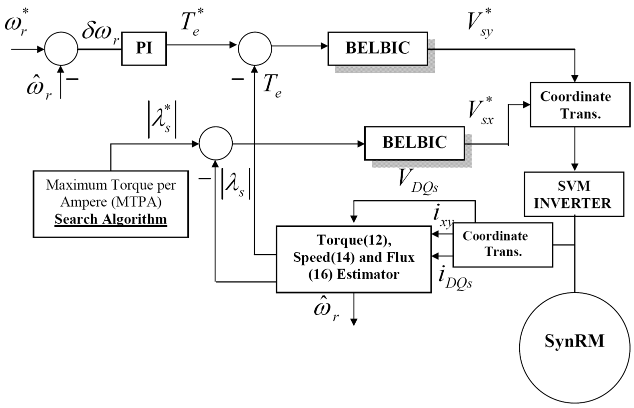


Fig. 4: The proposed MTPA DTC of encoderless SynRM Drives

$$\lambda_{Ds} = \int \left(v_{Ds} - R_s i_{Ds} \right) dt \quad (15)$$

$$\lambda_{Qs} = \int \left(v_{Qs} - R_s i_{Qs} \right) dt, \; \lambda_s = \sqrt{\lambda_{Ds}^2 + \lambda_{Qs}^2} \quad (16)$$

The precision of the $\hat{\omega}_{\lambda s}$ for (14) is not so important, since a PI regulator is present on the torque channel. It corrects the torque even if the last term in (14) is erroneously estimated.

The flux control is accomplished by modifying the real component V_{sx}, the flux component of the voltage vector. For each sampling period T_{samp}, one can approximate the V_{sx} voltage as

$$V_{sx} = R_s i_{sx} + \Delta\lambda_s / T_{samp} \quad (17)$$

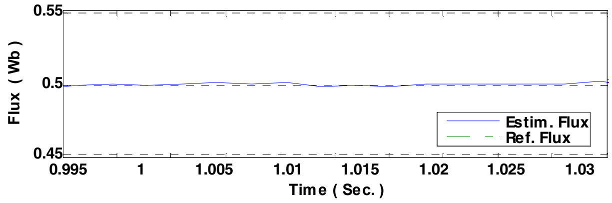
At high speed, the $\hat{R}_s \, i_{sx}$ voltage drop can be neglected and voltage becomes proportional with the flux change $\Delta\lambda_s$ and the switching frequency $1/T_{samp}$. At low speed, the $R_s i_{sx}$ term is not negligible.

The simplest way is to add the $R_s i_{sx}$ term at the output of the flux regulator in same manner as the speed dependent term was added to the torque controller output. However, the computation of the voltage drop term requires a time-consuming stator flux coordinate transformation. Instead of it, a PI controller was used on the flux channel.

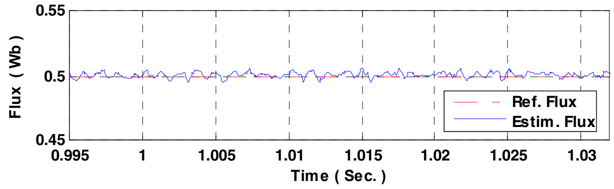
The symmetrical SVM applies six voltage vectors within a control period, and the duration of each vector is determined with high time resolution. The switching frequency of the power devices is constant and controllable.

IV. Simulation Results

Some simulations are performed to show that the proposed BELBIC-DTC is able to operate with reduced torque and flux ripple, without compromising the fast dynamic response and robustness of torque and flux control, of the classic DTC [8]. The BELBIC-DTC and classic DTC strategies are simulated for a 0.5 Hp four-pole three-phase SynRM drive (for more information see Appendix), at 5 KHz sampling frequency, and representative results are illustrated in Fig. 5. In both cases, at the instant 1 sec, the torque command is changed from -1 N.m to +1 N.m, with the stator flux maintained at the rated level, while the motor was running at 200 Rpm. The stator flux magnitude in the BELBIC-DTC drive is shown in Fig. 5(a), while Fig. 5(b) shows similar quantity in the classic DTC drive. Although the classic DTC was fine tuned to produce low flux ripple, the BELBIC-DTC exhibits much lower ripple. The proposed controller is superior to classic DTC flux control, it has low ripple, and is equally robust with respect to torque transients.



a) BELBIC-DTC



b) Classic DTC

Fig.5: Stator Flux magnitude in the BELBIC-DTC and Classical DTC

V. Exprimental Setup and Results

The overall block diagram of the proposed drive system is shown in Fig. 6. In order to evaluate the performance of the actual system, a PC-based prototype system was built and tested. The experimental setup is shown in Fig. 6 and consists of the following sections: A 0.5 Hp three-phase SynRM and a 1.1-kW dc generator as its load, a three-phase voltage source.

