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Emotional Controller based Torque Ripple Reduction of Switched Reluctance Motor (SRM)

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Abstract

This paper presents a modern control system for switched reluctance motor (SRM) drives. The control system is based on computational model of mammalian limbic system and emotional processes (BELBIC) which is presented as speed controller of the motor drive with attention to torque ripple decrease. In this work, a novel and simple model of SRM drives control plant is achieved by using the intelligent control system, which controls motor speed accurately and directly, without needing to use any conventional controllers and also, quite independent of the motor parameters. Then, proposed method is compared with a conventional PI controller and sliding mode as a nonlinear approach, which shows its advantages than both of them. The performance of the proposed controller is demonstrated by simulation and experimental results using a 4kW, four-phase, 8/6 pole SRM DSP-based drive system. This generation of the intelligent controllers that has high auto learning speed with simple structure shows excellent praxis for industrial scale utilization truly.

Reviewed by* **ICETSET'16 *organizing committee*

I. INTRODUCTION

In recent years, there is a growing concern about the use of switched reluctance motor.Switched reluctance (SR) motors have advantages due to their low cost, simple rugged structure, and relatively high torque-volume ratio and low maintenance cost. They are ideally suited for direct-drive application because of their ability to generate high torques at very low speed in comparison with other conventional motors [1], [2]. In addition SRM drives can work in a wide range of speed without a considerable reduction of efficiency. Therefore, among all different kinds of electrical motors, Switched Reluctance Motor drives (SRM) have attracted much attention in these years [3]. SRM drives are designed to operation in deep saturation to intensification the output power density. Due to saturation effect and variation of magnetic reluctance, characteristics of the machine model are highly nonlinear function of both rotor position and phase current [2], [3]. Also this is because a combination of the non-linear coupling between phase current, reluctance variation, and overlap angle and machine design. Therefore, despite the simple mechanical structure, they need complex algorithms for control and commutations. As well as high torque ripple and acoustic noise are the most disadvantages of the drives [4], [5].

However their high level of torque ripple (and hence acoustic noise), and speed fluctuation especially in low speed regions have limited the possibility of their direct-drive applications in industry. There are two methods to improve the performances of SRM drive systems. Firstly, designing structure of the SRM [7] and secondly, the control techniques are presented to improve the performance in dynamic response and torque ripple minimization [3], [4], [8].

SRM drives due to above-said problems have a complex control structure and modeling so that solving the problems are difficult with Conventional PI controllers [2], [6], [10].

Several control methods and schemes have been proposed to overcome these problems. For example, variable structure controller made the SRM drive system insensitive to parameter variations and load disturbance [11].

Model-based approaches to decision making are being replaced by data-driven and rule-based approaches in recent years [9]. Nowadays with developing control science, using intelligent control approaches could be resulted very of control problems [3], [8].

Also recently, intelligent methods were used to solve the In which $V j$ stands for $thi\ th$ phase winding voltage, problems, as artificial intelligent (AI). According to [9], there $i j$ for j phase current, λj for linking flux, R for the are many other feedforward and recurrent network topologies which require systematic exploration for their applications.

In [12] and [13], the comparison between fuzzy-neural network and sliding mode control methods was presented. It was proved that both methods ensure good characteristics, yet the fuzzy-neural network requires less control effort.Similar to AI techniques, other well-known nonlinear control strategies such as adaptive input-output feedback linearization [14], adaptive sliding mode [15] and adaptive backstepping methods [16] are complex to implement and are ohmic resistance of phase winding and λl stands for leaky linking flux. And in (3), $L\ inc$ increasing inductance and C is the back emf coefficient and both of them are dependent on current and rotor angular situation. Also, L_k) is the flux leakage.

The produced torque on the shaft gives the following equation:

$$T(i,\theta) = \sum_{j=1}^{3} \left(\frac{\partial W'}{\partial \theta}\right)_{i=\text{const}} \quad (4)$$

In which co-energy is defined as follows:

$$W'(i_j, \theta) = \int_0^{i} \lambda_j(i_j, \theta)\, di \quad (5)$$

Finally, mechanical equivalent is given as:

$$\omega = \frac{d\theta}{dt} \quad (6)$$

$$\frac{d\omega}{dt} = \frac{1}{J} \cdot \left(T(i,\theta) - T_L - B \cdot \omega\right) \quad (7)$$

Where, T_e , T_l , B and J are electrical and load torque, friction coefficient and inertia moment, individually. However, finding a lumped function for $T(i, \square)$ is very difficult and demands numerical or experimental data for a specific motor [1], [2], [6]. In this paper the aforementioned data has been obtained using Finite Element Method (FEM). For mathematical model of SRM is used (1-7) that for finding a lumped nonlinear function of torque is obtained by using demands numerical according to (4, 5).

I. 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 control, for control of engineering applications in general and SRMs motors in particular. We have adopted a network model already developed as a computational model that mimics amygdala, orbitofrontal cortex, thalamus, sensory input cortex and generally, those parts of the brain are thought to be responsible for processing emotions [22]. In Fig. 1(a), a biological schema of the limbic was shown. Two input signals exist in BELBIC: the first one is a sensory input and the second one is emotional cues (Reward signal) which are given by:

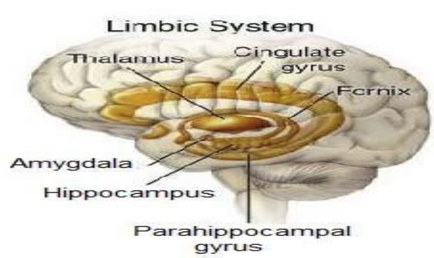


Fig. 1. a) Sectional view of the human brain for emotion processing

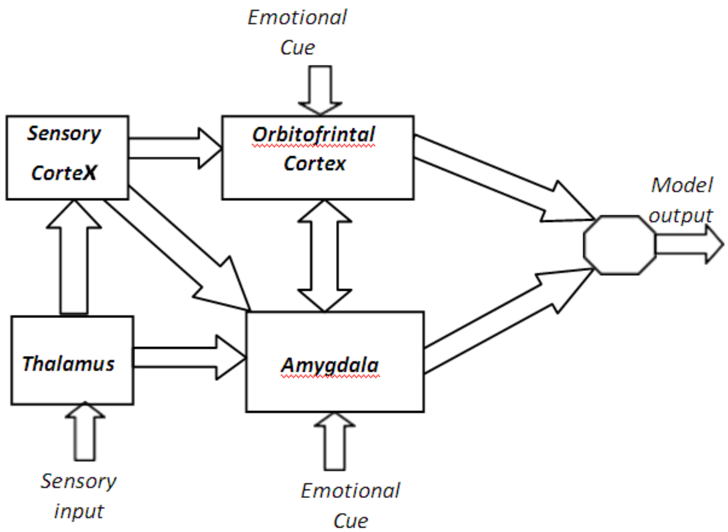


Fig. 2. Structure of the computational model mimicking some parts of mammalian brain.

