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Direct Torque and Flux Control of Dual Stator Winding Induction Motor Drives based on Emotional Controller

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Abstract—**Recently, Dual Stator Winding Induction Machines (DSWIMs) has attracted the attention of many researchers. These induction machines which have two sets of three phase windings with unequal pole pairs and standard squirrel cage rotors, can overcome the associated complications of conventional three phase induction machines in zero speed operation regions. Generally, having unequal pole pairs brings the ability of independent operation of winding sets and accurately flux estimation in various rotor speed ranges. This paper proposes a direct torque and flux control system for DSWIMs based on Brain Emotional Learning Based Intelligent Controllers (BELBICs). These controllers which are model and parameter independent, are auto learning and adaptive. Indeed, in the proposed DSWIM-drive system the reference values for d and q axis voltages of stator winding sets are determined through BELBICs to directly control flux and torque of each winding sets. The reference value of winding fluxes is determined to minimize the stator currents and the torque commands are assigned by a torque sharing algorithm which enables the DSWIM to operate in a wide speed region, ranging from nominal positive to nominal negative. The proposed control system simulation in MATLAB/SIMULINK verifies its excellent performance in various speed ranges including zero speed.**

Keywords-Dual Stator Winding Induction Machine (DSWIM), Brain Emotional Learning Based Intelligent Controllers (BELBIC), Direct Torque Control (DTC), Zero speed operation.

I. INTRODUCTION

From long ago, squirrel cage induction machines have proved to be an opportune candidate for numerous industrial applications. As they possess various advantages such as simple structure, capability of operation in various environmental circumstances, having self-start-up torque, low maintenance and low fabrication costs [1]. However, their operation in low speed ranges and mainly in zero speed have some challenges, since flux estimation in low speed ranges, involve inaccuracies. In 1998, a novel winding structure for induction machines was introduced which is able to solve zero speed operation difficulties involved with conventional induction machines [2]. This machine has two sets of three phase windings with different number of pole pairs in its stator operating with a common standard squirrel cage rotor and it is known as Dual Stator Winding Induction Machine (DSWIM) [3]. Further, two winding sets can work in different operation modes. Indeed, in zero speed ranges one of them works in generating mode and the other one operates in motoring mode. This brings accurate flux estimation capability in zero and very low speeds.

DSWIMs due to their advantages over other dual winding induction machines, such as high reliability, controllability in various speed ranges and low fabrication costs, have found applications in different industries both for generating and motoring operation modes [4]. In [5] this machine is applied in the generating operation mode. Where, the DSWIM output voltages are implemented to produce a controllable DC power source through PWM rectifiers. The proposed control strategy is based on Field Oriented Control (FOC). FOC utilizes linear controllers. As electrical machines have intrinsic nonlinear behavior, in [6] the same DC voltage generation system is proposed based on an Input Output Feedback Linearization (IOFL) control scheme. However, this nonlinear control technique is highly parameter dependent. Further, internal dynamics should be accurately taken to account to avoid instabilities.

In [7] a DSWIM is utilized in the motoring operation mode. The speed control in a wide range of operations, including zero speed, is fulfilled by both scalar and direct vector control techniques. The DSWIM drive system proposed in [8] which is also relates to the motoring operation mode, implements an indirect vector control strategy for rotor speed control. The indirect vector control is also implemented for the DSWIM drive system in [9]. Furthermore, there is provided an MRAS speed and flux estimation to guarantee stability in different load variation conditions.

Generally, the independent operation of two stator windings of a DSWIM is guaranteed if two windings are supplied by voltages with frequency ratios the same as the pole pair numbers and if the space harmonics are neglected [3]. Therefore saturation should be avoided. The DSWIM drive systems proposed in [10-13] are assigned to flux level determination which guarantees saturation avoidance. The load torque is supplied with minimum stator current in the indirect vector control scheme proposed in [10]. Although, the operation of the proposed control system is restricted to high speed ranges and it is dependent on the precise parameter values.

