Implementation of Emotional Controller (BELBIC) for Synchronous Reluctance Motor Drive

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***Abstract*--This paper describes an emotional controller for synchronous reluctance motor (SynRM) drive. 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. The proposed controller is successfully implemented in real-time through a PC-based three-phase, 0.5 Hp SynRM. In this work, the d-axis torque current and speed reference signals are accurately tracked. The performance of the proposed controller is compared with an optimized conventional PI controller in different operating conditions. The obtained results show superior proposed control characteristics, especially very fast response, simple implementation and robustness with respect to disturbances and parameter variations. This emotional intelligent controller consists of model-free simple structure with high auto learning feature, and therefore shows excellent promise for industrial scale utilization.**

***Index Terms*-- medial brain, emotional intelligent controller, model-free, synchronous reluctance motor, speed tracking control.**

I. INTRODUCTION

In recent years, the synchronous reluctance motor (SynRM) received much attention for many applications due to its simple and rugged construction [1-2].

The advent of vector control technique has made it possible to obtain an ac electrical drive quick torque responses, as in a dc motor [3-4]. The vector control algorithm of SynRM motor has been modified to achieve optimum operation at maximum torque, maximum torque per stator current, high efficiency, d-axis current constant and power factor [2]. These schemes been performed with conventional controller, in some papers [2, 4]; consequently, the system robustness is low [5-6]. So it is necessary to use modern controllers that act independently of the parameter variations. Variable structure control (VSC) is one of the robust control methods applicable to electromechanical systems [7]. The uncertainties, parameter variations and/or disturbances can be rejected for the variable structure control 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 [8].

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 [8], [9], also without any previous learning can't do the control process [9], and some of them are based on rule [10].

In reference [10], it has been claimed the fuzzy-neural network hybrid requires less control effort in compared to sliding mode.

Similar to AI techniques, other well-known nonlinear control strategies such as adaptive input-output feedback linearization [11] and adaptive backstepping methods [12] 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 [13, 14]. 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. [15], and during the past few years this controller has been used, with minimal modifications, in control devices for several industrial applications [16]. In reference [17], 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. [18]. The results show superior control characteristics, especially very fast response, simple implementation and robustness with respect to disturbances and parameter variations. In [19], 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 [16, 20, 21]. 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 new type of artificial intelligent controller based on medial brain model and emotional processes [16]. The control is achieved by quick auto learning, and proper tracking of reference adaptively, and quite independent of system parameters, which results performance improvement.

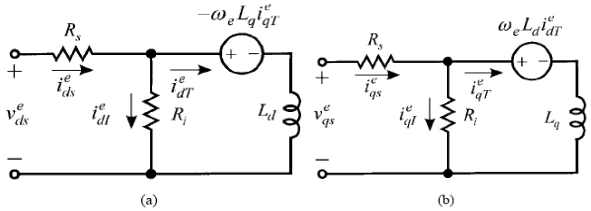


Fig. 1: The equivalent two-axis circuits of SynRM taking into account iron losses in dq rotor reference frame, a) d-axis circuit, b) q-axis circuit

The paper is organized as follows; at first, the SynRM drive model in the rotor d-q reference frame is presented in section II. Then in section III the structure of the novel intelligent controller based on medial brain and its emotional learning is explained. The block diagram of the control system is described in section IV. Hardware implementation is described in V section and the simulation and experimental results are presented and discussed in section VI. Finally, the conclusion is represented in section VII.

II. SYNRM MODEL

The equivalent two-axis circuits of SynRM taking into account iron losses in dq rotor reference frame is shown in Fig. 1. The mathematical model of a SynRM including iron loss can be described by the following equations in the rotor d-q reference frame as [22]. Where V_{ds} and V_{qs} are stator voltages, i_{dT} and i_{qT} are torque-producing current components, L_d and L_q are stator inductances, which are all in *d*- and *q*-axis rotor reference frame. R_s and R_i are stator and iron losses resistances respectively, ω_{er} is the rotor electrical angular velocity. The motor-generated torque is also given by

$$\frac{3}{2}\frac{P}{2}.(L_d - L_q).i^e_{dT}.i^e_{qT} = K_T i^e_{dT}\, i^e_{qT} \qquad (1)$$

Regarding above equation, the motor torque can be controlled by i_{qT} , when d-axis current i_{dT} is assumed constant.