$$S = k_1 e + k_2 \frac{d}{dt} e + k_3 \int e.dt \tag{8}$$

$$R = K_1 \left| e \right| + K_2 \left| \int e.dt \right| \quad K_3 \left| E \right| \tag{9}$$

where, e and E are a system error and a controller output respectively. Also, k_1 - k_3 and K_1 - K_3 are gains, that must be tuned for designing a satisfactory controller. The purpose of BELBIC is a reduction of the sensory input (8) with attention to the reward signal (7). The reward signal specifies quality and satisfactory surface of control process. A simple block diagram of the parts of controller is depicted in Fig. 2. Selecting those signals (S and R) is according to user's wants. This work enjoys using a developed version of the emotional controller [19, 21].

A networked structure of the computational model was indicated in Fig. 3, where is one node "A" (the values of amygdale output) for every stimulus *S*, including one for the thalamic stimulus. There is also one "*O*" (the values of orbitofrontal cortex output) node for each of the stimuli, except for the thalamic node. There is one output node "*E*" that is common for all the outputs of the model. The node "E" simply sums the outputs from the "*A*" nodes and then subtracts the inhibitory outputs from the "*O*" nodes. The result is the output from the model. In other words, *E* can be obtained from:

$$E = \sum_j A_j + A_{th} - \sum_j O_j \qquad (10)$$

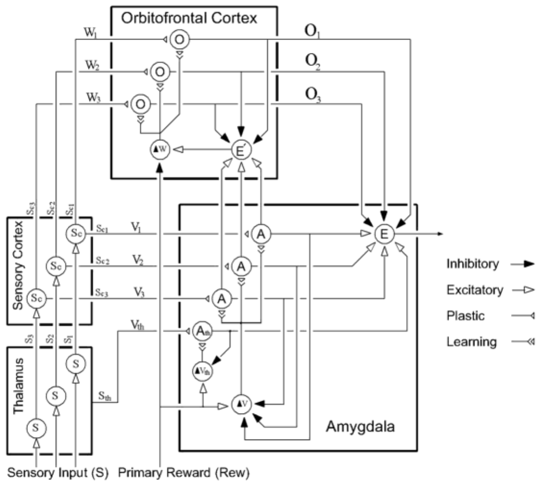


Fig. 3. Graphical depiction of the developed computational model of brain emotional learning process (BELBIC).

The internal areas output are computed based on (10)-(13).

$$A_{th} = V_{th} \cdot \{\max(S_j) = S_{th}\} \qquad (11)$$

$$A_j = S_j V_j \qquad (12)$$

$$O_j = S_j W_j \qquad (13)$$

$$Sc_j = S_j \otimes \left[e^{-k \cdot t}\right] \qquad (14)$$

Where A_j and O_j are the values of amygdale and orbitofrontal cortex outputs at each time, V_j is the gain in amygdala connection, W_j is the gain in orbitofrontal connection, S_j and $^{S}C_j$ are sensory input and sensory- cortex output respectivelyoutput respectively and j is input jth. Variations of V_j and W_j can be calculated as:

$$\otimes V_i = \alpha \left(\max \left(0, Sc_i \left(R - \sum_i A_i \right) \right) \right) \quad (14)$$

$$\otimes V_{th} = \alpha_{th} \left(\max \left(0, S_{th} \left(R - A_{th} \right) \right) \right) \quad (15)$$

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

$$E' = \sum_i A_j - \sum_i O_j \quad (16)$$

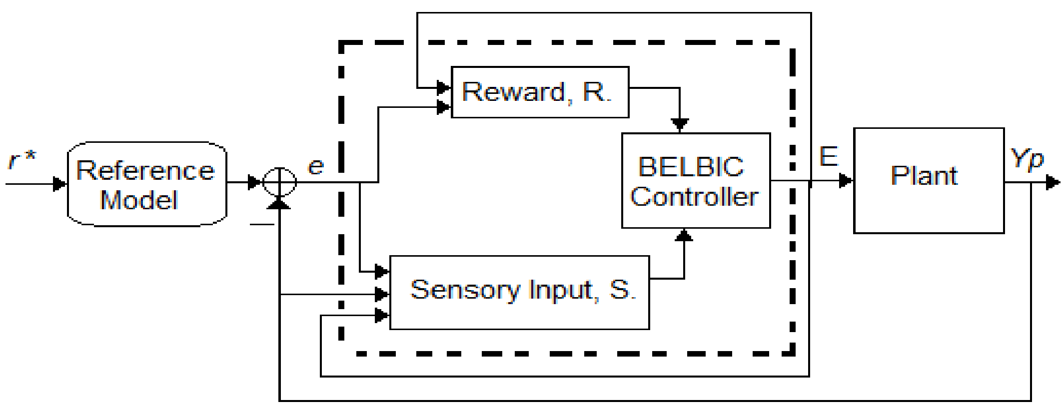


Fig. 4. Control system configuration using BELBIC

$$\otimes W_i = \beta \left(Sc_i \left(E' - R \right) \right) \quad (17)$$

where(□, □$_{th}$) and □ are the learning steps in amygdale and orbitofrontal cortex, respectively. R is the value of emotional cue function at each time. From (11-12) and (14-15), obviously conclude A_j values cannot be decreased by learning process in Amygdala, it means that forgetting information doesn't occur in amygdala. In biological environment, whereas "forgetting" or idiomatically, inhibiting is duty of orbitofrontal cortex [17]. It means that W_j (as orbitofrontal weights) can be decreased or increased by the learning equation (17). Eventually, model output obtains from (13). A general scheme of using the controller was shown in Fig.4.This type of model-free intelligent controller with high auto learning speed and simple structure shows excellent capability for use in industrial applications scale utilization [18]-[21].

