Speed Control of Brushless DC Motors Using Emotional Intelligent Controller

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Abstract:
This paper presents an emotional controller for brushless DC motor (BLDC) drive. The proposed controller is called brain emotional learning based intelligent controller (BELBIC). The utilization of the new controller is based on the emotion processing mechanism in brain. This intelligent control is inspired by the limbic system of mammalian brain, especially amygdala. The controller is successfully implemented in simulation using MATLAB software, brushless dc drive with trapezoidal back-emf. In this work, a novel and simple implementation of BLDC motor drive system is achieved by using the intelligent controller, which controls the motor speed accurately. This emotional intelligent controller has simple structure with high auto learning feature. Simulation results show that both accurate steady state and fast transient speed responses can be achieved in wide range of speed from 20 to 300 [rpm]. Moreover, to evaluate this emotional controller, the performance of the proposed control scheme is compared with both Fuzzy Logic (FL) and PID controllers, in different conditions. This indicates proper operating in comparison to the FLC and PID controllers. And also shows excellent promise for industrial scale utilization.

Keyword: Emotional controller, Fuzzy logic controller, Brushless motor DC, Speed controller, Intelligent controller.

I. INTRODUCTION

Brushless dc (BLDC) motors have been desired for small horsepower control motors such as: heating, ventilation, and air conditioning systems to achieve great energy saving effects for partial loads by lowering motor speeds [1]. In addition, BLDC motors have been used as variable speed drives in wide array of applications due to their high efficiency, silent operation, compact form, reliability, and low maintenance. However, there remain three problems to be considered: 1) the proper and reliability control in different conditions 2) the reduction of torque ripple and mechanical vibration noise, and 3) the implementation cost.

For the first & second problems, although various methods have been proposed to improve the robustness or to enhance the load disturbance rejection [2]–[4], the phase-locked loop (PLL) control can provide more accurate speed regulating control of motor. In fact, the more accurate speed regulation comes from the better current loop control. Hence, the ripple torque is simultaneously reduced to lessen the mechanical vibration noise. However, unlike applications to control signal synchronization, stable implementation of the PLL control for adjustable speed motor drives is rather difficult to achieve due to the large motor inertia. Hence, most existing conventional C_PLL motor speed controllers are mainly implemented for constant speed control [5]. Other problem for that, depend on system parameters and operating point, which are caused to not achieve a desirable control in different conditions. However, in [5] was proposed a new PLL control that claimed, that is independent on controller parameters, but can be seen, which isn't independent on variations of motor parameters utterly, because of existing conventional PID. Also in the BLDC motor, the torque ripple is decided by the back-

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electromotive force (EMF) and current waveform. If the back-EMF is constant in the conduction region of current, the torque ripple depends on the current ripple [6].

Except current loop control for a proper control of drives, DTC method is a good control scheme that therein, does not require any current regulator, coordinate transformation and conventional PWM inverter voltage [7].

In addition to simplicity, the DTC of the BLDC motor allows a good torque control in steady state and transient operating conditions. However, high torque pulsation is produced, which is reflected in speed estimation responses. It also increases acoustical noise [8]. The DTC method presents some other disadvantages, such as i) difficulty to control torque and flux at very low speed ii) relatively high noise level at low speed iii) lack of direct current control.

For these reasons, properly intelligent methods can be adopted to solve the problems of electric drives as BLDC motor control for high performance applications [10-13].

From the viewpoint of industrial applications, ANN applications can be divided into four main categories [10]:

1) Modeling and Identification [11]. 2) Optimization and Classification [12]. 3) Process Control [12]. 4) Pattern Recognition [13-14].

In [15] was presented a FLC set based on immune (IS) feedback for BLDC control, which have complexity of fuzzy implementations and also FLs are based rules. 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 needed in many industrial applications to meet lower power and space requirements [16].

Based on the cognitively motivated open loop model, brain emotional learning based intelligent controller (BELBIC) was introduced for the first time in 2004 [17], and during the past few years this controller has been used, with minimal modifications, in control devices for several industrial applications [18]-[21]. For the first time, implementation of the BELBIC method for electrical drive control was presented by Rahman et al. [18]. After that, the emotional controller has been implemented for an induction motor drive by experimental tests [22]. Also this method was used for some other electric drives control, successfully [19, 23, 24].

In [24], a brief comparison between BELBIC and FLC is reported for speed sensorless control of a switched reluctance motor drive. Also, the fault tolerant behavior of the BELBIC is proved by simulation.

Based on the above mentioned evidence of the emotional control approaches in computer and control engineering and presenting modified models of BLBIC, 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 acceptably.

The paper is organized as follows; at first, the mathematical model of BLDC is presented in Section II. Then in section III the structure of the novel intelligent controller is explained. A summary of the fuzzy logic is presented in section IV. The block diagram of the control system is described in section V and the simulation results are presented and discussed in section VI. Finally, the conclusion is represented in section VII.

II. MATHEMATICAL MODEL OF BLDC

Full Consideration of a PMBLDC motor with symmetric three-phase stator windings and trapezoidal air-gap flux distribution is done. When it is driven by an inverter, the circuit equations of the three windings in phase variables can be expressed as follows [25], and the typical waveforms are shown in Fig. 1:

$$V_j = R \times i_j + L_s \frac{di_j}{dt} + e_j \quad , j = a, b, c$$
$$L_s = L - M \tag{1}$$

Where V_{ab} and V_{bc} are stator line voltages, i_a, i_b and i_c are stator currents, R and L are stator winding resistance and self inductance and M is stator winding mutual inductance, e_a, e_b and e_c are back-electromagnetic forces (EMFs) voltages of each phase (a,b,c), respectively.

In addition, the peak value of the trapezoidal back EMFs is given as:

$$\left|e_j(t)\right|_{peak} = k_c \cdot \varphi \cdot \omega_r(t), \quad j = \{a, b, c\} \tag{2}$$

Where k_c, φ *and* ω_r are constant, magnetic flux and rotor mechanical angel velocity, respectively.