In the direct and indirect vector control methods, various Proportional Integral (PI) controllers are utilized which aren't accordant with the nonlinear behavior of induction machines. Therefore in [7] a PI-Sliding Mode Controller (SMC) is proposed for direct torque control of a 2.2 kW DSWIM. PI-SMC is robust against parameter variation and has fast response, if the control parameters are accurately designed.

Recently, the application of Artificial Intelligent (AI) techniques such as Fuzzy Logic (FL), Artificial Neural Network (ANN) and Genetic Algorithm (GA) in power electronics and electric drive systems is considerably developing. Nevertheless, implementing these methods involves with large volume of real-time calculations.

Hitherto, many efforts are made to model the emotional treatment of the human brain [14,15]. Amygdala computational models are known as the model of Brain Emotional Learning (BEL) [14]. The BEL based Intelligent Controller (BELBIC) was first introduced by Lucas in 2004 [16] and implemented for various industrial applications [17-21]. In [17] a BELBIC is utilized in heating and air conditioning systems, which are multi-variable and nonlinear control systems. BELBIC is implemented for controlling a washing machine in [18]. In [19] an automatic suspension control system is controlled by a BELBIC and in [20] the position tracking and controlling of an overhead crane is realized by a BELBIC. In [21] BELBIC is implemented for speed control of an Interior Pole Permanent Magnet Synchronous Motor (IPMSM) for the first time and the results are compared with a PID controller. This comparison verified that the proposed controller has some advantages in comparison with PID controller, such as very fast response and simple implementation. Further, it is more robust in parameter variation conditions.

According to the above mentioned discussions, a BELBIC can conveniently overcome the problems associated with linear and nonlinear control strategies. Therefore, in this paper direct torque and flux control of a DSWIM is fulfilled based on BELBIC controller. In the proposed DSWIM derive system the reference values of each stator winding is determined according to the MTPA realization technique proposed in [7] and the torque command is specified such that the DSWIM can operate in various speeds, including zero speed.

The rest of this paper is structured as follows: section II is assigned to DSWIM modeling. The proposed BELBIC based control system is characterized in section III. Section IV renders the simulation results and the conclusions are given in V.

II. Electrical Model of a DSWIM

As previously discussed, if the stator windings of a DSWIM are supplied by the voltages having the equal frequency ratio with the pole pair ratio and if the saturation neglected, this machine can be modeled as two independent three phase induction machine. Indeed, every unequal combination can be selected as the pole pair ratio for two winding sets in a DSWIM. Nevertheless, if this ratio is selected equal to 3, the saturation will be minimized [1]. Consequently the DSWIM model utilized in the simulations of the proposed control system in this paper has a two pole and a six pole three-phase winding sets. In the

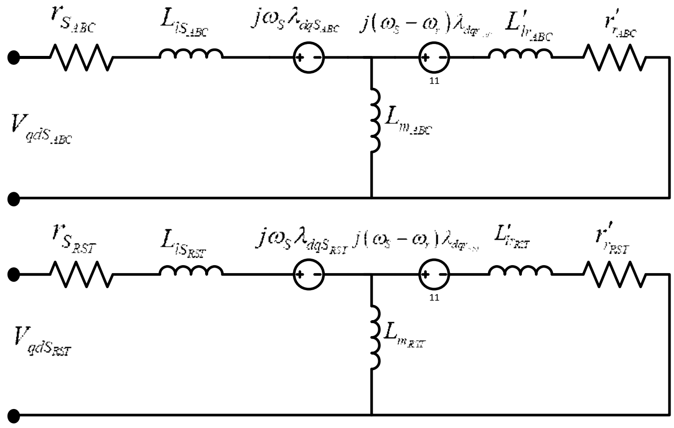


Fig. 1. Electrical model of a DSWIM

following, the two and six pole windings are nominated by *ABC* and *RST*, respectively. Fig. 1 illustrates the electrical model of a DSWIM. In the synchronous reference frame the stator d and q axis voltages can be written as:

$$V_{S_i d} = R_{S_i} I_{S_i d} + \frac{d\lambda_{S_i d}}{dt} - \omega_S \lambda_{S_i q} \tag{1}$$

$$V_{S_i q} = R_{S_i} I_{S_i q} + \frac{d\lambda_{S_i q}}{dt} + \omega_S \lambda_{S_i d} \tag{2}$$

$$V_{r_i d} = R_{r_i} I_{r_i d} + \frac{d\lambda_{r_i d}}{dt} - (\omega_S - \omega_r)\lambda_{r_i q} = 0 \tag{3}$$

$$V_{r_i q} = R_{r_i} I_{r_i q} + \frac{d\lambda_{r_i q}}{dt} + (\omega_S - \omega_r)\lambda_{r_i d} = 0 \tag{4}$$