The steady-states of speed, torque and flux at 1400 rpm with 50% full load under proposed BELBIC-DTC are shown in Fig. 8. From this figure, it can be seen the ripples in speed and torque are reduced significantly.

The chattering free torque and flux dynamics are illustrated in Fig. 7 when the torque command reverses between ±1 N.m. The corresponding trajectories of estimated rotor speed, flux and phase current are in this figure.

Fig. 8 shows the experimental results of drive performance under the search algorithm. The motor is started under a low load condition in response to a medium step speed command as shown in Fig. 8.a. The original stator flux command is set at maximum value to provide fast dynamics. At about t = 1.0 seconds, a steady state speed is detected by the ALMC. Then, the direction test determines a decreasing direction for λ_s^*. Subsequently, the adjustment of λ_s^* is started towards its optimal value as shown in Fig. 8.b. After only about one second, the motor terminal current reaches its minimum value as shown in Fig. 8.c. This is about a 50% reduction in the input motor current. Then, the triangular mode of operation is initiated. By applying a speed command change at t = 7 s promptly, λ_s^* returns to its original value, $\lambda_{sMax.}^*$, and a new steady state speed is reached after a desirable transient period. The search algorithm becomes active again, and a minimum input motor current is obtained at the new operating point.

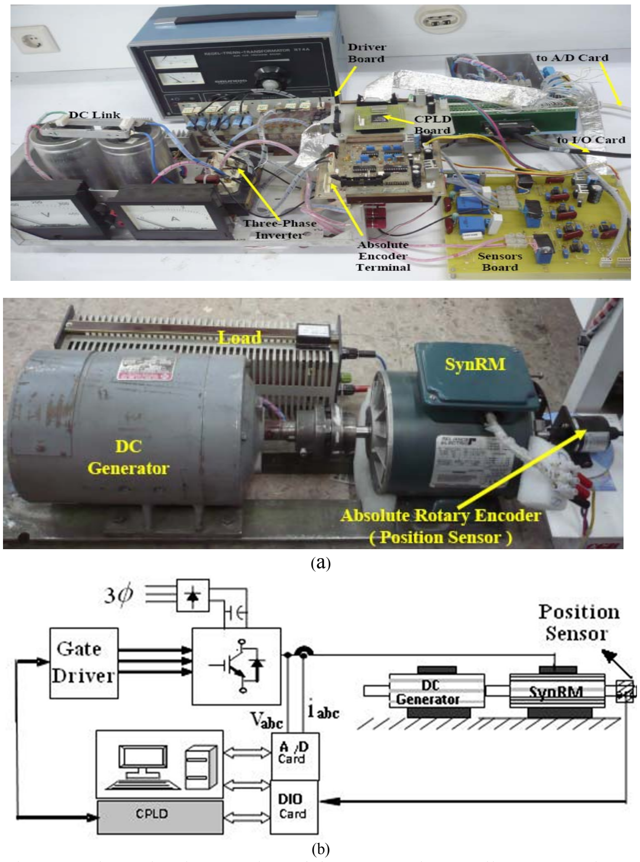


Fig.6. Hardware implementation of the proposed controller, a) experimental setup, b) Literary implementation block diagram,

VI. CONCLUSION

This paper has presented a real-time implementation of an emotional controller (BELBIC) based SVM-DTC for encoderless three-phase SynRM drive in stator flux reference frame. In particular, the BELBIC-DTC contributes to robustness of the drive as well as a fast dynamic response, and the SVM improves the torque, flux and current steady-state waveforms by ripple reduction. In addition, a search algorithm minimizes the motor stator current amplitude by a continuous change in stator flux level at each operating point. The proposed emotional intelligent controller consists of model-free simple structure with high auto learning feature, and therefore can be easily adapted for large scale industrial applications.