As shown in Fig. 1, one can define three commutating functions, i.e., $Z_a(a)$, $Z_b(t)$, and $Z_c(t)$, as follows:

$$Z_a(t) = \sum_{k=0}^{\infty} \frac{1}{\sqrt{2}} \left[u(t - \frac{2k\pi}{\omega_e} - \frac{\pi}{3\omega_e}) - u(t - \frac{2k\pi}{\omega_e} - \frac{\pi}{\omega_e}) - u(t - \frac{2k\pi}{\omega_e} - \frac{4\pi}{3\omega_e}) + u(t - \frac{2k\pi}{\omega_e} - \frac{2\pi}{\omega_e}) \right] \quad (3)$$

$$Z_b(t) = Z_a(t - \frac{2\pi}{3\omega_e}) \quad (4)$$

$$Z_c(t) = Z_a(t - \frac{4\pi}{3\omega_e}) \quad (5)$$

where $u(t)$, is the unit step function. Following the commutating functions in Fig.1, one can also define a transformation that transfers the three-phase variables, i.e. $f_a(t)$, $f_b(t)$, and $f_c(t)$, to the equivalent variable of a dc brush motor, i.e., $f_{eq}(t)$, as follows:

$$f_{eq}(t) = [Z_a \quad Z_b \quad Z_c] \begin{bmatrix} f_a(t) \\ f_b(t) \\ f_c(t) \end{bmatrix} \quad (6)$$

Substituting (2)–(5) into (6) yields the following equivalent
Back-EMF $e_{eq}(t)$, :

$$e_{eq}(t) = \sqrt{2} \cdot k_c \cdot \varphi \cdot \omega_r(t) \quad (7)$$

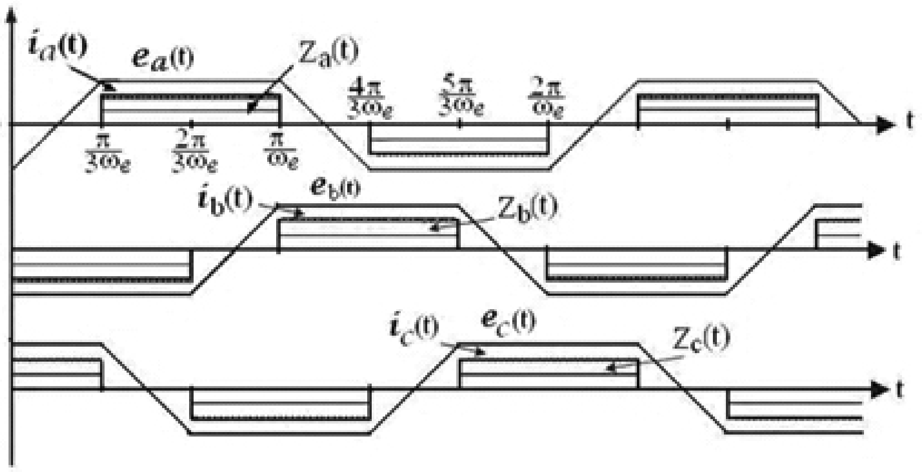
Let $i_{eq}(t)$, be the equivalent armature current of the equivalent dc brush motor for the PMBLDC motor. Since the stator currents $i_a(t)$, $i_b(t)$, and $i_c(t)$ of the PMBLDC motor is controlled using an inverter to generate three-phase rectangular shape currents, as shown in Fig. 1, $i_{eq}(t)$, can, thus, be derived from (6), and the corresponding electromagnetic torque is given as following:

$$T_e = \frac{(e_a i_a + e_b i_b + e_c i_c)}{\omega_r} = \sqrt{2}\, k_c\, \varphi\, i_{eq} \quad (8)$$

Similarly, once the torque command or, equivalently, $i_{eq}(t)$ is obtained, the corresponding phase currents can be obtained as: $[i_a(t)\, i_b(t)\, i_c(t)]^T = [Z_a(t)\, Z_b(t)\, Z_c(t)]^T \cdot i_{eq}(t)$. Now, consider the motion equation of the BLDC motor, i.e.

$$J \frac{d\omega_r}{dt} = T_e - T_l - B \cdot \omega_r \quad (9)$$

Where T_e, T_l, B and J are the electromagnetic and load torques, friction coefficient and moment of inertia, respectively. It follows from (8) and (9) that the equivalent armature current to the rotor angular speed transfer function becomes:



Fig(1). Waveforms of the EMFs, phase currents, and the corresponding commutating signals for the BLDC motor drives.

$$\frac{\omega_r(s)}{i_{eq}(s)} = \frac{\sqrt{2}\, k_c\, \phi}{Js + B} \quad (10)$$