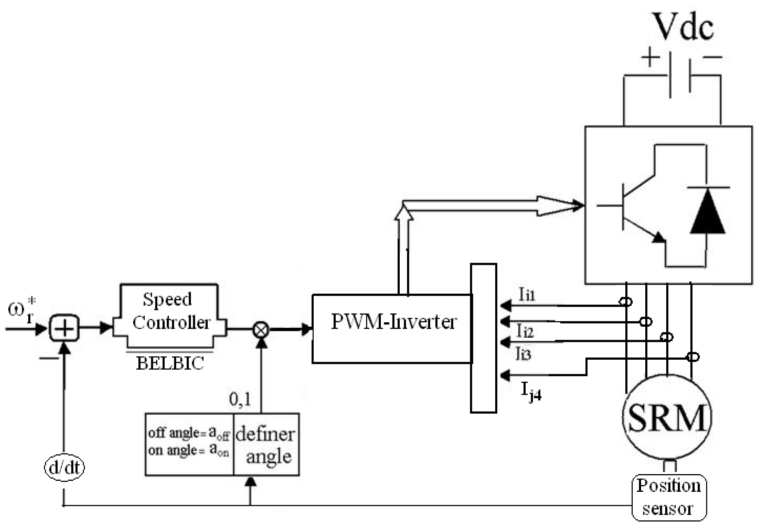


Fig. 5. Control system structure of SRM drive.

I. THE SRM DRIVE CONTROL SYSTEM DESIGN

The control method for the SRM is chosen based on the parameters, which include the usage, performance and speed range. Fig. 5 shows the block diagram of the new control system incorporating the emotional controller (BELBIC). The emotional control system receives the error signal between the command speed and the actual motor speed as part of inputs according to (8-9) and generates the output signal (10)

as command current i^*.

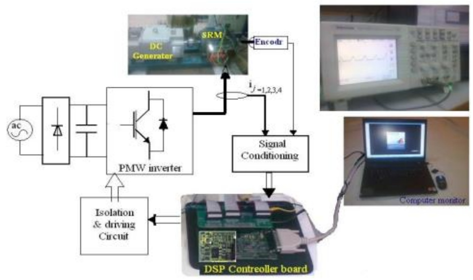


Fig.6. Hardware implementation of the proposed controller board With DSP-Based drive system

Also recognition of rotor angular position for exciting stator windings is done with an encoder. The reference current is compared to actual stator current, and then generated current error is entered to PWM inverter for generating gate pulses to fire the IGBT switches. Then according to pulse commands, stator winding is excited. Switches of each stator phase only were fired between on and off angles, which were recognized by a definer angel Fig.5. According to above-said control procedure, be saw that proposed control plant controls motor without any requirement to other conventional controllers (such as; PI controllers …) and quite independent of motor parameters. This is an important consequence in designing of power drives control plants Fig.5.

I. REAL-TIME EXPRIMENTATION

The work presented here employs a conventional digital- control platform. It is based on the eZdsp F2812 board as a suitable platform for implementing motor controllers. This board is built around the TMS320F2812 digital signal processor (DSP). This platform is compatible with SIMULINK and includes four dual pulse-width modulation (PWM)

channels (8 channels total), 4 analog-to digital converters (ADCs), and a speed-encoder input. The processor is a 32-bit DSP with fixed-point arithmetic; thus, discrete and fixed-point math blocks from Simulink can be used to program it. Also a generator DC was used as mechanical load, which was coupled to the SRM motor. The complete experimental hardware used for evaluating the 8/6 SRM drive is shown in Fig. 6.

I. 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 SRM drive based on the proposed control scheme is investigated in simulation & experimental tests scrutiny at different operating conditions. To make a fair judgment, the PID controller is tuned at rated conditions also because having a proper comparison, the SRM control is done by using a sliding mode control (SMC) as a non linear approach in a same condition then BELBIC [15].

Digital computer simulations have been performed using Matlab/Simulink [22]. The simulated responses in Fig.7-8 investigate the tracking of the system. In these cases the drive system is started and operated according to the flowing sequence in test1:

Test1: For speed command given by the flowing tables I:

