Implementation of Emotional Controller for Interior Permanent Magnet Synchronous Motor Drive

R. M. Milasi, Caro Lucas, B. N. Arrabi
Center of Excellence for Control and Intelligent Processing, Department of Electrical and Computer Engineering, University of Tehran, Tehran, Iran
rmilasy@ece.ut.ac.ir, lucas@ipm.ir, arrabi@ut.ac.it

T.S. Radwan, M. A. Rahman
Faculty of Engineering & Applied Science
Memorial University of Newfoundland, St. John’s, NL, Canada A1B 3X5
tsradwan@ieee.org, rahman@engr.mun.ca

Abstract—This paper presents for the first time the real-time implementation of an emotional controller for interior permanent magnet synchronous motor (IPMSM) drives. The proposed novel controller is called brain emotional learning based intelligent controller (BELBIC). The utilization of BELBIC is based on emotion processing mechanism in brain, and is essentially an action, which is based on sensory inputs and emotional cues. The emotional learning occurs mainly in the amygdala. The amygdala is mathematically modeled, and the BELBIC controller is introduced. This type of controller is insensitive to noise and variance of the parameters. The controller is successfully implemented in real-time using a digital signal processor board ds1102 for a laboratory 1-hp IPMSM. The results show superior control characteristics especially very fast response, simple implementation and robustness with respect to disturbances and manufacturing imperfections. The proposed method enables the designer to shape the response in accordance with the multiple objectives of choices.

Keywords: Amygdala, speed control, interior permanent magnet motor, disturbance, nonlinear model, vector control, real-time implementation, emotional controller.

I. INTRODUCTION

The advances in power semiconductor technology, digital electronics, magnetic materials and control theory have enabled modern ac motor drives to face challenging high efficiency and high performance requirements in the industrial sector. Among ac drives, the interior permanent magnet (IPM) motor has been gaining popularity owing to its high torque to current ratio, large power to weight ratio, high efficiency, high power factor and robustness. These features are due to the incorporation of high-energy rare-earth alloys such as Neodymium-Boron-Iron (NdBFe) in its construction. Especially, the interior permanent magnet synchronous motor (IPMSM), in which magnets are buried in the rotor core exhibit certain good properties, such as mechanically robust rotor construction, a rotor non-saliency, smooth and small effective air gap. The rotors of these machines have a complex geometry to ensure optimal use of the expensive permanent magnet material while maintaining a high magnetic field in the air gap. These features allow the IPMSM drive to be operated in high-speed modes by the field weakening.

Usually, high performance motor drives require fast and accurate response, quick recovery from any disturbances and insensitivity to parameter variations. The dynamic behavior of an ac motor can be significantly improved using vector control theory, where motor variables are transformed into an orthogonal set of d-q axes such that speed and torque can be controlled separately [1]. This gives the IPMSM machine the highly desirable dynamic performance capabilities of the separately excited dc machine, while retaining the general advantages of the ac over dc motors. Originally, the vector control technique was applied to the induction motor and a vast amount of research work has been devoted to this area. The vector control method is relevant to the IPMSM drive as the control is completely carried out through the stator, and the rotor excitation control is not possible.

However, precise speed control of an IPMSM drive becomes a complex issue due to complex coupling among its winding currents and the rotor speed as well as the nonlinearity present in the torque equation. The system nonlinearity becomes severe, if the IPMSM drive operates in the field weakening region where the direct axis current $i_d \neq 0$. This results in the appearance of a non-linear term, which would have vanished under the existing vector control scheme with $i_d = 0$.

There have been significant developments in nonlinear control theory applicable to electric motor drives [16]. Interestingly, the d-q transformation applicable to ac motors can be considered as a feedback linearization transformation. However, with the recent developments in nonlinear control theories, a modern control engineer has not only found a systematic approach in dealing with nonlinearities but has managed to develop approaches, which had not been considered previously. The surges of such nonlinear control methods applicable to electromechanical systems include variable structure systems [2], differential geometric approach [3-4] and passivity theory [5]. But most of these controllers are complex to implement and are costly, so it is important to design a controller that requires less cost with good
performance. This paper focuses on solving these complex control problems via an innovative approach by the use of an emotional controller.