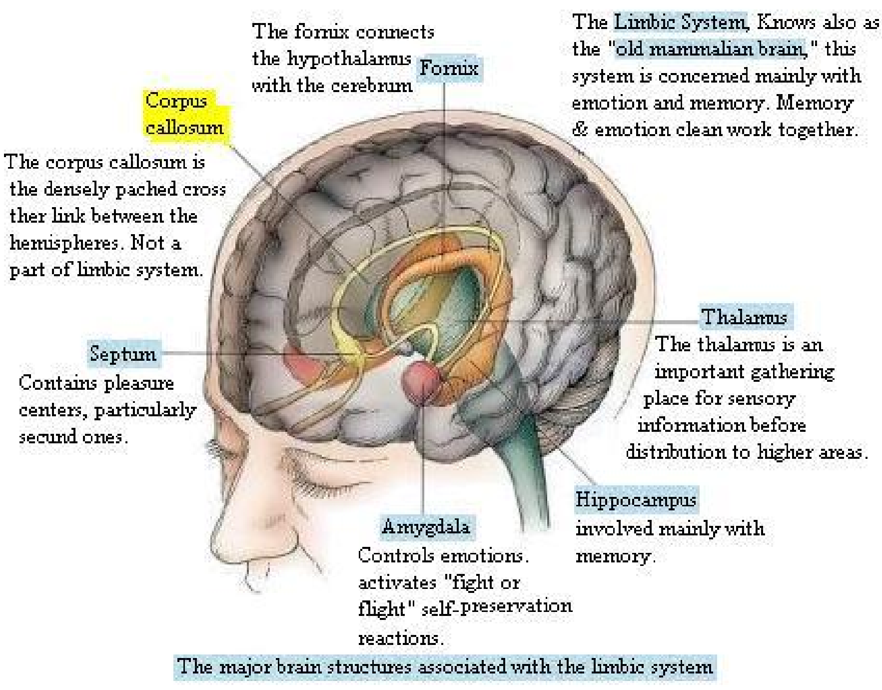
It is shown that the three-phase BLDC motor can now be considered as an equivalent dc brush motor with equivalent back EMF $e_{eq}(t)$ and equivalent armature current $i_{eq}(t)$, which is proportional to the generating torque Te. Hence, the three phase driver control can be reduced to a simple scalar control.

III. COMPUTATIONAL MODEL of BELBIC

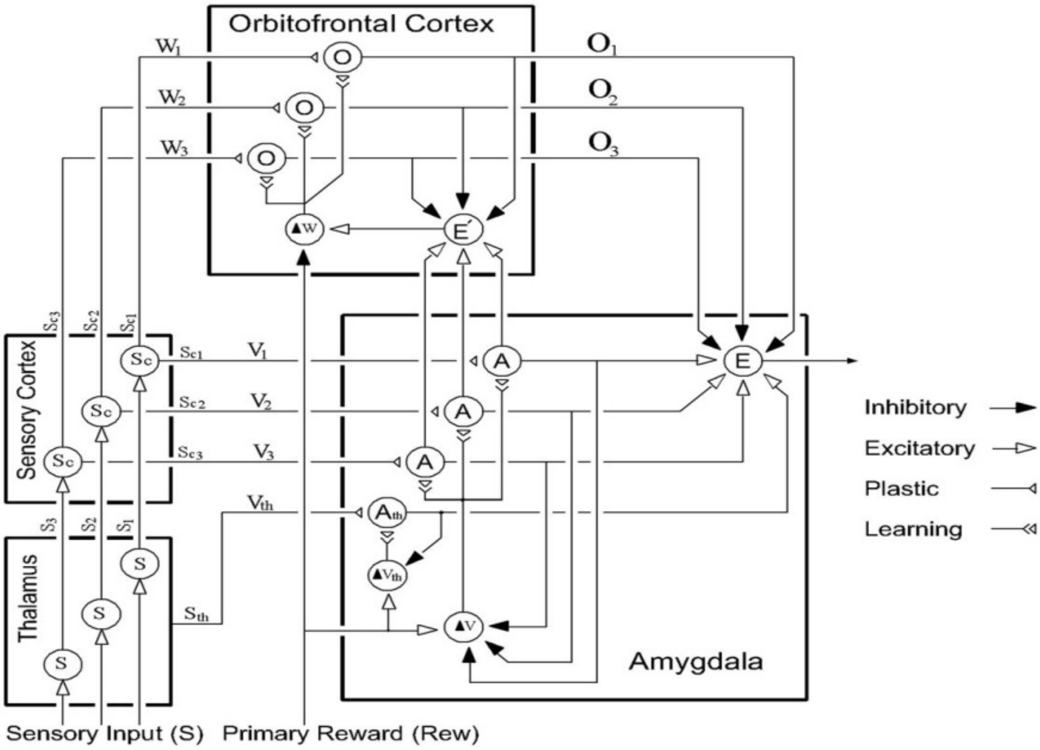
Motivated by the success in functional modeling of emotions in control engineering applications [17]-[23], the main purpose of this paper is to use a structural model based on the limbic system of mammalian brain and emotional learning based action selection, for decision making and control engineering applications. Fig. 2 shows the pertinent pictures of the human brain, and Fig. 3 provides a graphical depiction of the modified sensory signal and learning network connection model inside the brain.

The small almond-shaped subcortical area of the amygdala, as illustrated in Figs. 2& 3, is very well placed to receive stimuli from all sensory cortices and other sensory areas of the hippocampus [26]. There are two approaches to intelligent and cognitive control; direct and indirect approaches. In the indirect approach, the intelligent system is utilized for tuning the parameters of a good controller. Here, we adopt the direct approach via using the computational model as a feedback control system selecting the control action to be applied to the plant. The intelligent computational model termed BELBIC is used as the controller block [17, 20]. The model of the proposed BELBIC structure is illustrated in Fig. 3. 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 depend on the performance objectives in that application. Amygdala is a part of brain that must be responsible for processing emotions and correspond to orbitofrontal cortex, thalamus, and sensory input cortex.

Also, there is another connection for thalamus input within amygdala. The value of this input is equal to maximum



Fig(2). Sectional view of the human brain for emotion processing.



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

sensory inputs value. In Fig. 3, there is one A node for every stimulus S, including one for the thalamic stimulus. There is also one O 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 E node simply sums the outputs from the A nodes and then subtracts the inhibitory outputs from the O nodes. The abstract structure of the computational model mimicking some parts of mammalian brain is depicted in Fig. 4.
The result is the output from the model. In other words, E can be obtained from:

$$E = \sum_j A_j + A_{th} - \sum_j O_j \tag{7}$$

The internal areas output are computed pursuant to (8)-(11).