In the above equations ω_S and ω_r are synchronous and rotor speeds, respectively. *i=1 and 2* stands for *ABC* and *RST* winding sets, respectively. λ represents the linkage flux and defined as:

$$\lambda_{S_i d} = L_{S_i} I_{S_i d} + L_{m_i} I_{r_i d} \tag{5}$$

$$\lambda_{S_i q} = L_{S_i} I_{S_i q} + L_{m_i} I_{r_i q} \tag{6}$$

$$\lambda_{r_i d} = L_{m_i} I_{S_i d} + L_{r_i} I_{r_i d} \tag{7}$$

$$\lambda_{r_i q} = L_{m_i} I_{S_i q} + L_{r_i} I_{r_i q} \tag{8}$$

If the stator linkage flux orientation is considered $\lambda_{s_i} = \lambda_{s_i d}$ and $\lambda_{s_i q} = 0$. Consequently the electromagnetic torque produced by ABC and RST winding sets can be obtained as (9) and (10), respectively.

$$T_{e_{ABC}} = 3 I_{S_{ABC} q} \lambda_{S_{ABC}} \tag{9}$$

$$T_{e_{RST}} = 6 I_{S_{RST} q} \lambda_{S_{RST}} \tag{10}$$

The electromagnetic produced by a DSWIM is the sum of the electromagnetic torques of its winding sets:

$$T_e = 3 I_{S_{ABC} q} \lambda_{S_{ABC}} + 6 I_{S_{RST} q} \lambda_{S_{RST}} \tag{11}$$

III. Proposed Control System

This section presents a direct flux and torque control system for a DSWIM. In this control system the torque and stator fluxes are compared with their command signals and passing the resultant errors through a controller, the reference d and q axis voltages are produced for a Voltage Source Inverter (VSI) feeding each winding set.

The proposed BELBIC based control system block-diagram is represented in Fig. 2. The torque and stator windings flux errors are fed to the BELBIC controllers as the input parameters. As illustrated, two BELBIC controllers are implemented for each winding set: one of which ($BELBIC_{Fi}$) produces V_{di}^{*} based on the i[th] winding flux error and the other ($BELBIC_{Ti}$) generates V_{qi}^{*} according to its torque error. The BELBIC controller will be discussed in details as follows.

A. BELBIC Controller

Recently, computational models of one of the human brain parts which is responsible for the emotional processing, has attracted the attention of many researchers. In this paper a structural model based on limbic system of mammalian brain and its emotional learning process is implemented for DSWIM drive. This controller has been designed based the amygdala computational model proposed by Moren and Balkenius. Indeed, amygdala is the brain part that is responsible for emotional processing and associated with sensory cortex, thalamus and orbitofrontal cortex [22]. Learning is done in amygdala and orbitofrontal cortex modifies the inappropriate responses of amygdala. The amygdala-orbitofrontal emotional learning response (MO) for control system input (SI) and emotional control signal (EC) is determined as (12):

$$MO = AO - OCO \tag{12}$$

Where, AO and OCO are:

$$AO = G_a .SI \tag{13}$$

$$OCO = G_{oc} .SI \tag{14}$$

The learning lows in amygdala and orbitofrontal cortex are as (15) and (16), respectively.

