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A new intelligent adaptive mechanism for sensorless control of permanent magnet synchronous motor drive

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ABSTRACT

This paper presents an intelligent adaptive mechanism for sensorless permanent magnet synchronous motor drive. The mammalian brain inspired intelligent controller named as brain emotional controller is introduced in adaptive mechanism of model reference adaptive system to estimate rotor speed, rotor position and for motor parameters identification. The brain emotional controller design includes certain parts of limbic system of mammalian brain. The brain emotion based adaptive mechanism is constructed with state tracking error of reference and adjustable models using Lyapunov function. Moreover, to control the speed of drive the brain emotional control based speed regulator is designed to achieve improved performance. The effectiveness of adaptive mechanism is verified using simulations and results obtained are analyzed by real time implementation using hardware-in-loop set up. The performance of proposed strategy is validated by operating at different operating and loading conditions. The results show the effectiveness and robustness of proposed brain emotional control strategy.

Introduction

The advancements of modern control theory concepts have introduced different intelligent control techniques to solve nonlinear problems of industrial applications (Henson & Seborg, 1997; Murray-Smith & Johansen, 1997; Rodriguez, Gutierrez-Garcia, & Ramos, 2016). Many intelligent controllers design is based on behaviour of different mammalian organs for which mammalian brain is responsible to finish the allocated task of an organ (Dancy, 2013; Hudlicka, 2014). The mammalian brain gives necessary signal to corresponding organ to attend the task very swiftly and more accurately (Larue, Poirier, & Nkambou, 2013; Taylor, 2010; Vallverdu et al., 2016). The limbic system of mammalian brain plays a vital role in decision making process of organ as it provides very fast and accurate signal in the form of emotions to finish a task, thus as per the neurobiological aspect it is called as centre of emotions (Lautin, 2002; Samsonovich, 2013). The process of emotional intelligence of Limbic system can be modeled and designed as a controller to obtain fast and accurate solution especially complex problems of engineering applications Moren and Balkenius developed a computational network for Limbic system to analyse behaviour of animals (Moren & Balkenius, 2000a, 2000b). Caro Lucas et al. modified and extended the network model to introduce brain emotional controller to find solution for complex nonlinear control engineering systems (Lucas, Shahmirzadi, & Sheikholeslami, 2004). In design of brain emotional controller each part behaviour is modeled with a mathematical function with the inspiration of limbic system of mammalian brain which includes certain parts namely sensory cortex, thalamus, amygdala and orbitofrontal cortex (OFC). This controller is modified to solve the control problems of electrical drives and power systems (Dehkordi, Kiyoumarsi, Hamedani, & Lucas, 2011; Qutubuddin & Yadaiah, 2017; Soreshjani, Markadeh, Daryabeigi, Abjadi, & Karga, 2015). In this paper, Permanent Magnet Synchronous Motor (PMSM) drive which is a typical nonlinear system is considered for estimation and control. The brain emotional controller is introduced in adaptive mechanism to estimate rotor speed (ω_r), rotor position (δ) and motor parameters identification *i.e.* resistance (R_s) and inductance (L_s).

PMSM drive is gaining popularity due to its compact size and is used replacing other drives of same size. Developments in compact size magnet materials made to design PMSM drive for variety of industrial applications such as robotics, renewable energy applications, chemical industries process control, domestic applications and many more. The PMSM drive when operated with vector controlled algorithm which requires precise information about rotor speed and rotor position to synchronize with inverter to generate phase excitation pulses. The rotor information of PMSM drive can be measured by sensors and optical encoders, but in the case of sensorless applications these are absent, as

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Nomenclature

V_d,V_q	stator voltages
I_d,I_q	reference currents
ω_r	rotor speed
$\hat{\omega}_r$	estimated rotor speed
δ	rotor position
	adjustable currents
R_d,R_q	stator resistance per phase
L_d,L_q	d-axis and q-axis inductance
P	no. of Pole pairs of motor
Ψ_f	rotor magnetic flux linking the stator
T_L	load torque
T_e	electromagnetic torque
B_m	friction coefficient of motor
J_m	moment of inertia of the motor and load
A	amygdala
O	orbitofrontal cortex
S_i	sensory input
SC	sensory cortex
EC	emotional cue
u_p	plant output
u_c	controller output