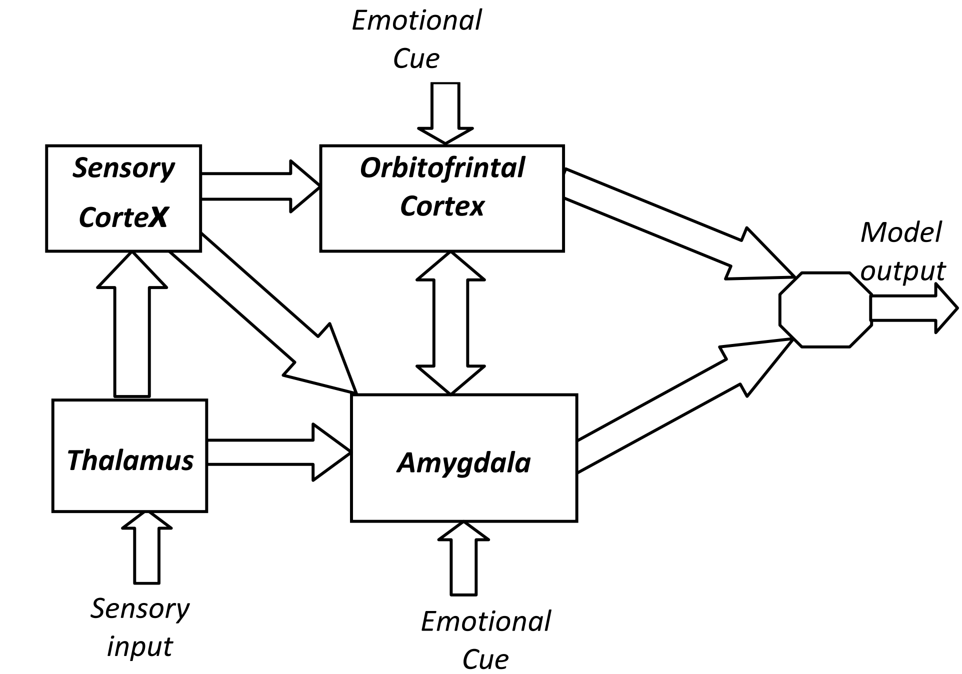
$$A_{th} = V_{th} \cdot \{\max(S_j) = S_{th} \} \tag{8}$$

$$A_j = S_j V_j \tag{9}$$

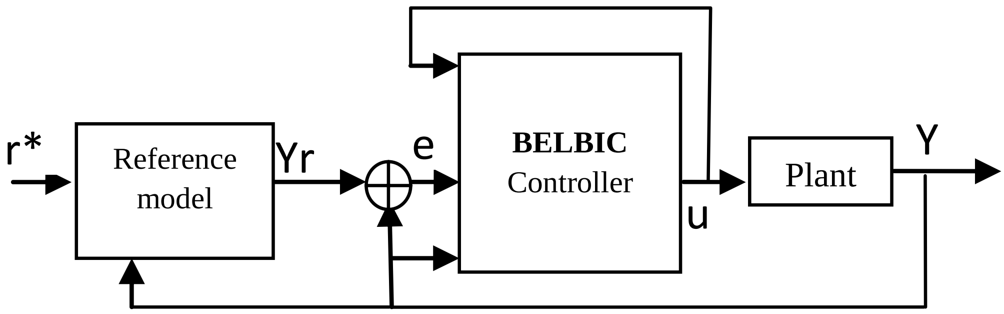
$$O_j = S_j W_j \tag{10}$$

$$Sc_j = S_j \otimes \left[e^{-k \cdot t}\right] \tag{11}$$

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



Fig(4). The abstract structure of the computational model mimicking some parts of mammalian brain.



Fig(5). Control system configuration using BELBIC.

Orbitofrontal connection S_j and S_{Cj} are sensory and sensory-cortex outputs respectively and j is the jth input. Variations of V_j and W_j can be calculated as:

$$\Delta V_i = \alpha \left(\max \left(0, Sc_i (R - \sum_i A_i) \right) \right) \quad (12)$$

$$\Delta V_{th} = \alpha_{th} \left(\max \left(0, S_{th} (R - A_{th}) \right) \right) \quad (13)$$

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

$$E' = \sum_j A_j - \sum_j O_j \quad (14)$$

$$\Delta W_i = \beta \left(Sc_i \left(E' - R \right) \right) \quad (15)$$

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 (13) which cannot decrease. It means that it does not forget information in amygdala. Whereas idiomatically inhibiting (forgetting) is the duty of orbitofrontal cortex (12). Eventually, model output is obtained from (7). Fig. 5 shows the BELBIC controller configuration. The used functions in emotional cue R and sensory input S blocks can be given by the following relations:

$$R = f(E, e, y, y_d) \quad (16)$$

$$S = g(y, y_d, e) \quad (17)$$

In this application, the functions f and g are given by relations:

$$g = k_1 e + k_2 \frac{d}{dt} e + k_3 \int e.dt \quad (18)$$

$$f = K_1 |e| + K_2 |e \cdot y| + K_3 |y_p| \quad (19)$$

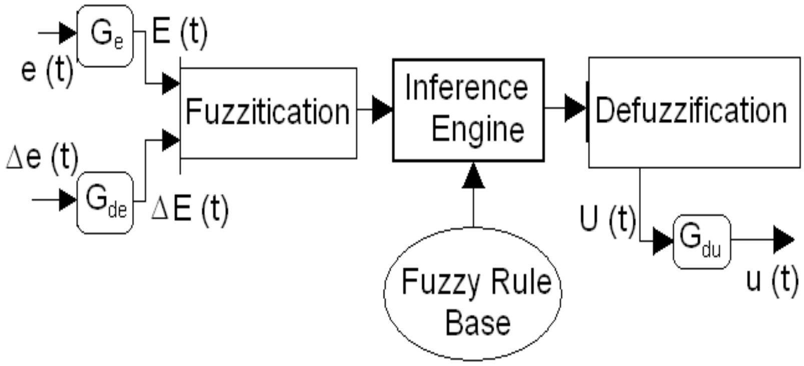
Where e, y_p and y are system error, controller output and system output respectively. Also, k_1 and K_1, k_2 and K_2 as well as k_3 and K_3 are gains, which must be tuned for designing a satisfactory controller. Eventually, initial values for α and β in O and A and functions R and S should be selected for emotional signal generation.

