VOL. 9, NO. 12, DECEMBER 2014 ISSN 1819-6608
ARPN Journal of Engineering and Applied Sciences
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PERFORMANCE ANALYSIS OF AN INTERIOR PERMANENT MAGNET SYNCHRONOUS MOTOR USING BRAIN EMOTIONAL LEARNING BASED INTELLIGENT CONTROLLER

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ABSTRACT

This paper presents a novel Brain Emotional Learning Based Intelligent Controller (BELBIC) for controlling some of the parameters, such as speed, torque, quadrature and direct axis current and voltage of an Interior Permanent Magnet Synchronous Motor (IPMSM). PI controllers are widely used as speed controllers in industries. IPMSMs are characterized as complex, highly non-linear and time-varying dynamics. Conventional PID controllers are unable to sustain satisfactory performance for IPMSM running at high speeds, where the non-linearity is severe. The paper introduces a simple arithmetical model of emotional controller for ease of its implementation in a closed loop drive system..Moreover, control commands such as Maximum Torque per Ampere (MTPA) control and flux weakening (FW) control as well as voltage and current constraints have been successfully applied. Proto type IPMSM drive incorporating the proposed BELBIC has been successfully implemented in real time a user friendly interface based on LabView is used for controlling the system. Performance of the emotional controller is compared with Antiwindup PIcontroller. The simulation and experimental results demonstrate the effectiveness of the controller during the conditions of starting, step change in speed and load perturbations.

Keywords: IPMSM, PWM, anti windup PI LabVIEW, BELBIC, embedded system.

INTRODUCTION

The traction motors in railway applications must be robust, compact and lightweight [1]. IPMSM possesses the characteristics of easy maintenance, good reliability, and high efficiency. IPMSM fed by PWM inverters are widely used for industrial applications, especially servo drive applications [2] such as traction and spindle drives. Many researchers' has analyzed the IPMSM drive system to enhance its performance. The PI controlled IPMSM drive is simple to design and control [3]. It results reduced steady-state error. However, it produces the poor performance in the case of the load disturbance. Fuzzy logic controller (FLC) improves the transient responses, load disturbance rejection capability, tracking ability, and robustness [4]. The control technique used has several disadvantages such as in fuzzy logic control, framing the rules is a complex task [5-6]. The IMC controller needs large mathematical models so the calculations are very difficult. In artificial neural network it will take more time for processing and taking the samples for iterations. But in BELBIC there is no need of framing rules. It needs only simple equation to determine the desired output [7]. It has less iterations and the processing time is very less. FLC output depends on proper selection of rules only. If no of rules increased, processing time is also increased.

However, these methods are complex to implement and very costly. Hence, it is essential to implement a simple, effective and low cost system

MATHEMATICAL MODEL OF IPMSM

The mathematical model of IPMSM is similar to that of wound rotor synchronous motor [8] - [9].

The equivalent circuits of IPMSM in the d and q axis are shown in Figures 1 and 2, respectively.

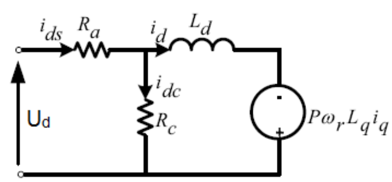

Figure-1. D axis equivalent circuit.

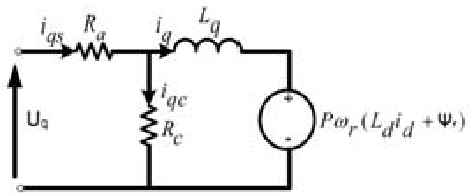

Figure-2. Q Axis equivalent circuit.

The following assumptions are made in the IPMSM modeling.

a) Saturation is neglected.
b) The induced EMF is sinusoidal.
c) Eddy currents and hysteresis losses are negligible.

With these assumptions, voltage equations are given by:

$$Vq = Riq + p\lambda q + P\omega r\lambda q + P\omega r\psi f \quad (1)$$

$$Vd = Rid + p\lambda d + P\omega r\lambda q \quad (2)$$

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The developed electric torque motor is being given by

$$Te = 3P/2\,[\psi f\, iq + (Ld - Lq)\, id\, iq] \quad (3)$$

The torque balance equation for the motor is given by

$$Te = Jm\, p\, \omega r + Bm\omega r + TL \quad (4)$$

Solving for the rotor speed from equation (4)

$$\omega r = \int [(Te - TL - Bm\omega r) / Jm]\, dt \quad (5)$$

where

Vd and Vq are the d, q axis voltages,
id ,iq are the d, q axis stator currents,
Ld, and Lq are the d, q axis inductances,
Ψd and Ψq are the d, q axis stator flux linkages,
Rs is the stator winding resistance per phase
P is the number of poles.
ωr is rotor electrical speed.
J is the moment of inertia.
p is the differential operator

Based on the above motor equations the IPMSM is modelled.