it occupies additional space for electronics converting circuit and frequent maintenance (Acarnley & Watson, 2006; Boldea, 2008). In sensorless control application rotor speed and rotor position is estimated rather than measured, which reduces space, cost and frequent maintenance. Different estimation techniques are readily available to implement out of which Model reference adaptive system (MRAS) is one of the promising, most popular and wide accepted technique (Kwon & Jin, 1999; Piippo, Hinkkanen, & Luomi, 2009; Sun, Xiaopeng, Bai, Wei, & Sun, 2016). MRAS construction includes reference model and adjustable model with suitable adaptive mechanism. The adaptive mechanism is designed with comparative output analysis of the reference and adjustable models using gradient, least square and Lyapunov approach. The adaptive mechanism of MRAS technique contains PI, Sliding mode controller (SMC) and artificial intelligent techniques. The PI and SMC controller's performance is step fall at sudden load disturbance, speed variations and change in motor parameters. These variations impact on stator winding currents, deviations in stator voltages and in electromagnetic torque production. The SMC involves in chattering problem which creates noise, worsens the performance of machine and also requires additional hardware in real time implementation (Baik, Kim, & Youn, 2000; Foo & Rahman, 2010). The adaptive mechanism can modify with artificial intelligent (AI) techniques to obtain better performance but these models do not have exact mathematical relations. In case if the system stability is main concern the validation of AI techniques based adaptive mechanism has limitations of not ensuring the stability. The fuzzy logic controller based adaptive mechanism cannot be applied for the systems where stability is main concern due to lack of exact mathematical function (Chaoui & Sicard, 2012). The Neural networks based adaptive mechanism can be used to solve the problems but in training algorithm a fixed learning rate which converges speed and includes complex design structure (Elmas, Ustun, & Sayan, 2008). Other intelligent controllers ANFIS and Optimization techniques are proposed but they are shortfall in performance and also require extensive information of system which increases complexity in design (Jon, Wang, Luo, & Jong, 2017; Liu, Zhu, Zhang, & Zhang, 2008).

In this paper, it is proposed to design and development brain emotional controller for three different major objectives (i) speed control of PMSM drive, (ii) estimation of state variables of PMSM (rotor speed and rotor position) and (iii) identification of motor parameters (Resistance and Inductance). These concepts are applied for sensorless vector control of PMSM drive. The design structure of brain emotional controller for said applications is alike but differs in selection of sensory signal and emotional cue or reward functions. The adaptive law for state variables and motor parameters is constructed with Lyapunov design approach (Sassano & Astolfi, 2013). In adaptive law the variable gain plays a major role which speeds up and slows down the adaptive mechanism performance which may limit overall performance of system. The brain emotional controller is designed for the variable gain used in adaptive mechanism to achieve improved performance. The estimated speed is given as feedback signal to control the drive where the speed regulator is also designed with brain emotional controller strategy to reduce variations in stator phase winding currents and electromagnetic torque at different operating conditions. Fig. 1 shows structure of proposed technique, brain emotional controller used in adaptive mechanism and to control the speed of PMSM drive. The brain emotional controller has unique and simple designing which overcomes the complexity associated in other intelligent controllers. The input to brain emotional controller used in adaptive mechanism is fed from adjustable and reference models of MRAS technique, the reference model taken from plant *i.e.* motor and adjustable model is dynamic one in which estimated speed and parameters are variables. Further the estimated rotor speed is fed to control PMSM drive for sensorless application.

This paper organized as follows: Section 'Development of brain emotional controller' deals with architecture of brain and focused in limbic brain and their associated parts to develop as a controller, Section 'Brain emotional controller based adaptive mechanism' explains about the adpative mechanism and significance to use brain emotional controller, the Section 'Brain emotional controller based MRAS technique for PMSM drive' the developed adaptive mechanism is applied to PMSM drive to verify the effectiveness, the results and discussions are explained in Section 'Results and discussions' and finally conclusions in Section 'Conclusions'.

Development of brain emotional controller

The structure of brain emotional controller with Limbic system of mammalian brain, and parts associated to generate emotional signal is shown in Fig. 2. Amygdala plays a key role in limbic system to generate emotional signal with its connections to other parts of brain. The output of amygdala is considered as primary reinforce signal, further the response is processed in motor cortex with OFC to generate predicted emotional response to attend the task. Moren and Balkenius developed a computational network model to design limbic system with amygdala and OFC as main parts (Moren & Balkenius, 2000a, 2000b). The same component model has been considered in this paper to design brain emotional controller. The thalamus is designed in a superficial way for the sake of simplicity to onward transmission of sensory signal to amygdala and OFC.

The emotional signal generation mechanisms is initiated by collecting inputs to controller and modify as sensory signal with a suitable function. The sensory signal is processed in sensory cortex, amygdala and OFC. The inputs to the amygdala are sensory cortex, emotional cue and sensory signal. Amygdala output response is very fast which needs to be conditioned with OFC to generate appropriate emotional signal response. The inputs to OFC are sensory cortex, sensory signal, emotional cue and resultant.

The output of the controller is emotional response signal which is obtained from the outputs of amygdala and OFC. The emotional cue is reinforcing signal which trims amygdala and OFC response with appropriate weight to accord actual emotional response. The design