Selecting R and S signals is very important and shows user's aims; firstly, constant values should be selected to ensure primary stability of the system. During implementation of the system, the learning weights (V, V_{th} and W) are updated for tracking improvement. Consequently, with each sudden change in system, the weights are tuned adaptively according to R and S signals (6, 7, and 8).

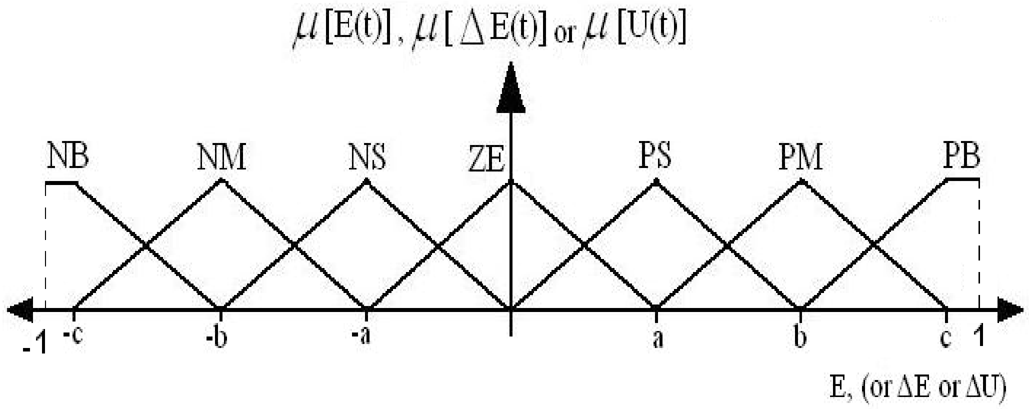
The tuning of k_1 and K_1 through k_3 & K_3 is carried out similar to the tuning of a conventional PID controller coefficients. The gains k_1 & K_1 are determined for the settling time adjustment and the gains k_2 & K_3 are responsible for smoothing the system response. Also, k_3 & K_2 affect the steady-state error. It should be noticed that a controller is preferred to be near the dynamic of system in order to present an acceptable tracking behavior. The emotional controller is capable of programming with any system dynamic. Slow and soft dynamic can be implemented by decreasing the impacts of A_{th} with $k_{th} < 1$ and also fast dynamic can be obtained by increasing the effects of A_{th} with $k_{th} \geq 1$. Furthermore, the controller behaves softer by selecting ($\alpha > \alpha_{th}$) and performs faster response with $\alpha < \alpha_{th}$ according to entering the emotions in R and S signals.

IV. FUZZY LOGIC CONTROLLER

Structure of FLC is shown in Fig. 6. It is well known that FLC consists of fuzzification process, linguistic rule base and defuzzification process. $E(t)$ and $\Delta E(t)$ are two inputs of the fuzzy system and $U(t)$ is defined as output. In this work, these inputs and outputs are speed error and differential of the speed error and current/torque reference. Figure (7) shows membership function of input variables $E(t)$, $\Delta E(t)$ and $U(t)$ which are with conventional triangular shapes and with 50% overlapping, basic magnitude between (-1, 1). As shown in Fig. 2, each membership function is assigned with seven fuzzy sets, which are Negative Big (NB), Negative Medium (NM), Negative Small (NS), Zero (ZE), Positive Small (PS), Positive Medium (PM), and Positive Big (PB) [27].



Fig(6). FLC block diagram



Fig(7): Membership functions for input variables.

Table (1): LINGUISTIC RULE BASE FOR FLC

$\Delta E(t)$ / $E(t)$	NB	NM	NS	ZE	PS	PM	PB
NB	NB	NB	NB	NB	NM	NS	ZE
NM	NB	NB	NB	NM	NS	ZE	PS
NS	NB	NB	NM	NS	ZE	PS	PM
ZE	NB	NM	NS	ZE	PS	PM	PB
PS	NM	NS	ZE	PS	PM	PB	PB
PM	NS	ZE	PS	PM	PB	PB	PB
PB	ZE	PS	PM	PB	PB	PB	PB

Linguistic rules, which depend on the type of FLC, are set up for fuzzy inference and are shown in Table I.

Once the fuzzy inference results are derived, the control output can be calculated from the defuzzification process, to give crisp value of output. In this paper, the inferred fuzzy control action is converted to a crisp value, Δu through the widely used Center of Area (COA) method to yield

$$\Delta u(t) = \frac{\sum_{i=1}^{M} \Delta u_i \mu C_i}{\sum_{i=1}^{M} \mu C_i} \qquad (20)$$