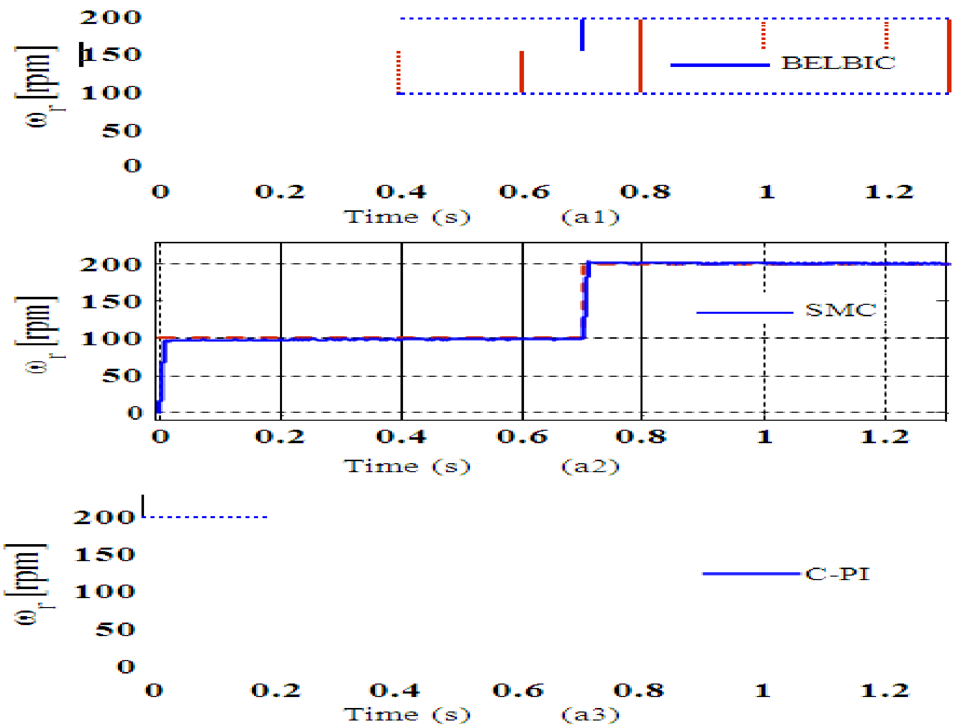
Time [sec]	0	0.7	0.7	1.3

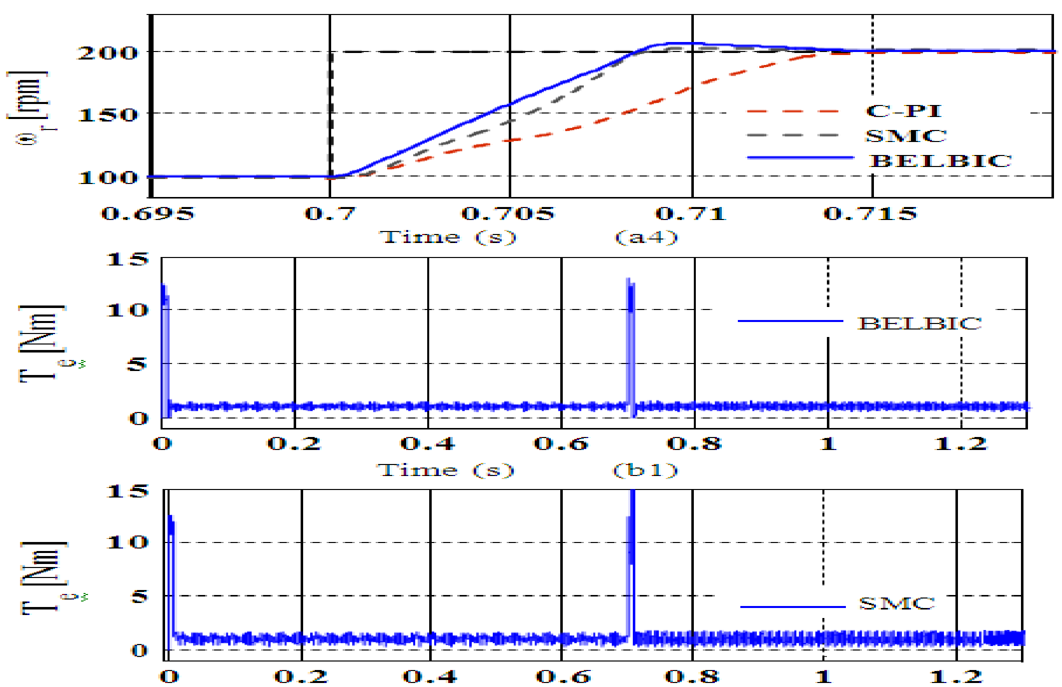
□*	100	10	20	20

Time	0	1.2
T_L [Nm]	1	1

Simulation results of the test1 using BELBIC, SMC and C-PI were shown in Fig.7 respectively. 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(a1, a4) shows actual speed that converges to the step +100 rpm at t=.1s and then converges to the step +200 rpm at 0.71 s without any considerable overshoot and while steady state error is equal to zero. Also, electromagnetic toque T_e value shown in Fig. 7(b1), seen torque ripple is acceptable in rated

limit (□ T□ 0 . 4).


BELBIC
Time (s) (a1)
SMC
Time (s) (a2)
C-PI
Time (s) (a3)