The paper is organized as follows; firstly, the IPMSM drive model in the d-q reference frame is presented in section II. Then in section III the structure of the novel emotional controller is explained. The block diagram of control system is described in section IV. The real-time implementation of the proposed controller is described in section V and the results are presented and discussed in section VI. Finally, the conclusion is presented in section VII.

II. IPMSM MODEL

The mathematical model of an IPMSM drive can be described by the following equations in a synchronously rotating rotor d-q reference frame as [6]:

\[
\begin{align*}
\frac{dv}{dt} &= \begin{bmatrix} r_s + pL_{d,s} & -Pw_rL_{q,s} \\ Pw_rL_{d,s} & r_s + pL_{q,s} \end{bmatrix} \begin{bmatrix} i_d \\ i_q \end{bmatrix} + \begin{bmatrix} 0 \\ Pw_r \Phi_f \end{bmatrix} \\
T_e &= T_L + J_m p_w_r + M_m w_r \\
T_e &= \frac{3P}{2} [\Phi_f i_q + (L_d - L_q) i_di_d]
\end{align*}
\]

(1)

(2)

(3)

It is well known that a synchronous motor is unable to self-start when supplied with a constant frequency source. A rotor squirrel cage winding provides the required starting torque in the IPMSM drive fed from the mains. The starting process of the IPMSM drive can be considered as a superposition of two operating modes, namely, unsymmetrical asynchronous motor mode and permanent magnet-excited synchronous generator mode [7]. Therefore, the effects of shorted rotor windings have to be considered, if one wants to examine the process of run-up to the synchronization. However, the model in equations (1) to (3) does not describe the unsynchronous behavior of the IPMSM drive, since the motor is fed from variable frequency inverter. The IPMSM drive using modern NdBFep magnets can be operated over a wide temperature range [8]. It has been shown that, within normal operating temperature range, the residual flux density and intrinsic coercivity will decrease as the temperature is increased. However this is considered, as a reversible process as the temperature comes down to normal value, the flux density and coercivity will return to their original values. This variation in residual flux along with the stator resistance, in turn affects the dynamic behavior of the motor controller. The standard linear d-q axis IPMSM model with constant parameters will lead to an unsatisfactory prediction of the performance of a permanent-magnet motor owing to the saturation of these machines during normal operation. It has been shown that improved prediction of IPMSM behavior can be accomplished by adjusting the model parameters according to the changing saturating conditions [9]. Various researchers have reported that there exist variations in \(X_d, X_q\) and \(\Phi_f\) with the direct and quadratic axis saturation as well as with the direction of rotation [7,9]. In light of these findings we propose to use the brain emotional learning based intelligent controller (BELBIC), wherein this controller responds to all of these variations in the drive system.

The objective of this paper is to obtain the IPMSM control voltages in order to achieve high performance speed tracking. According to the motor model given in equations (1-3) of section II, it can be seen that the speed control can be achieved by controlling the q-axis component \(i_q\) of the supply voltage as long as the d-axis current \(i_d\) is maintained at zero. This results in the electromagnetic torque being directly proportional to the current \(i_q\). Since \(i_d = 0\) for the sake to validate the principle of the new BELBIC technique, the d-axis flux linkage depends only on the rotor permanent magnets. The resultant IPMSM model can be represented as,

\[
\begin{align*}
pl_q &= \frac{1}{L_q}(v_q - r_i i_q - Pw_r \Phi_f) \\
v_g &= -Pw_r L_q i_q \\
T_e &= T_L + J_m p_w_r + M_m w_r \\
T_e &= \frac{3P}{2} (\Phi_f i_q)
\end{align*}
\]