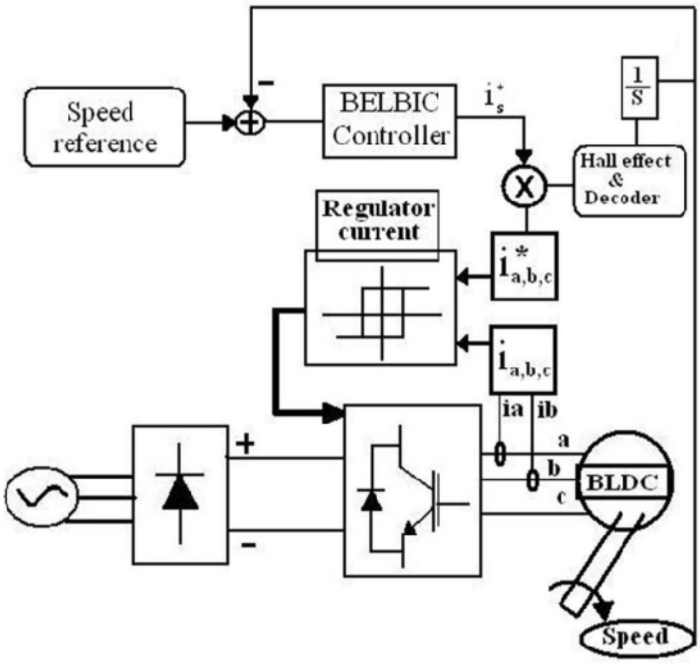
Where Δu_i is grade value of $\Delta u_i(t)$ derived from the fuzzy inference results and membership function, Δu , as shown in Fig. 7. M is number of rules. Also μC_i is compatibility (weighting factor); derived by using Mamdani's minimum fuzzy implication rules according to table I.

In Fig. 6 G_e , G_{de} and G_{du} coefficients are determined to fix the input variables to (-1 and 1) and output variable to (U_{min} and U_{max}), respectively.

V. BLDC DRIVE CONTROL SYSTEM DESIGN

The block diagram of the new control system based on BELBIC is shown in Fig. 8. The emotional control system receives the error signals between the command speed and the actual motor speed as part of inputs according to equations (12)-(16). And it generates the output signals following equations (7)-(11). In this control system design of Fig. 6, the emotional intelligent controller

(BELBIC) receives motor speed error as input and then generates i_s^* as output, directly. So, according to III section, the drive can be controlled with control of stator winding current (i_s^*).



Fig(8). Control system structure of BLDC drive using BELBIC.

The three phase currents are controlled to take a form of quasi-square waveform in order to synchronize with the trapezoidal back-EMF to produce the constant torque. In each time only two phases are excited, so it is possible to use only one current sensor which is placed in DC-link voltage.

Speed controller block generates the current demand to maintain the speed at reference value. Back-EMF voltage block calculates the phase back-EMF voltages according to rotor position. Phase current block calculates the phase current. Current control block controls the phase current via hysteresis current control and generates the switching signals for Inverter. In Inverter block, phase voltages are obtained. According to 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 current, and quite independent of motor parameters. Unlike in conventional PI controllers, the proposed emotional control technique is auto learning, model-free and the controller coefficients are adaptive, which facilitate the vector control of the BLDC motor drive to be controlled independent of parameters variations.

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 performances of proposed control scheme for the BLDC drive are investigated in simulation test at different operating conditions.

Digital computer simulations have been performed using Matlab/ Simulink [28]. The simulated responses are given in Figs 9-13. In all cases, the drive system is started and operated according to the following sequence of tests:

Test1: The speed command and load torque are given in Table II:

TABLE II. REFERENCE COMMANDS for TEST 1

Time [sec]	0	0.2	0.5	1
ω_r^* [rpm]	300	300	300	300

Time [sec]	0.2	0.4	0.4	1
T_L [Nm]	1	1	11	11

According to Fig. 9 control system of BLBIC operated properly. Actual speed tracked its reference and also rotor flux is fixed at its reference. Rotor speed and electromagnetic torque, stator current and voltage are shown in Figs. 9(a, b, c, d), respectively. At Fig. 10, responses of control system of conventional PID are shown by an overshoot at speed curve.

Test(2): The speed and External signal commands are given in Table III:

TABLE III
REFERENCE COMMANDS for TEST 2

Time, [sec]	0	0.35	0.4	0.6	0.7	1
ω_r^* [rpm]	300	300	150	150	20	20

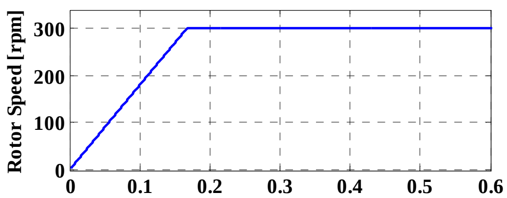
Time, [sec]	0	0.2	0.2	1
T_L [Nm]	1	1	8	8

Time, [sec]	0	0.2	0.3	0.3
$Ex.sig^*$. [A] $f_{Ex}=10/3[Hz]$	0	20	-20	0

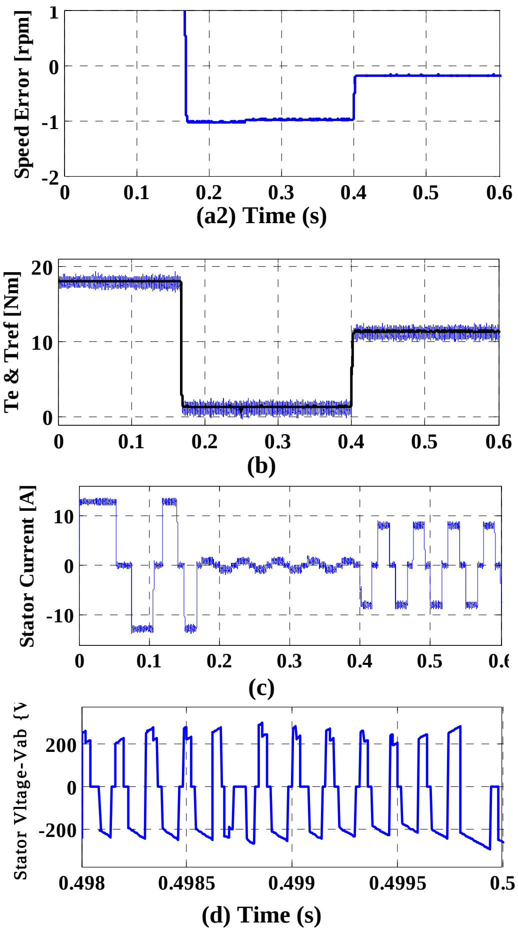
In test 1, an external alternative signal (Ex. Sig*.) added a control signal (Te* or i_s*, the relation between them has been given by (6)), as a disturbance signal. Fig. 11 shows the operating responses of the drive system using emotional controller BELBIC. It can be seen that the proposed controller gives regulated responses in terms of fast tracking, small overshoot and zero steady-state errors, which adapts itself with the external signal.