C-PI
SMC
BELBIC
Time (s) (a4)
BELBIC
Time (s) (b1)
SMC

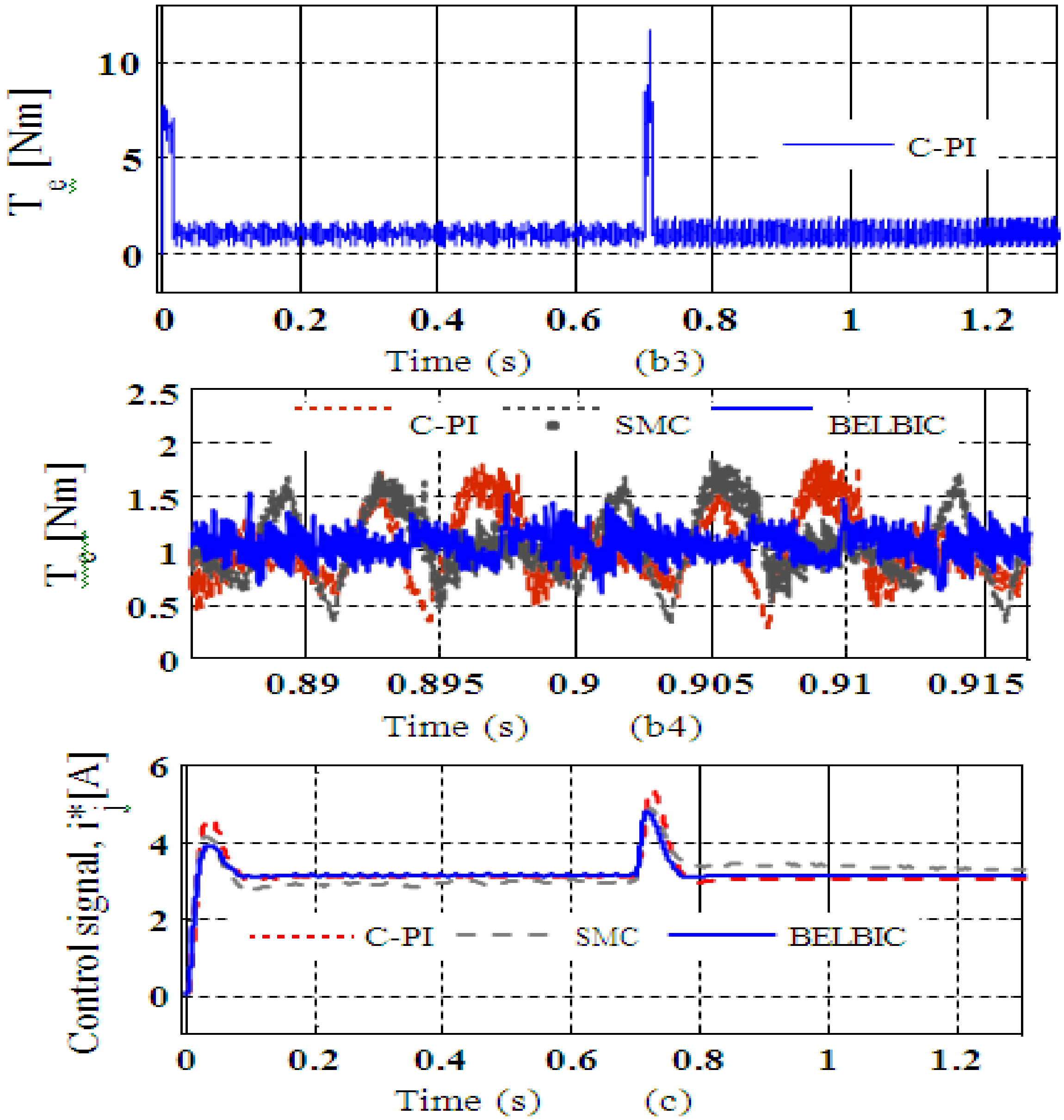
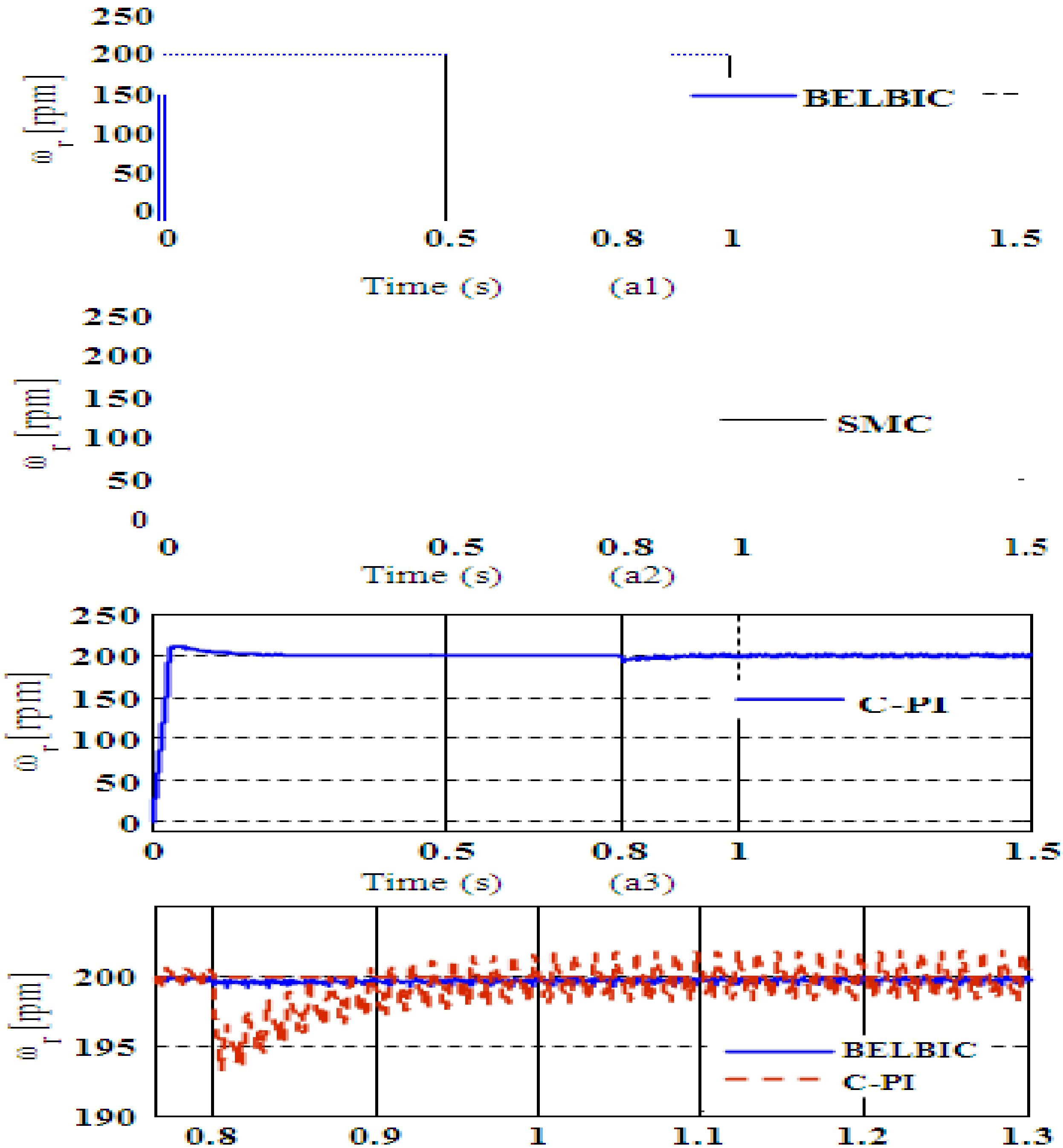


Fig. 7. Simulation results, the SRM control speed using BELBIC, C-PI & SMC, Test1: a) Rotor Speed, b) Electromagnetic torque, c) Control signa1 i_j .


250
200
150
100
50
0
ωr [rpm]
BELBIC
0
0.5
0.8
1
1.5
Time (s)
(a1)
250
200
150
100
50
0
ωr [rpm]
SMC
0
0.5
0.8
1
1.5
Time (s)
(a2)
250
200
150
100
50
0
ωr [rpm]
C-PI
0
0.5
0.8
1
1.5
Time (s)
(a3)
200
195
190
ωr [rpm]
BELBIC
C-PI
0.8
0.9
1
1.1
1.2
1.3