$$\Delta G_{a} = c_1 . \max(0, EC - AO) \geq 0 \tag{15}$$

$$\Delta G_{oc} = c_2 .(MO - EC) \tag{16}$$

The orbitofrontal gain can be positive or negative to be able to modify the inappropriate responses of amygdala. From equation (12) to (14) it is concluded that:

$$MO = (G_a - G_{oc}).SI \tag{17}$$

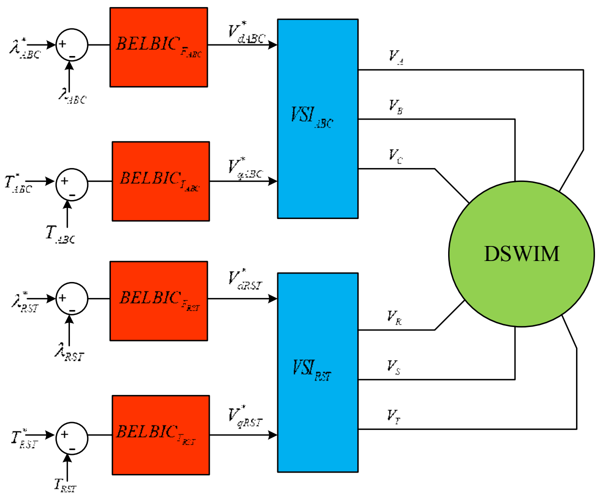


Fig. 2. Proposed Control System

Generally, the emotional control signal (EC) stands for the overall control system and closed loop control system performance. Accordingly, EC equals:

$$EC = \alpha.e + \beta.MO \tag{18}$$

The amygdala and orbitofrontal gains are determined as (19) and (20), respectively.

$$G_a(t) = \frac{c_1}{\Delta t}\int \max(0, EC(t) - AO(t))dt + G_a(0) \tag{19}$$

$$G_{oc}(t) = \frac{c_2}{\Delta t}\int (MO(t) - EC(t))dt + G_{oc}(0) \tag{20}$$

According to the above discussion and equations (12) to (20) the BELBIC controller block-diagram is as Fig. 3. It should be noted that in Fig. 3, c_1' and c_2' are defined as:

$$c_1' = \frac{c_1}{\Delta t} \tag{21}$$

$$c_2' = \frac{c_2}{\Delta t} \tag{22}$$

Along with the proposed controllers, the reference voltages are determined without utilizing conventional classical controllers such as PI, PID and etc. Moreover, these controllers are parameter and model independent and auto-learning. In addition, the control parameters are adaptive and they are specified independent of machine parameters variations.

IV. Simulation Results

The proposed control scheme is implemented on a DSWIM with the parameters tabulated in table I. In order to verify the performance of the applied BELBIC based control strategy in wide speed ranges, including zero, nominal positive and nominal negative speeds, the proposed motor drive system is simulated in MATLAB/SIMULINK environment. The simulation results are illustrated in Figs 4-7.