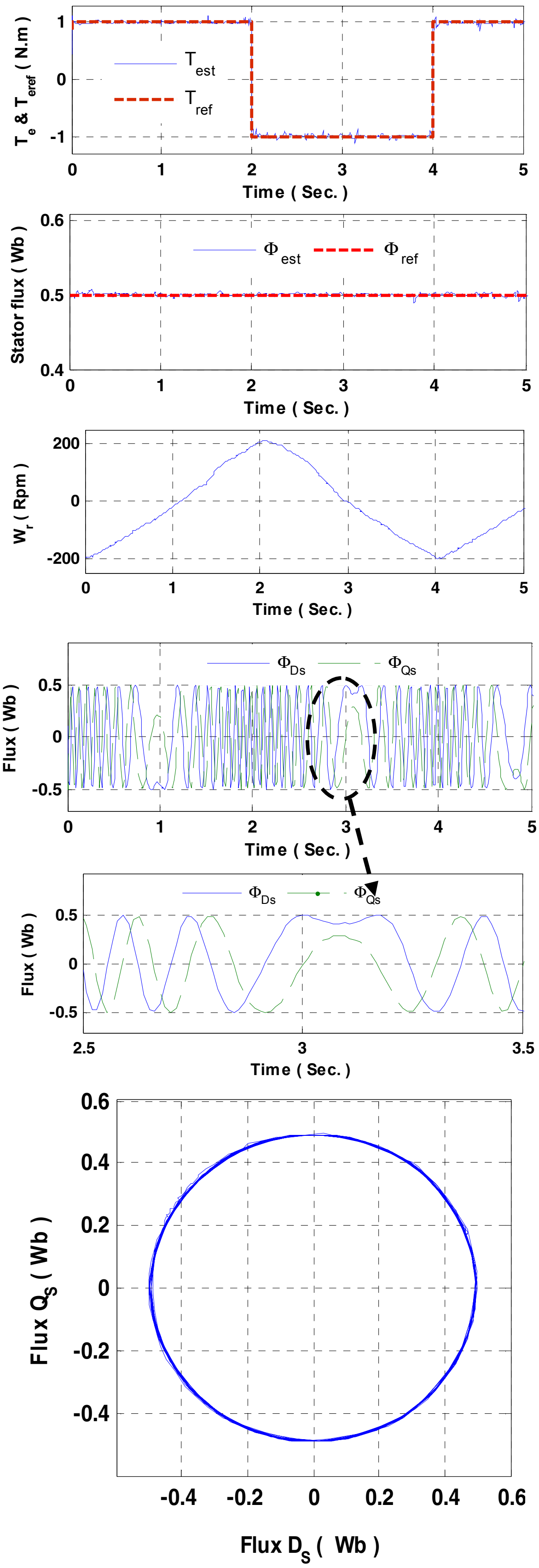


Fig. 7: Chattering Free Responses of SynRM Drive System under Proposed VS-DTC, when Torque Reverses.

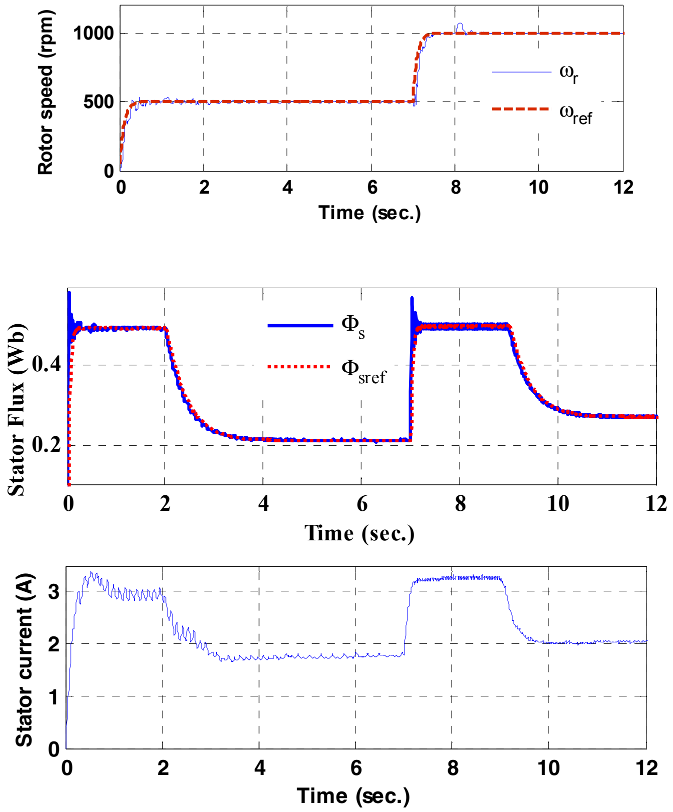


Fig. 8: Experimental results of drive performance under ALMC. a) Speed response, b) Reference and estimated stator fluxes, c) Motor input power.

Appendix

Specifications and Parameters of three-phase SynRM

$P_n = 370W$	$V_n = 230$	$I_n = 2.8\,A$
$L_{mdunSat}$=$232mH$	$L_{md,Sat} = 178mH$	$L_{mqn} = 118mH$
$R_{sn} = 2.95\Omega$	$f_n = 60$ Hz	$No.\ of\ Poles = 4$
$T_{en} = 1.9\,N.m$	$J_m = .015\,\text{Kg.m}^2$	$B_m = .003$ Nm/rad/sec
$\lambda_{s,Rated} = .5Web$	$L_{dr} = 10mH$	$L_{qr} = 8mH$
$L_{ls} = 8mH$	$R_{dr} = 2\Omega$	$R_{qr} = 2\Omega$

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