Also, rotor speed value as shown in Fig. 11(a) converges to its reference properly. As one can see that the control system BLBIC can control the BLDC drive at wide region of speed (between 20 to 300 rpm) with existence of a disturbance signal, which is added to the control signal.

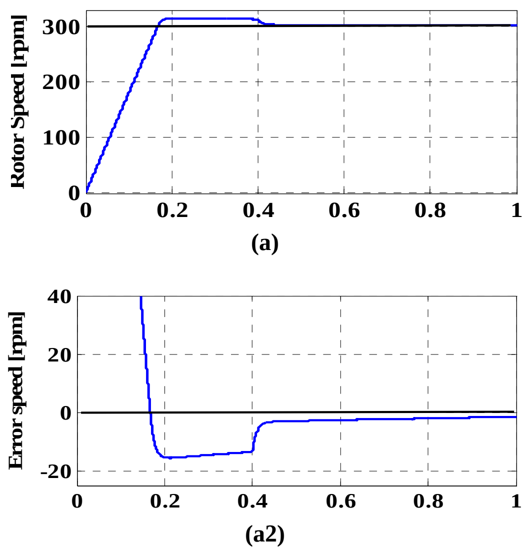
Fig. 12 shows the simulation responses of the drive system using conventional PID for test 2. It can be seen that, there are significant ripples in electromagnetic torque curve Fig. 12(d). Moreover, the controller doesn't produce a smooth speed for the BLDC drive Fig. 12(a). The controller doesn't give tuned response against a wide range of functions.

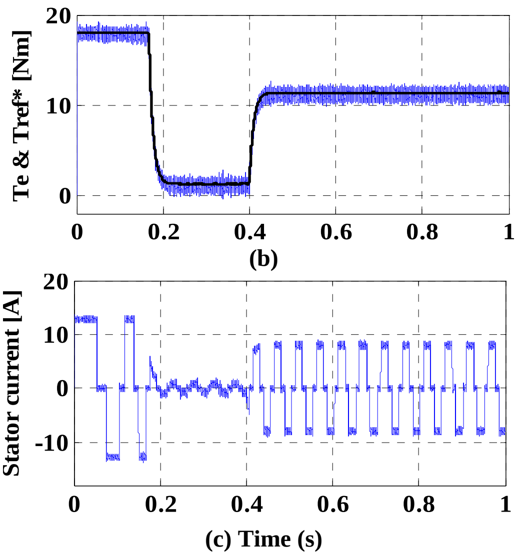


(a1)



Fig(9). Simulation results of BLBIC, the BLDC control speed, Test1: a) Motor Speed, b) Electromagnetic torque, c) Steady-state stator current phase-a, d) Stator voltage-ab.

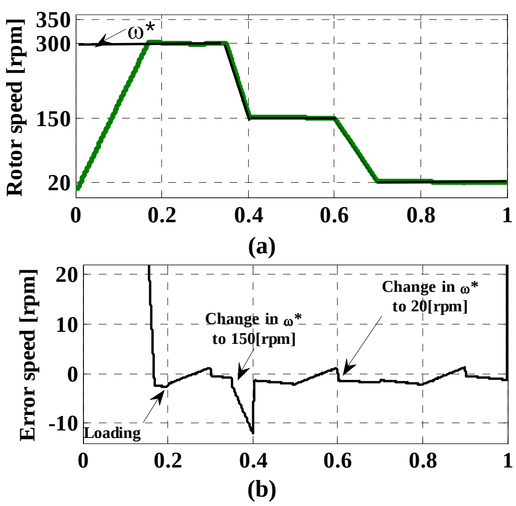


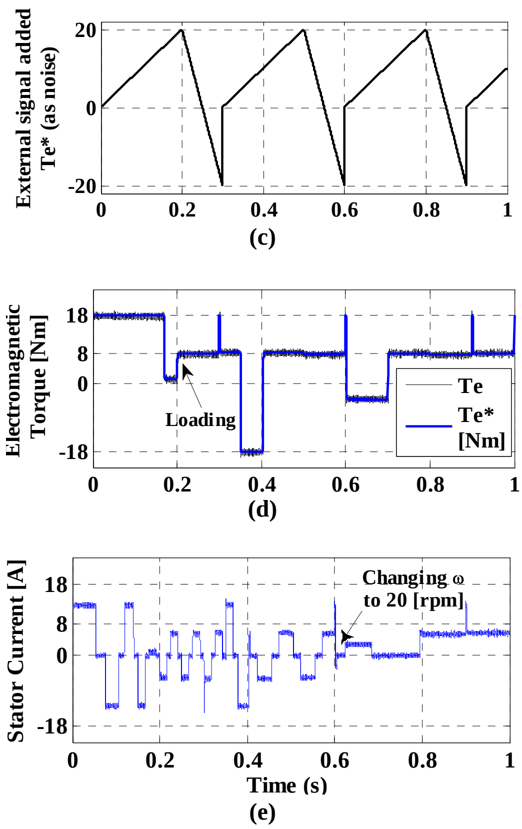


Fig(10). Simulation results of PID, the BLDC control speed, Test1: a) Motor Speed, b) Electromagnetic torque & control signal (Te*), c) Steady-state stator current phase-a.