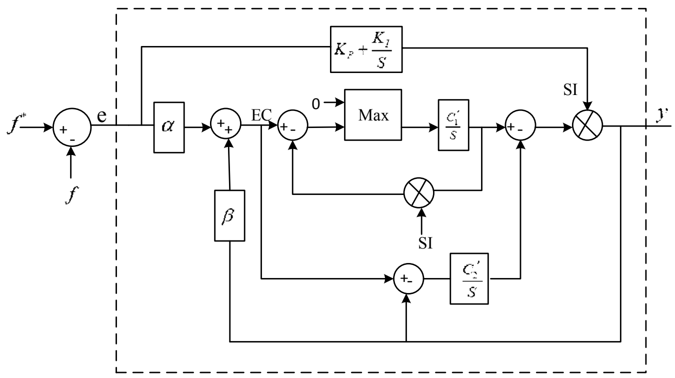


Fig. 3. BELBIC block-diagram

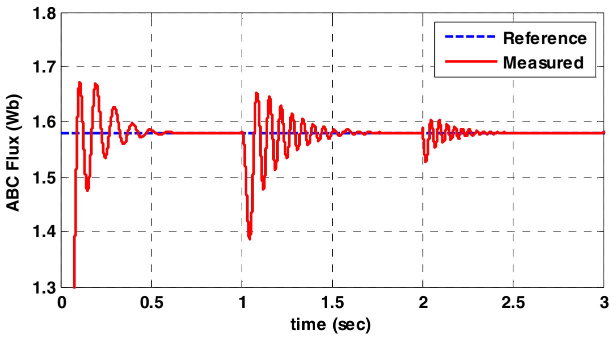
TABLE I. DSWIM Parameters Values

parameter	value	parameter	value
P_{ABC}	2	P_{RST}	6
R_{sABC}	3.4Ω	R_{sRST}	1.9Ω
R_{rABC}	0.61Ω	R_{rRST}	0.61Ω
L_{mABC}	0.336H	L_{mRST}	0.93H
L_{sABC}	0.342H	L_{sRST}	1.02H
L_{rABC}	0.342H	L_{rRST}	1.02H
ω_{sABC}	100π/3	ω_{sABC}	100π

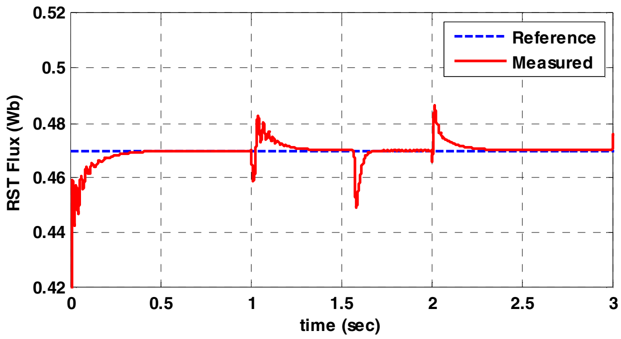
The flux references for ABC and RST winding sets are determined to obtain the desired torque with minimum stator current based on the Maximum Torque per Ampere (MTPA) strategy proposed in [1]. According to the simulated machine parameters the values of the stator fluxes are 1.58 and 0.47 wb for ABC and RST winding sets, respectively. Figs 4 (a) and (b) represents the flux produced by ABC and RST winding sets and their reference values. As it is clear, the produced fluxes follow their commands properly and there is no steady-state error.

The reference values for torques is specified such that the rotor speed follows its command accurately and the desired torque is shared between winding sets based on their nominal power ratio. Therefore, they won't be any overloaded. The torque sharing algorithm is shown in Fig. 5. As mentioned before, in zero and very low speed ranges one of the winding sets operates in generating mode and the other compensates for the load torque and generating winding. Accordingly, in the illustrated algorithm in speeds lower than 5 rpm the reference torque of RST winding set is negative and the other torque command is positive. As two winding sets have the same power ratings, both of them operate in motoring mode in other speed ranges and they have equal reference torques.

The rotor speed and its command signal is presented in Fig. 6(a). As shown, the speed appropriately follows its reference signal and the proposed control system functions properly in a wide speed region, ranging from nominal positive to nominal negative. Fig. 6(b) demonstrates the speed error. The maximum error which is 5 rpm, occurs when the operation mode of winding sets is changed and in the steady state operation the speed error cancels.



(a)



(b)

Fig. 4. Stator winding fluxes and their reference values;
a) ABC winding b) RST winding