III. 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. 2 (a) shows the pertinent pictures of the human brain, and Fig. 2 (b) provides a graphical depiction of the modified sensory signal and learning network connection model inside the brain [32]. 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. 2 (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 [16].

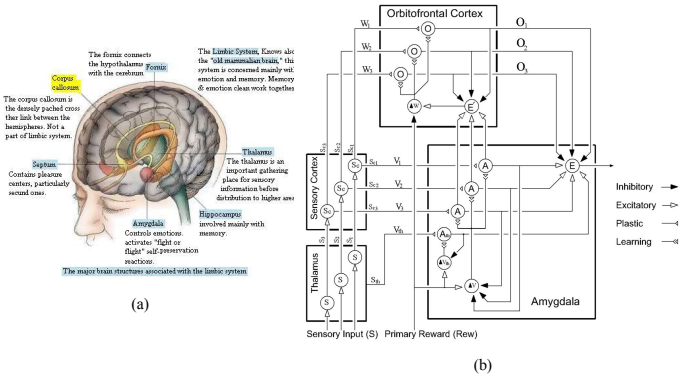


Fig. 2. a) Sectional view of the human brain for emotion processing.b) Graphical depiction of the developed computational model of brain emotional learning process (BELBIC).

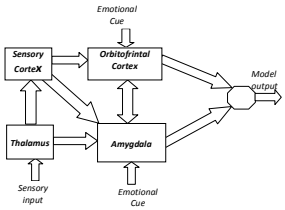


Fig. 3. The abstract structure of the computational model mimicking some parts of mammalian brain,

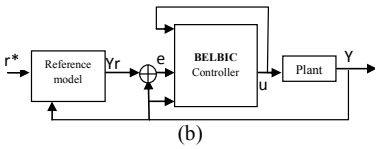


Fig. 4. Control system configuration using BELBIC.

In Fig. 2 (b), there are some nods in different part of the model, that each of them is model by same mathematical equations.

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:

$$E = \sum_j A_j + A_{th} - \sum_j O_j \qquad (2)$$

The internal areas output are computed pursuant to (3)-(4).

$$A_{th} = V_{th} \cdot \{\max(S_j) = S_{th}\} \qquad (3)$$

$$A_j = S_j V_j \quad \& \quad O_j = S_j W_j \qquad (4)$$

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 jth input. Variations of V_j and W_j can be calculated as:

$$\Delta V_i = \alpha \left(\max \left(0, Sc_i (R - \sum_i A_i) \right) \right) \qquad (5)$$

$$\Delta V_{th} = \alpha_{th} \left(\max \left(0, S_{th} (R - A_{th}) \right) \right) \qquad (6)$$

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

$$E' = \sum_j A_j - \sum_j O_j \qquad (7)$$

$$\Delta W_i = \beta \left(Sc_i \left(E' - R \right) \right) \qquad (8)$$

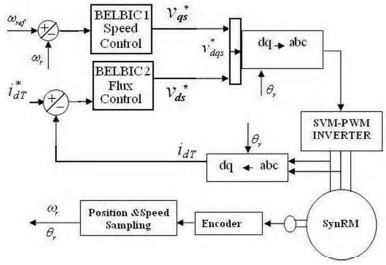


Fig. 5. Block diagram of control structure of SynRM drive using BELBIC

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 (5, 6) 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:

$$R = f(J, e, y, u) \;\&\; S = g(y, u, e) \tag{9}$$

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 [16].

IV. SynRM Drive Control System Design

The block diagram of the new control system incorporating the emotional controller (BELBIC) is shown in Fig. 6. The emotional control system receives the error signals between the command speed and torque-producing current d-axis component i_{dT} with the actual components in mold of equation (9). It then generates the output signals following equations (2)-(8). As shown from Fig. 5, two emotional intelligent controllers (BELBIC) are used; the first (BELBIC1) receives motor speed error as input and then generates v_{qs}^* as output, and the second (BELBIC2) uses d-axis torque component current error as input and generates v_{ds}^* as output directly.