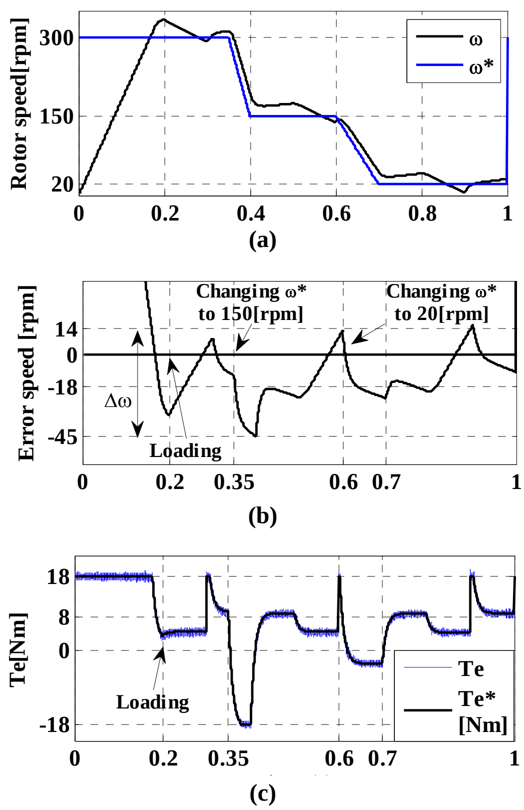
Additionally, in order to present a fair judgment, the simulation results are achieved by a FLC only for Test 2, which are shown in Fig.13. Albeit, FLC is like BELBIC to track speed commands (Fig.13 (a, b)), torque ripple is significantly higher than BELBIC. One can see in Fig.13 (c), this torque ripple, which has been caused by high control effort, is about twice BELBIC's. Moreover, as Fig.13 (a) shows, FLC has a longer raise time in comparison to BELBIC.

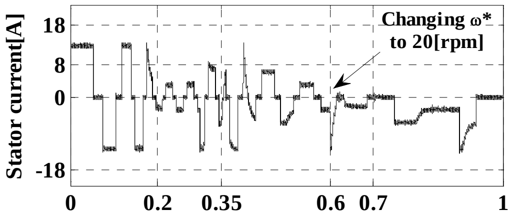
Another important advantage of the proposed emotional intelligent controller is that it is relatively easy to tune the gain parameters of the controllers effectively and efficiently for high performance BLDC drives.





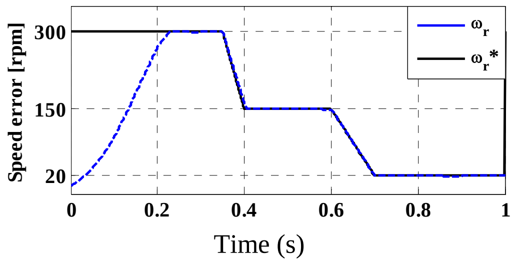
Fig(11). Simulation results of BLBIC, the BLDC control speed, Test2: a) Motor Speed, b) Error of speed, c) disturbance signal d) Electromagnetic torque & control signal, e) Stator phase-a.



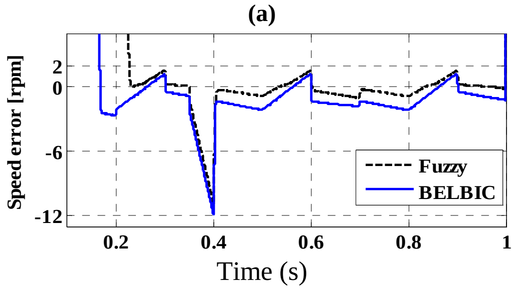


(d) Time (s)

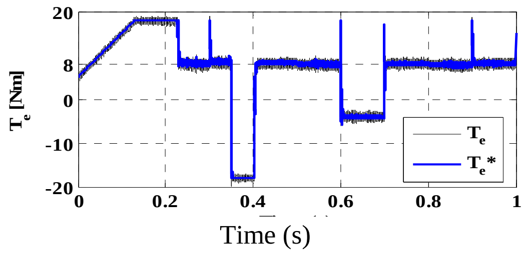
Fig(12) Simulation results of PID, the BLDC control speed, Test2: a) Motor Speed, b) Error of speed, c) Electromagnetic torque & control signal, d) Stator phase-a.



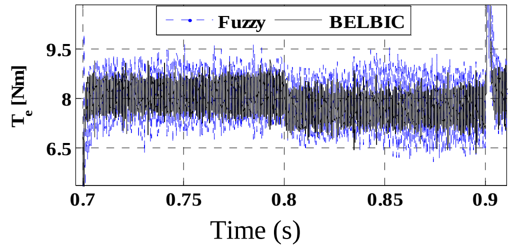
(a)



(b)



(c)



(d)

Fig(13). Simulation results of the FLC, the BLDC control speed, Test2: a) Motor Speed, b) Error of speed, c) Electromagnetic torque & control signal, d) Zoomed Electromagnetic torque.

TABLE IV. PARAMETERS OF THE BLDC DRIVE

18Nm	Rated Toque	0.2 ohm	Stator Resistance
320V	DC link Voltage	1.8 ohm	Rotor Resistance
4	Number of Poles	0.175 V.S	Flux Inductance by Magnet
0.089 Kg.m^2	J. Inertia	8.5 mH	Stator phase-Inductances
0.005 N.m.s	Friction Factor	0.175 V.S	Flux Inductance by Magnet

VII. CONCLUSION

This paper presents an emotional controller for a brushless DC motor drive. The implementation of emotional controller shows excellent control performance and good robustness and adaptability, even in presence of a disturbance signal. At a comparison with FLC and conventional PID controllers was seen that, although FLC operates like to BELBIC in tracking speed commands, it suffers a higher torque ripple and control effort than BELBIC. Moreover, BELBIC benefits a less raise time compared to the FLC. On the other hand, the simulation evidences show the conventional PID can't properly operate at wide range of operating points and in disturbance condition. A simple structure of BELBIC with its fast auto learning, model-free and good tracking features is used. The proposed emotional intelligent technique can be easily adapted for large scale industrial applications.

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