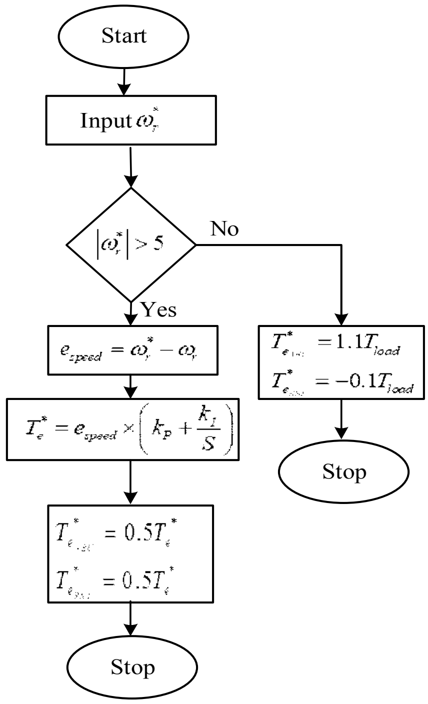
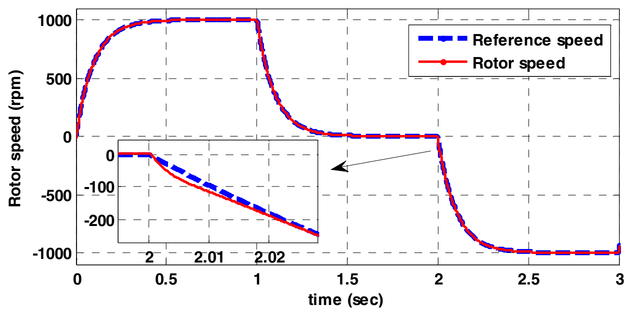
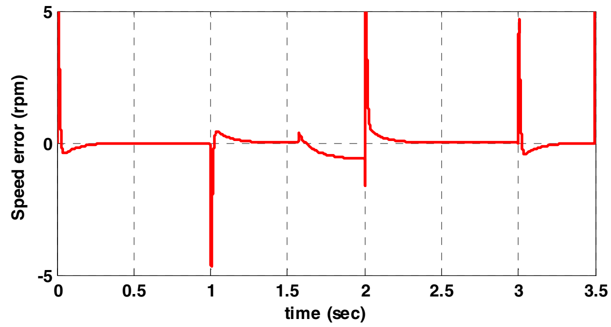


Fig 5. Torque sharing algorithm



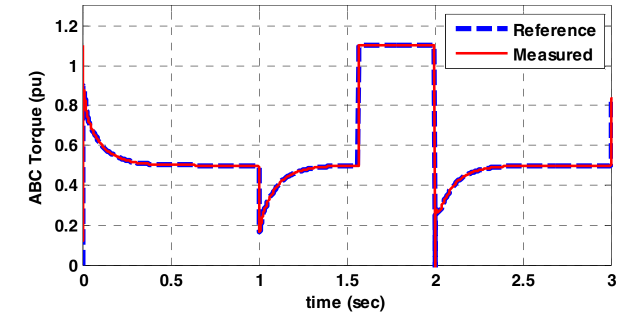
(a)



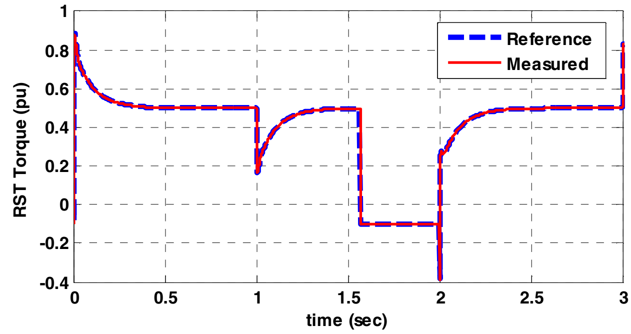
(b)

Fig 6. a) Rotor speed and its reference b) Speed error

Figs 7 (a) and (b) shows the electromagnetic torques produced by the ABC and RST winding sets respectively and their reference values. As illustrated, the electromagnetic torques are equal positive in high speed ranges and in zero speed range, lower than 5rpm, ABC winding operates in motoring and RST winding operates in generating mode.



(a)



(b)

Fig 7. Produced electromagnetic torques and their reference values; a) ABC winding b) RST winding

V. Conclusion

The electrical equivalent model of a DSWIM presented which consisted of two independent parts, each of them stand for a winding set. A direct torque and flux control system proposed for DSWIMs. This control system implemented four autonomous BELBICs for stator winding fluxes and torques to follow their commands. The flux references were determined to optimize the stator winding currents. The torque commands were dictated by a torque sharing algorithm guaranteeing the DSWIM wide speed operation. The applied BELBICs were discussed in details. Some simulations were done to evaluate the performance of the proposed control scheme. Simulation results confirmed that DSWIM drive system utilizing the proposed control strategy is able to operate in a wide speed range containing zero speed region and high speed regions in both directions. Besides, the stator fluxes were controlled properly.

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