All of them are in the rotor reference frame and then are transferred to stationary-reference frame. In order to generate the logic signals to control the inverter switches, the space vector pulse width modulation (SV-PWM) technique is used.

According to the above mentioned control procedure, it is evident that proper control is achieved without any requirement to other conventional controllers (PI, PID controllers, etc.) in generating command voltages, and quite independent of motor parameters. Unlike conventional PI controllers, the proposed emotional control technique is auto learning, model-free and the controller coefficients are adaptive, which facilitates vector control of the synchronous reluctance motor drive to be controlled independent of parameter variations.

V. Real-Time Experimentation

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

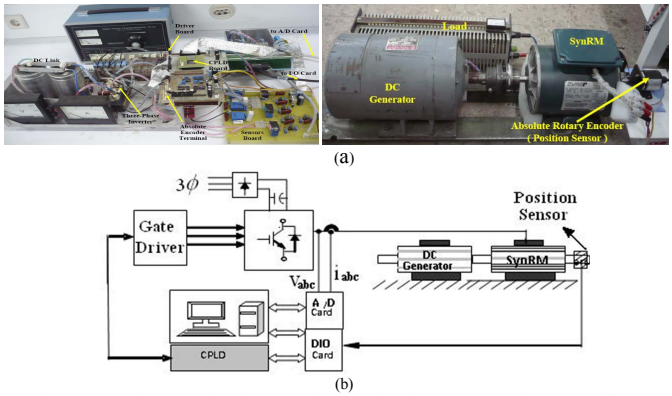


Fig.6. Hardware implementation of the proposed controller, a) experimental setup, b) Literary implementation block diagram,

tested. The experimental setup is shown in Fig. 6 and consists of the following sections: A 0.37-kW three-phase SynRM and a 1.1-kW dc generator as its load, a three-phase voltage source [11].

VI. Results and Discussion

In order to evaluate this emotional controller and hence, to assess the effectiveness and control capability of the proposed BELBIC scheme, the performance of the SynRM drive based on the proposed control scheme is investigated in simulation and experimental tests scrutiny at different operating conditions (the SynRM characteristics have been given in appendix) . And also for more evaluation and to make a fair judgment, the same tests have been performed to use the optimal conventional controller PI (OCC) and compared to the purposed controller BELBIC. The controller PI was optimized by using the known optimization algorithm GA [23].

Digital computer simulations have been performed via Matlab/Simulink [24]. The simulated responses in Figs.7-10 evaluate the tracking of the system according to the flowing tests:

Test1: Reference speed ω_r^* and current i_{dT}^* commands, given in TABLE I, under no-load condition

TABLE I
Reference Commands for Test 1

Time, [S]	0	3	3	10
ω_r^* [rpm]	500	500	1000	1000

Time, [S]	0	7	7	10
i_{ds}^* [A]	1	1	1.5	1.5

Simulation results of the test1 using BELBIC are shown in Fig.7. It can be seen that the proposed controller gives regulated responses in terms of fast tracking, small overshoot and zero steady-state errors. Fig. 7(a) shows actual speed that converges to the step +500 at t=.2s and then converges to the step +1000 at 3.02 s without any considerable overshoot and while steady state error is equal to zero. Also, i_{dT} value shown in Fig. 7(b) converges to its reference properly and tracks step change in the command. One can see that, suddenly changes in both speed and i_{dT} simultaneously, don't have any indelible effect on the together. The response in Fig. 7(c, d) is within the permissible value.

In Fig.8 show the results obtained by OCC-PI, that can be seen, there is a little error and near to zero in steady state in

the first step of command speed (+500), and also the system was a soft starting Fig.8 (a, b). It should be noted that; the optimization of PI has been done under this condition (+500 rpm & $i_{dT}^{*} = 1\,A$). But there is a significantly error in motor speed in the second step of the speed command, as the system couldn't properly track its reference. This is because of changing in operating-point, so the coefficients of controllers aren't optimal for that. But i_{dT} value tracks the command adequately. Test1 was performed for suddenly changes in speed and torque-producing current component under no load.