III. BELBIC MODEL

Motivated by the success in functional modeling of emotions in control engineering applications [10-13], the main purpose of this paper is to use a structural model based on the limbic system of mammalian brain, for decision making and control engineering applications. We have adopted a network model developed by Moren and Balkenius [14], as a computational model that mimics amygdala, orbitofrontal cortex, thalamus, sensory input cortex and generally, those parts of the brain thought to be responsible for processing emotions. 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 the controller. One can adopt the first one as the so called the direct approach. Here the intelligent system, the computational model termed BELBIC, is used as the controller block. For sake of simplicity, the term BELBIC is called emotional controller in this paper. The model of the proposed BELBIC structure is illustrated in Fig. 1. The BELBIC technique is essentially an action generation mechanism based on sensory inputs and emotional cues. In general, these can be vector valued, although in the benchmarks discussed in this paper for the sake of illustration, one sensory input and one emotional signal (stress) have been considered. The emotional learning occurs mainly in amygdala. The learning rule of amygdala is given in Eqn. (8):
$\Delta G_o = k_1 \max(0, EC - A)$  
(8)

Where $G_o$ is the gain in amygdala connection, $k_1$ is the learning step in amygdale, and $EC$ and $A$ are the values of emotional cue function and amygdala output at each time. The term $\max$ in equation (8) is for making the learning changes monotonic, implying that the amygdala gain can never be decreased. This rule is for modeling the incapability of unlearning the emotion signal (and consequently, emotional action), previously learned in the amygdala [14-15]. Similarly, the learning rule in orbitofrontal cortex is given by Eqn. (9) as:

$\Delta O = k_2 (MO - EC)$  
(9)

where $G_o$ is the gain in orbitofrontal connection, $k_2$ is the learning step in orbitofrontal cortex and $MO$ is the output of the whole model (amygdala output), which can be calculated as:

$MO = A - O$  
(10)

in which, $O$ represents the output of orbitofrontal cortex.

In fact, by receiving the sensory input $S$, the model calculates the internal signals of amygdala and orbitofrontal cortex by the following relations in equations (11) and (12), and eventually yields the output as:

$A = G_o S$  
(11)

$O = G_o S$  
(12)

Since amygdala does not have the capability to unlearn any emotional response that it ever learned, inhibition of any inappropriate response is the duty of orbitofrontal cortex.

A. Emotional controller realization

Controllers based on emotional learning have shown very good robustness and uncertainty handling properties [11-12], while being simple and easy to implement. In order to utilize this version of the Moren-Balkenius model as a controller for IPMSM drive, it is essential to convert two sets of inputs into the decision signal as its output. We have implemented a closed loop configuration using the BELBIC in the feed forward loop of the total system in an appropriate manner so that the input signals have the proper interpretations. The block implicitly implemented the criteria: the learning algorithm and the action selection mechanism used in functional implementations of emotionally based (or generally reinforcement learning based) controllers, all at the same time [10-12]. The structure of the control configuration implemented in this work is illustrated in Fig. 2. The functions used in emotional cue and sensory input blocks are given by the following relations:

$EC = W_1 \int e dt + W_2 CO$  
(13)

$SI = W_3 PO + W_4 PO$  
(14)

where $EC$, $CO$, $SI$ and $PO$ are emotional cue, controller output, sensory input and plant output (IPM motor speed), and the $W_j$ through $W_4$ are gains that must be tuned for designing a satisfactory controller. The gain $W_1$ is responsible for tuning the overshoot, the gain $W_2$ is responsible for tuning the settling time, while the gain $W_3$ is responsible for tuning the steady state error, and finally the gain $W_4$ is responsible for smoothing the beginning of the response.