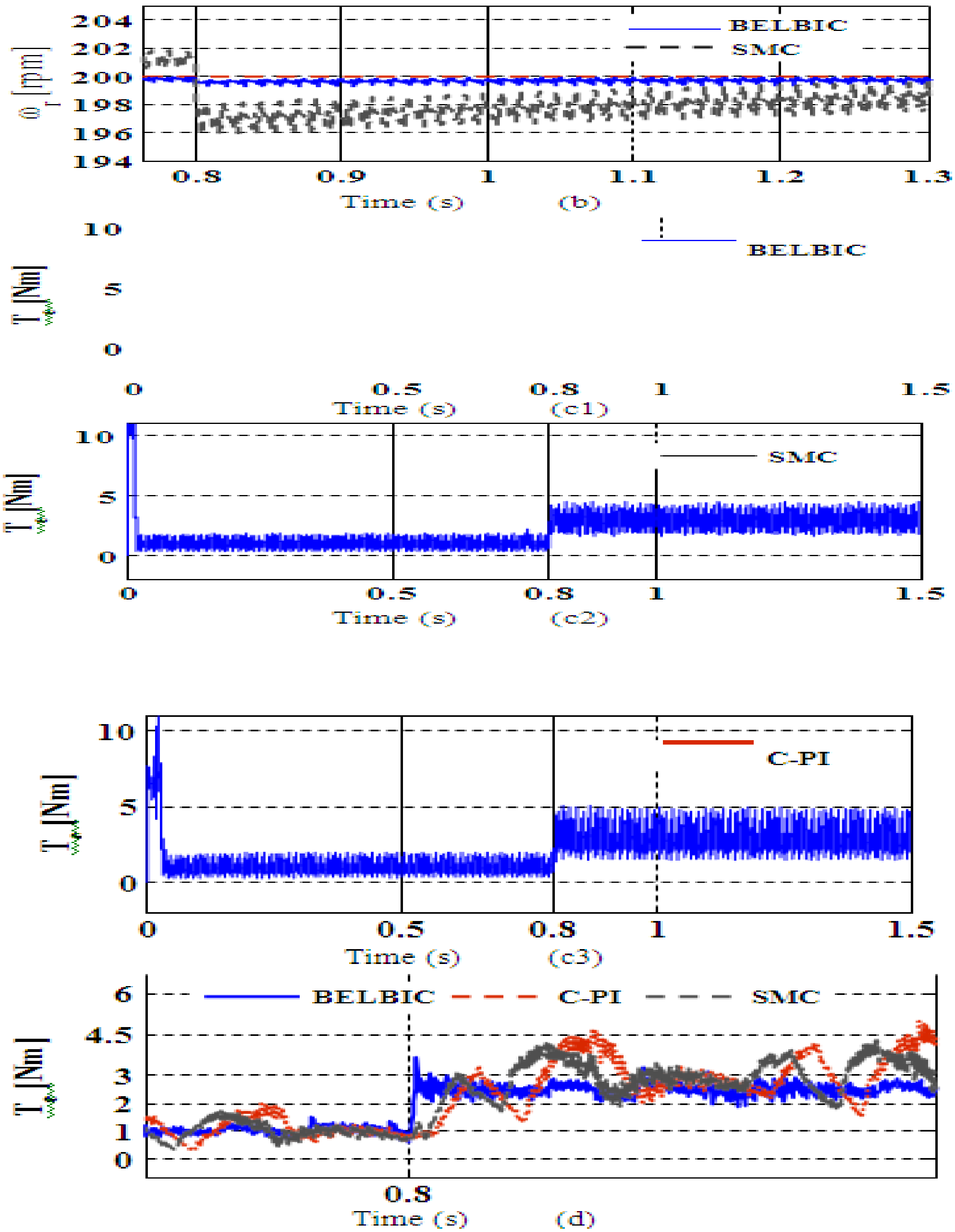


Fig. 8. Simulation results, the SRM control speed using BELBIC, C-PI & SMC,

Test II: a) Rotor Speed, b) Dynamic response of speed to step load, c) Electromagnetic torque, d) Dynamic response of torque to step load.

TABLE II. REFERENCE COMMANDS FOR TEST2

Time [sec]	0	1.3
□ * [rpm]	200	200

Time	0	0.8	0.8	1.2
T_L [Nm]	2	2	3	3

However, Fig. 7(a4) shows transient responses using BELBIC, SMC and C-PI in the same scale of them. According to the response, BELBIC has higher dynamic response than C-PI. In addition, SMC almost gives the same response than BELBIC. But using the proposed controller BELBIC, torque ripple is lower than other ones Fig.7 (b). Also control signals are seen in Fig. 7(c), which was filtered.

According to Fig. 8, the control system operated under test II. This test was done under step load and shows its effect on speed curve using BELBIC, C-PI and SMC respectively.

So that can be seen, the results using BELBIC are in terms of good tracking, no significantly overshoot and undershoot at start time and step load for speed curve. But using both of other ones at step load, there is undershoot in the position. However value of the undershoot using C-PI is more than SMC Fig.8 (b). Also Fig. 8(c, d) explain torque ripple using BELBIC, SMC & C-PI respectively. With attention to the results, BELBIC has controlled the drive SRM by small torque ripple in speed and torque, fast dynamic and converging to the command with zero steady-state error. Fig.8 (d) shows a high dynamic of torque response using BELBIC, which is faster than both of the other ones.

Experimental results for the same tests can be seen in Fig. 9 and Fig. 10 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. 8 respectively.