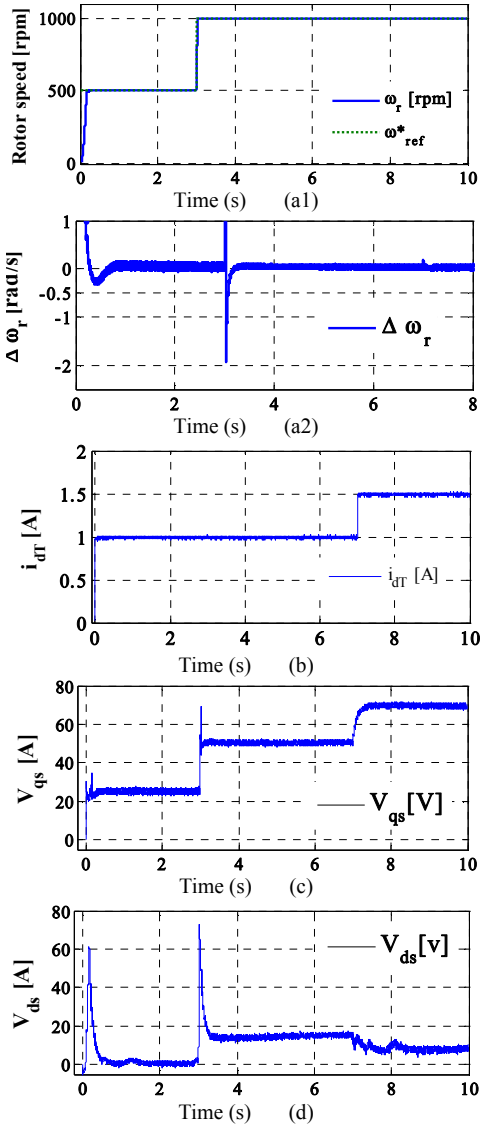


Fig.7. Simulation results using BELBIC, speed and i_{dT} control of SynRM, Test1: a) Motor Speed and speed error, b) current d-axis component i_{dT} , c) stator voltage q-axis component V_{ds} ,d) stator voltage d-axis component V_{ds} .

Test2: Test: Reference speed and current i_{dT}^{*} commands, given in TABLE II, under loading condition

TABLE II
REFERENCE COMMANDS for TEST 2

Time [S]	0	5	9
ω_r^{*} [rpm]	1000	1000	1000

Time [S]	0	5	9
i_{ds}^{*} [A]	1	1	1

Time [S]	0	3	3.2	6	6.2	9
T_L [Nm]	0.5	0.5	1	1	0.5	0.5

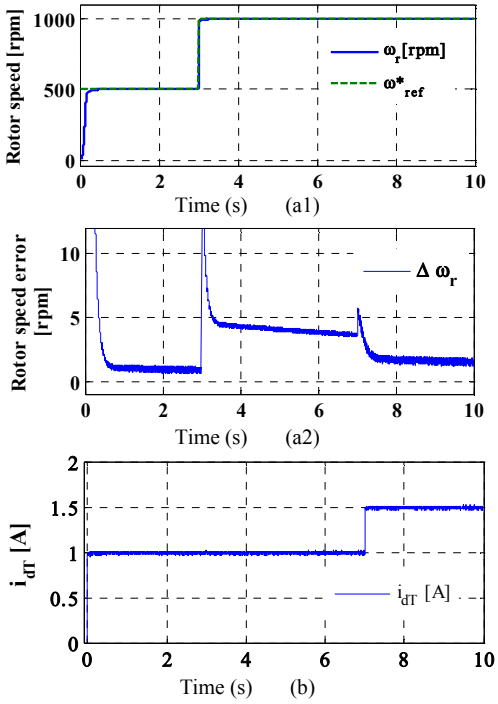
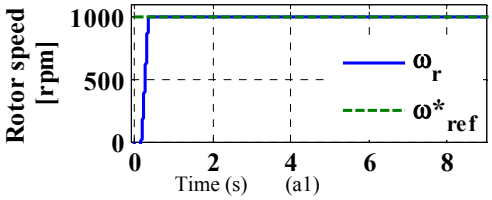


Fig.8. Simulation results using OCC-PI peed and i_{dT} control of SynRM, Test1: a) Motor Speed and speed error, b) current d-axis component i_{dT}

Fig. 9 shows the operating responses of the drive system using emotional controller BELBIC in test2. It can be seen that the proposed controller gives tuned response in terms of fast tracking, without any overshoot and zero steady-state errors notwithstanding it was under loading with suddenly changes in load torque, motor speed has a short undershoot which return to the reference quickly.