The simulation model of IPMSM and vector rotator shown in Figure-3 and Figure-4, respectively.

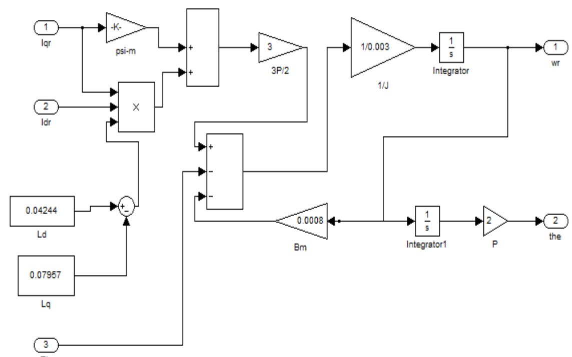

Figure-3. IPMSM Model.

A. Vector rotator

The dq0_to_abc transformation performs the reverse of the Park transformation, which is commonly used in three-phase electric machine models. It transforms three quantities expressed in a two-axis reference frame back to phase quantities.

$$I_a = I_q \cos\theta + I_d \sin\theta \quad (6)$$

$$I_b = I_q \cos(\theta - 2\pi/3) + I_d \sin(\theta - 2\pi/3) \quad (7)$$

$$I_c = I_q \cos(\theta + 2\pi/3) + I_d \sin(\theta + 2\pi/3 \quad (8)$$

where, Ia, Ib and Ic are stator currents.

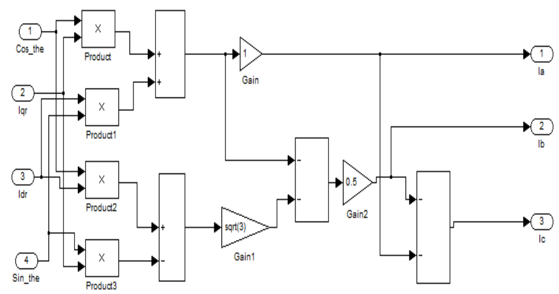

Figure-4. Vector rotator.

B. Current and voltage constraints

Considering the voltage and current constraints, the armature current Ia and the terminal voltage Va are limited as

$$Ia = \sqrt{(id2 + iq2)} \le Im \quad (9)$$

$$Va = \sqrt{(vd2 + vq2)} \le Vm \quad (10)$$

Below the base speed the absolute value of stator current Ia is maintained as constant at its maximum value Im. The id can be calculated in terms of iq for maximum torque per ampere control. This is obtained by equation (11)

$$id = \{ \psi/[2(Lq - Ld)] - \sqrt{[\psi 2/[4(Lq - Ld)2] + iq2]} \} \quad (11)$$

Above the base speed id can be calculated in terms of iq in order to maintain the stator voltage Va constant at its maximum value Vm.

$$id = \{[-\psi/Ld] + 1/Ld[\sqrt{[(Vm')2/(P2\omega r2) - (Lq2 - iq2)]}]\} \quad (12)$$

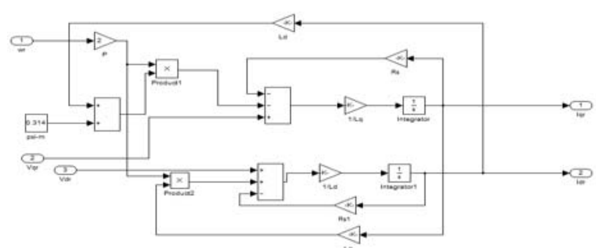

Figure-5. Current transformation.

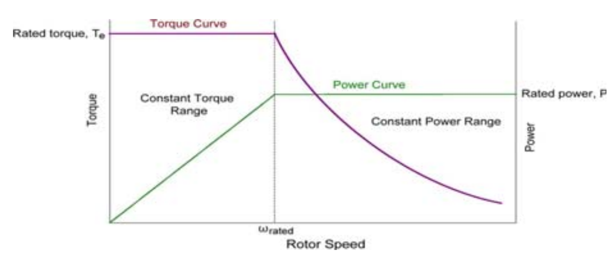

Figure-6. Torque and power curve in wide speed range.