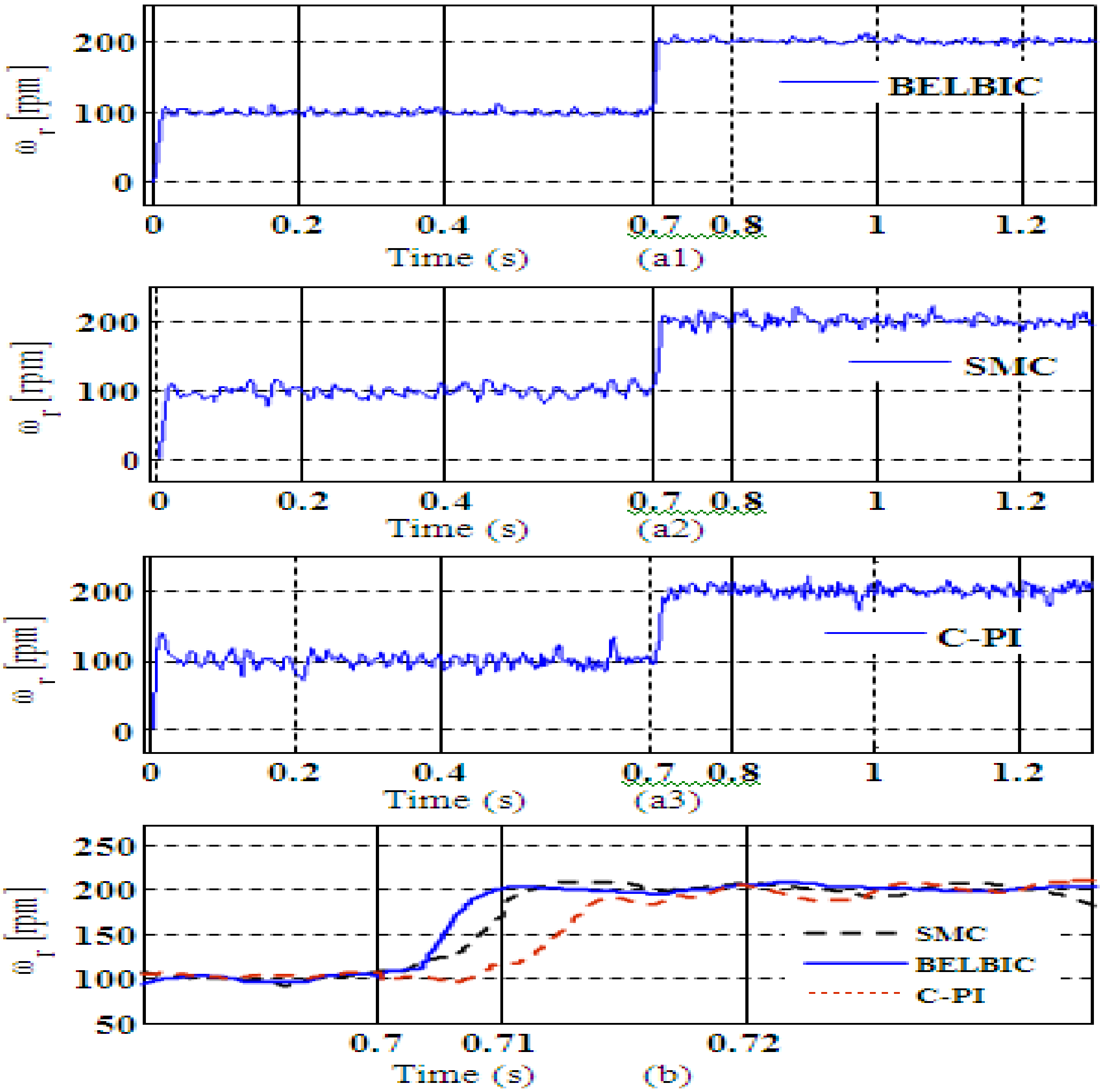
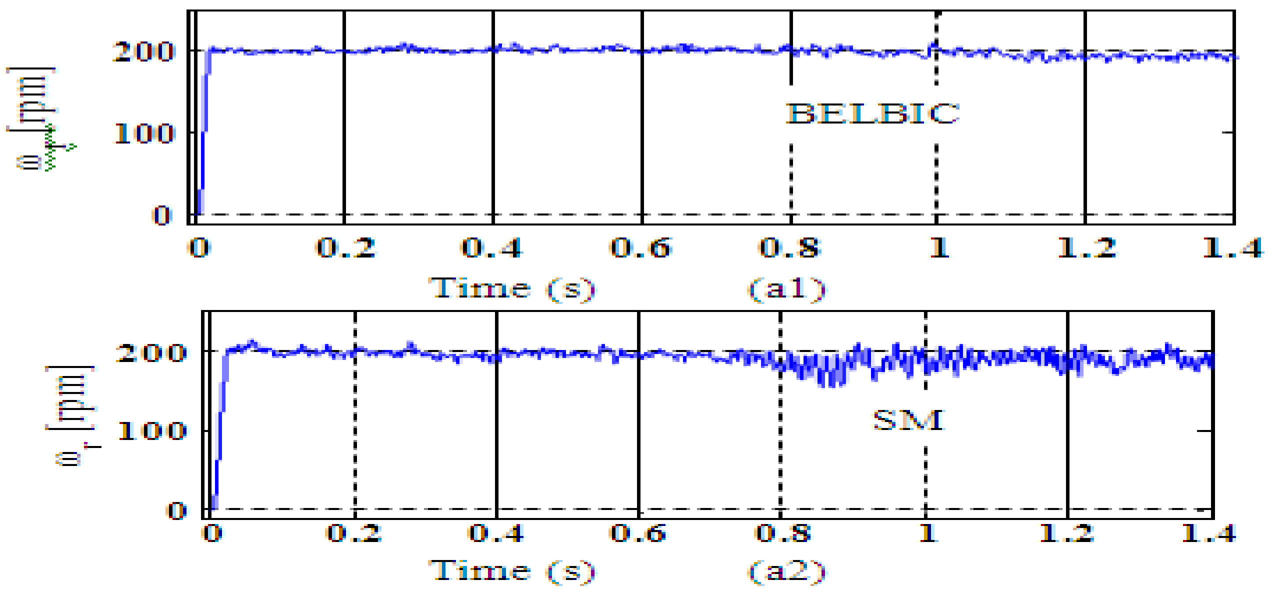
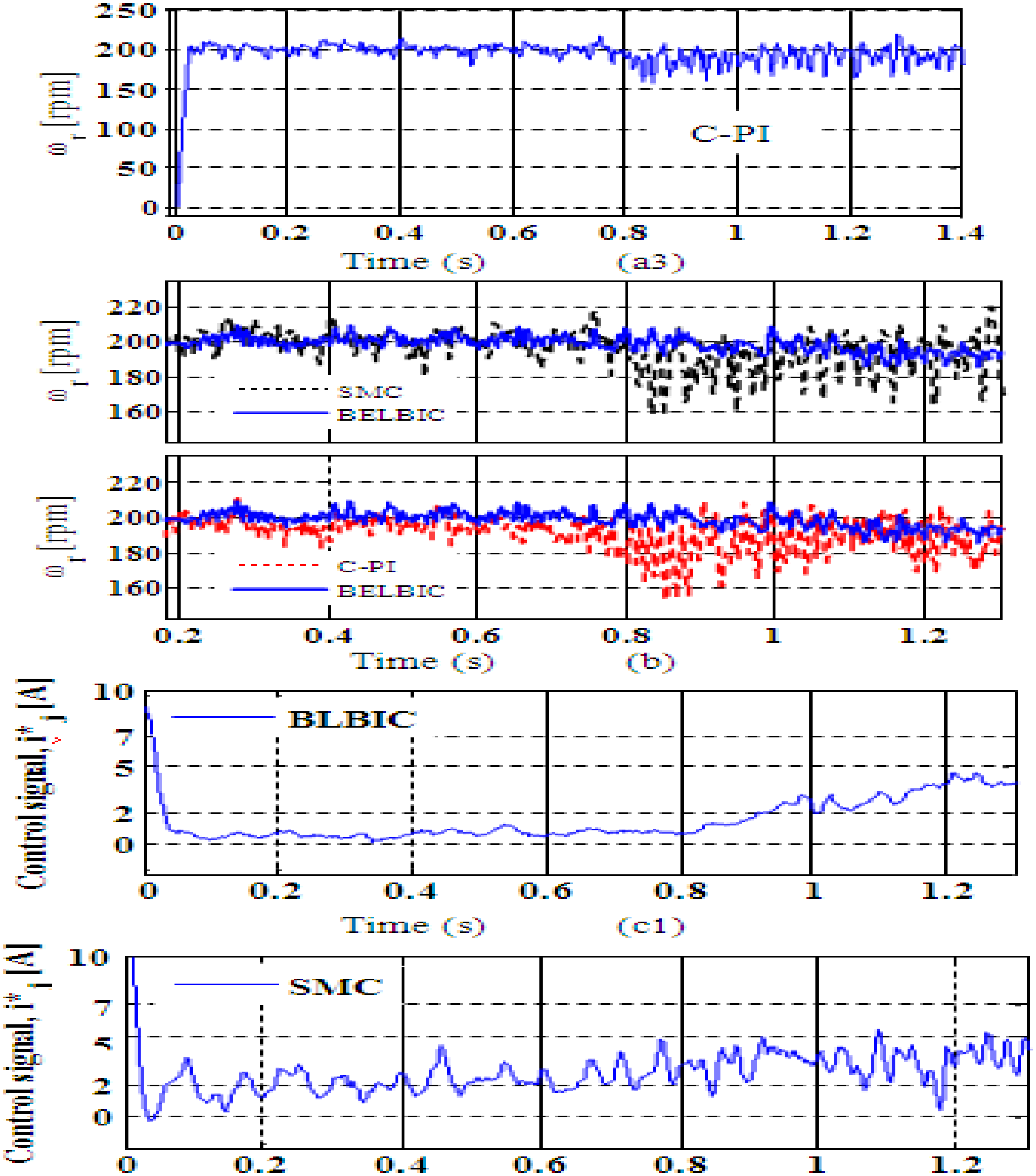