In compared with Fig. 10 which presents results of using the OCC-PI, there isn't a proper tracking and responding to the operate-point changes. Also, in Fig. 10(b) it is shown that i_{dT} converges to its reference properly. But Fig. 8 (a) shows actual speed has a stead-stead error and also a significantly undershoot under loading condition.



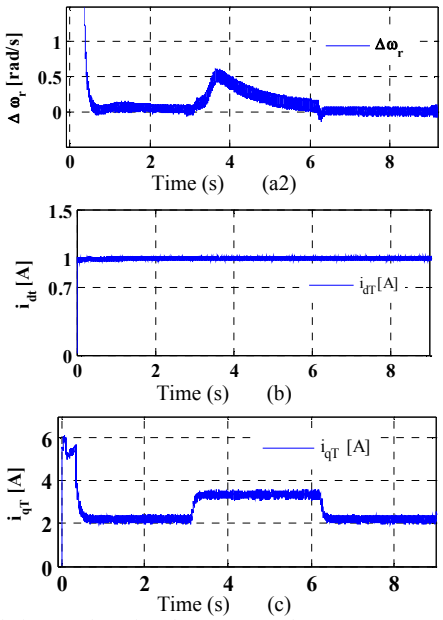


Fig. 9. Simulation results using the BELBIC, the SynRM control speed under loading, Test2: a) Speed and speed error, b) i_{dT} , c) i_{qT} .

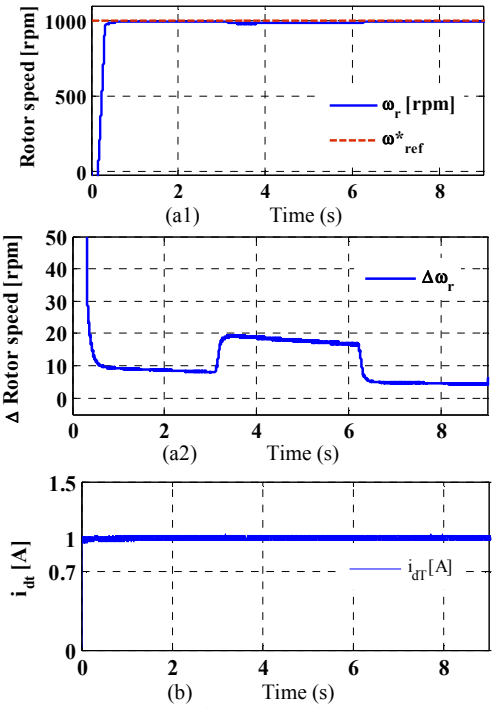
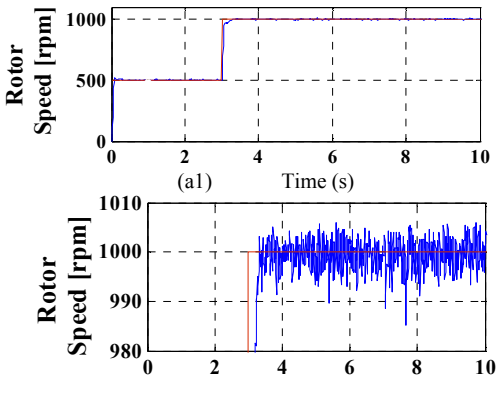


Fig 10. Simulation results using the OCC-PI, the SynRM control speed under full loading, Test2: a) Speed and speed error, b) i_{dT} .