Figure 2. Control system configuration using BELBIC

IV. THE CONTROL SYSTEM

The control method for the IPMSM is chosen based on the parameters, which include the usage, performance and speed range. Figure 3 shows the block diagram of the new control system incorporating the emotional controller (BELBIC). The emotional controller receives the error signal between the command speed and the actual motor speed as an input and generates the output signal. The controller output is $v_d$ according to the simplified model of equations (4)-(7) and the controller model of equations (8)-(14). From the controller output $v_d$, the command quadratic axis current component, $I_d$, can be calculated according to the motor model equations (4-7). Using $I_d$ and the pre-calculated $I_q$, the command a-b-c phase currents are generated using inverse Park’s transforms [6]. In order to implement the vector control algorithm, the hysteresis current controller is used. The current controller compares the command currents with the corresponding actual motor currents and generates the logic signals to fire the inverter switches.

V. REAL-TIME IMPLEMENTATION

A. Hardware implementation.

The proposed emotional controller (BELBIC) for IPMSM is experimentally implemented using TMS320C31 DSP floating point processor. The DSP is integrated with inputs/outputs
peripherals to build a DSP controller board DS1102 [17]. The block diagram for the hardware implementation is shown in Fig. 4. The actual motor currents are sensed using Hall-effect transducers with high accuracy and fed to the DSP controller board through A/D converters. The rotor position is measured by an optical incremental encoder, which is mounted at the rotor shaft end. Then, it is fed to the DSP board DS1102 through the built in encoder interface. The index line of the encoder is used and programmed to initialize the rotor position. The motor speed is then calculated from the rotor position by backward difference interpolation [6]. According to the implementation algorithm, the output of the DSP board are six pulse-width-modulation (PWM) logic signals. Those pulses come out through the digital I/O ports of the DSP board and are fed to the inverter switches through isolation and driving circuit.

The DSP board DS1102 is installed into a dedicated laboratory PC computer. The communication between the board and the computer is done through a dual port memory with out interrupt to the DSP program.

B. Software implementation.

The entire control algorithm for the IMPSM drive system is implemented through software by developing a program in high-level “C” programming language. The program is compiled by TI “C” compiler and the generated objective code is then downloaded to the DSP processor using the dSPACE 1102 utilities [17]. The sampling time for experimental implementation of the proposed IPMSM drive system with emotional controller is determined to be 100 µS. This time includes the execution of the proposed emotional controller (BELBIC), vector control algorithms, hysteresis current controller, logic signals generation, and acquisition /setting the input/output signals. The flowchart for implementing the control algorithm is shown in Fig. 5.

VI. RESULTS AND DISCUSSION

In order to validate this emotional controller and hence, to establish the effectiveness of the proposed BELBIC scheme, the performances of the IPMSM drive based on the proposed control scheme are investigated both in simulation and experimental investigations at different operating conditions. The speed control loop of the drive system was also designed, simulated and experimentally implemented with an industry
standard proportional-integral-derivative (PID)-controller, in order to compare the performances of those obtained from the proposed BELBIC-based drive system. In order to make a fair judgment the PID controller is tuned at rated conditions to give the quick and smooth response (settling time and under/over shoot).

Digital simulations have been carried out using Matlab/Simulink [18]. The parameters of the laboratory IPMSM drive are given in Table-I. The simulated response in Fig. 6 investigates the tracking of the system. In this case the drive system is started at a rated load conditions of 3 N-m with the speed reference set at 1800 r/min (188.5 rad/s). It can be seen from Fig. 6 that the actual speed converges to the reference value within 0.1s. However, according to Fig. 6C, the torque producing current component I\textsubscript{qc} shows an overshoot but it lasts for only 0.08 s and the motor starting current. The response in Fig. 6(d) is within the permissible limit. Another simulated speed response for a sudden increase in command speed is shown in Fig. 7. It is evident from figure 7 that BELBIC technique is also capable of handling the disturbance in speed command with fast tracking, no overshoot and zero steady state error. Other simulated speed responses of the drive for a sudden change in the load torque are shown in Fig. 8. The load torque is changed from 1N-m to 3N-m at t = 0.5s. The actual speed does not change during the disturbance, while the stator current swiftly reaches to its new value corresponding to the load applied. This shows the capability of the new emotional controller in terms of disturbance rejection. Thus, perfect speed tracking has been achieved for the emotional controller (BELBIC).