Fig. 9. Experimental results, the SRM control speed using BELBIC, SMC& C-PI, Test I: a) Rotor Speed, b) Dynamic response of speed.


200
100
0
ωr [rpm]
BELBIC
0
0.2
0.4
0.6
0.8
1
1.2
1.4
Time (s)
(a1)
200
100
0
ωr [rpm]
SM
0
0.2
0.4
0.6
0.8
1
1.2
1.4
Time (s)
(a2)


C-PI
Time (s)
(a3)
SMC
BELBIC
C-PI
BELBIC
Time (s)
(b)
BLBIC
Time (s)
(c1)
SMC

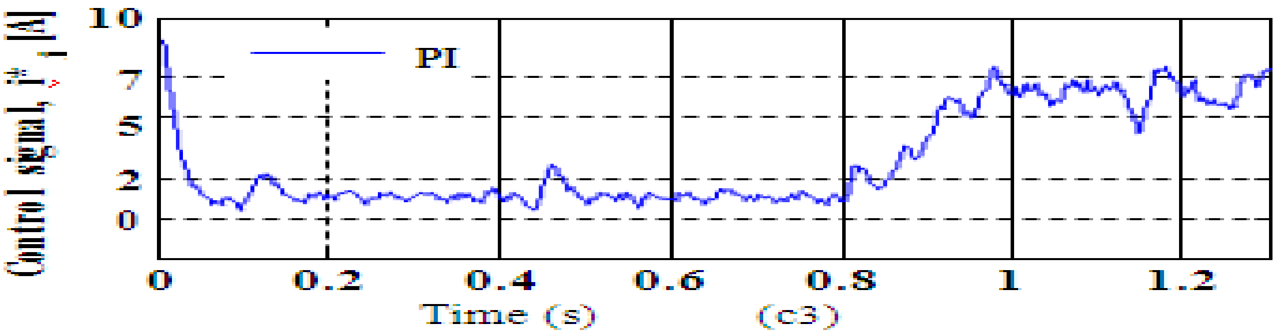


Fig. 10. Experimental results, the SRM control speed using BELBIC, SMC & C-PI, Test II: a) Rotor Speed, b) Dynamic response of speed to step load, c) Control signal i^*_j.

TABLE III. COMPARING ACHIEVED RESULTS WITH BELBIC, SMC & C-PI CONTROLLERS.

	Test I. (step speed)		Test II. (step	
Signal.	Spee	Torq	Spee	Torq
BELBIC	Very fast	low ripple	Continuously Steady &	low ripple, fast
SM	Fast	high ripple	Lumpy & high	High ripple, low
C-	Slow	high ripple	Lumpy & higher	High ripple, lower

As well as, in Figs. 7(a4) and 9(b) is depicted dynamic of speed command, which using BLBIC is higher than C-PI & SMC methods. In also it has sitting and rest time shorter than other ones. Also, according to Fig. 10(c), BELBIC has lower control effort than both of other ones. Also BELBIC operated continuously after step loading, but in this position, using C- PI and SMC, show higher torque ripple than before loading, which ware shown in Figs. 8(d) and its effects on rotor speed were indicated in Fig. 9. According to Figs. 8 and 9, dynamic response using BELBIC was faster than other ones in sudden loading.

Comparing the simulation and experimental tests, be saw that the intelligent control based on emotional learning can achieve our requirements for the SRM derive control properly. Also there is a useful summary of the results in Table III.

I. CONCLUSION

According to given description in this paper about new type of intelligent controllers based on brain emotional processes in limbic system and medial brain. Achieved results using that, as speed controller of SRM drive and comparing with Conventional PI Control and sliding mode approach in simulation & experimental areas, showed that BELBIC is a reliable and effective control method. Also it has seen that the torque ripple was decreased by proper control with BELBIC, and also dynamic response using that is higher than the other methods. As well as the control effort was softer than both of other ones. Moreover, Simple structure, fast auto learning and high tracking potency of BELBIC have been made a new control plant that is independent of the motor parameters and controls speed considering torque ripple reduction, and eliminated conventional PI controllers in that. These trains make BELBIC an ideal candidate for industrial level implementation.

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