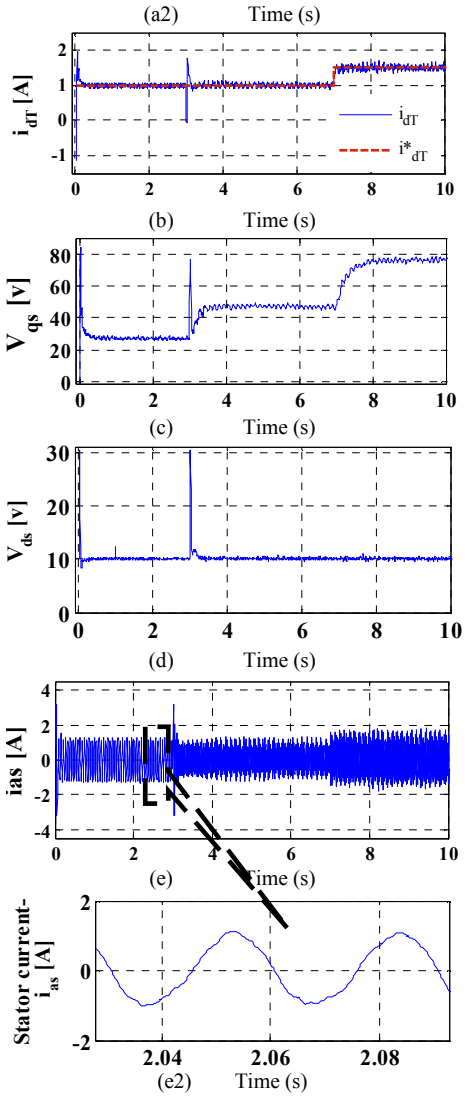
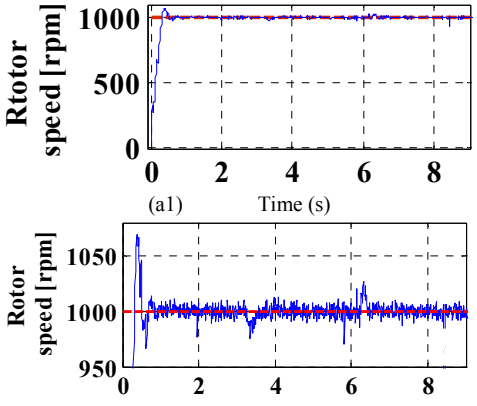


Fig. 11. Experimental result, the SynRM speed and flux-producing current component, simultaneously, using BELBIC, Test1: : a) Motor Speed, b) i_{dT} , c) stator voltage q-axis component V_{qs} ,d) stator voltage d-axis component V_{ds} , e) Steady-state stator phase-A current

Experimental cases:

Experimental results for the same tests can be seen in Fig. 11 and Fig. 12 for tests 1 and 2, respectively. As shown in these figures, the obtained results are equal and very similar to achieved simulation ones in Fig. 7 and Fig. 9 respectively. Comparing the simulation and experimental tests, be saw that the intelligent control based on emotional learning can achieve our requirements for the SynRM derive control properly.



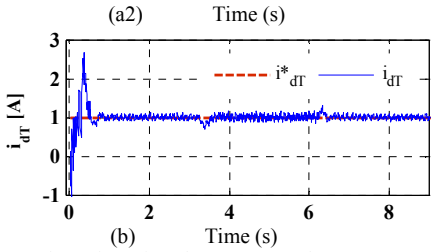


Fig. 12. Experimental results using the BELBIC, the SynRM control speed under loading, Test2: a) Motor Speed and error speed, b) stator current d-axis component i_{ds} .

TABLE III

Specifications and Parameters of three-phase SynRM for Simulations and Experiments

$P_n = 370W$	$V_n = 230$	$I_n = 2.8A$
$L_{md,unSat} = 232mH$	$L_{md,Sat} = 178mH$	$L_{mq} = 118mH$
$R_s = 2.95\Omega$	$f_n = 60$ Hz	$No.\ of\ Poles = 4$
$L_{ls} = 10mH$	$J_m = .015$ Kg.m^2	$B_m = .003$ Nm/rad/sec

VII. CONCLUSION

This paper presents a real-time implementation of an emotional controller for a 3-phase SynRM drive. The implementation of emotional controller shows excellent control performance and good robustness and adaptability. There exists close agreements between the experimental and simulation results. Also in the proposed control method the conventional PI and PID controllers, which are conventionally used in the vector control of SynRM drive, are eliminated. A simple structure of brain emotional learning based intelligent controller with its fast auto learning, model-free and good tracking features is used. In compared with OCC-PI, the proposed emotional intelligent technique is robustness with respect to disturbances and parameter variations. The proposed controller can be easily adapted for large scale industrial applications.

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