Computer simulations have been carried out to determine system responses for an industry standard proportional-integral-derivative (PID) controller. The parameters for PID controller of this control system are given in the Appendix. Corresponding simulation results of Figs. 6-8 are obtained for the PID controller. The simulation results of IPMSM drive with PID controller are shown in Figs. 9-11. Both I\textsubscript{qc} and control signal exhibit large overshoots during transient conditions before the speed settles to its steady-state value. These overshoots are significantly larger than those in the emotional controller (BELBIC). This is also reflected on the motor current. The motor draws more current during transient states. In all cases using PID controller a steady-state speed error existed. The overall performances with PID controller are inferior to those of the proposed emotional controller.

The simulated results are verified by the experimental tests. Figure 12 shows the starting responses of the drive system using emotional controller. It is to be noted from Fig. 12(a) that the proposed controller gives tuned response in terms of fast tracking, overshoot and steady-state error. Also, the motor starting current is only limited to 2.5 times the rated value as shown in Fig.12(b). Moreover, with this controller the hysteresis current controller works perfectly. The motor current follows exactly the command one as shown in Fig. 12(c). The experimental speed responses of the drive system with step changes of speed from 100 to 188.5 and from 188.5 to 100 rad/sec. and the load change for BELBIC technique are shown in Figs. 13 and 14, respectively. These figures confirm that the proposed new emotional controller is superior in terms of fast response, zero steady-state error and insensitiveness to load disturbances. Thus, the proposed emotional controller (BELBIC) is robust for high performance drive applications.

<table>
<thead>
<tr>
<th>TABLE-I. Machine Parameters</th>
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<tbody>
<tr>
<td>Motor rated power</td>
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<tr>
<td>Rated voltage</td>
</tr>
<tr>
<td>Rated current</td>
</tr>
<tr>
<td>Rated frequency</td>
</tr>
<tr>
<td>Pole pair number (P)</td>
</tr>
<tr>
<td>d-axis inductance, I\textsubscript{dq}</td>
</tr>
<tr>
<td>q-axis inductance, I\textsubscript{d}</td>
</tr>
<tr>
<td>Stator resistance, R</td>
</tr>
<tr>
<td>Motor inertia, J\textsubscript{m}</td>
</tr>
<tr>
<td>Friction Coefficient, D\textsubscript{m}</td>
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</tbody>
</table>

Magnetic flux constant, \( \Psi_r \) = 0.311 volts/ rad/s

Figure 6. Speed control of PMSM using BELBIC. (a) command and motor speeds, (b) control signal, (c) torque current component, and (d) motor phase current.
Figure 7. Simulated response for sudden increase in speed for the proposed control system. (a) command and motor speeds, (b) control signal, (c) torque current component, and (d) motor phase current.

Figure 8. Simulation response for sudden increase in load for the proposed control system. (a) command and motor speeds, (b) control signal, (c) torque current component, and (d) motor phase current.

Figure 9. Speed control of PMSM using PID controller. (a) command and motor speeds, (b) control signal, (c) torque current component, and (d) motor phase current.
Figure 10. Simulated result for sudden increase in speed for PID controlled system. (a) command and motor speed, (b) control signal, (c) torque current component, and (d) motor phase current.

Figure 11. Simulated result for sudden increase in load for PID controlled system. (a) command and motor speed, (b) control signal, (c) torque current component, and (d) motor phase current.

Figure 11. (continued)

Figure 12. Experimental starting response of the drive system for BELBIC. (a) command and motor speeds, (b) motor phase current, and (c) steady-state current.
BELBIC could make it so much more efficient. It is possible to pursue other different goals simultaneously or to consider goal fusion methodologies, e.g. fuzzy aggregation of goals, so as to form a suitable emotion signal.

APPENDIX

The following parameters of PID controller are chosen as

\[ K_p = 14.3927, \quad K_i = 5.9946, \quad K_d = 0.4332. \]

REFERENCES