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VECTOR CONTROL OF IPMSM DRIVE

Block diagram of IPMSM drive is shown in Figure-7; it is a dual loop control such as speed loop and current loop.

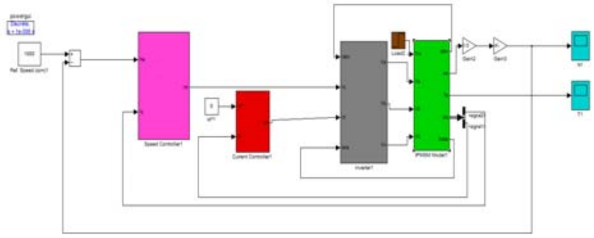

Figure-7. Simulation model of IPMSM Drive

The drive system consists of a proposed speed controller, hysteresis current controller, IGBT based voltage source inverter and IPMSM. Speed loop has three inputs such as reference speed, measured speed and iq. Error of reference speed and measured speed are processed in the proposed controller for each sampling interval. The output of the controller is considered as the quadrature axis reference current iq* which is given to current loop. Current loop has id*, id, iq and iq* as inputs. Output of speed controller is compared with the measured iq. This error signal produces iq reference, when it passes through PI controller. Inverse Park transformation receives the two reference current signals id* and iq* from speed loop and current loop and converts it into ia*, ib* and ic*. These currents are then compared with the actual motor currents ia, ib and ic to generate PWM signals, which will fire the IGBTs in the three phase inverter to produce the actual voltages to the motor. Based on the current speed of the motor, quadrature axis command current iq*is controlled thus voltage supplied to motor adjusted to achieve the command speed. Where id, iq are the d and q axis stator currents.

ANTI WINDUP PI CONTROLLER

To improve the stability of the IPMSM drive Anti windup PI Controller is proposed in this paper. AW PI tracking method has good tracking capability [10]. Main task of anti wind up method is to avoid over value of integration. AW PI is similar to PI controller except that the integral controller has a feedback from output. Feedback is difference of output signal from before and after saturation. Feedback gain is referred as F(s) =1/Kp. The block diagram of Anti windup PI controller is shown in Figure-8. With the effect of saturation, Anti windup PI controller improves the system performance by allowing it to operate in the linear region most of the time and recover quickly from nonlinearity.

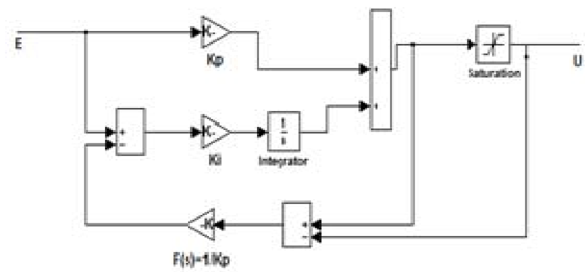

Figure-8. Block diagram of anti windup PI controller.

BELBIC CONTROLLER

BELBIC is based on the architecture of the "Limbic System" of the human brain [11]. The limbic system is responsible for the emotional learning in human beings. Figure-9 shows the simulation model of BELBIC.

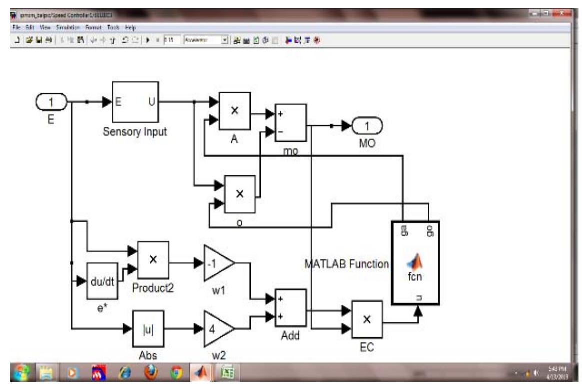

Figure-9. Simulation Model of BELBIC.

The main components of the limbic system are the amygdala, orbitofrontal cortex, thalamus and the sensory cortex. The amygdala can communicate with all other cortices within the limbic system. A simple limbic system of the brain is shown in Figure-10. Pre-processing on sensory input signals such as noise reduction or filtering can be done in Thalamus. Association with the stimulus and its emotional consequence take place in the amygdala. [12]. The task of the amygdala is to assign an emotional value to each stimulus that has been paired with a primary reinforcement signal. This task is aided by the orbitofrontal cortex [13]. In terms of learning theory, the amygdala performs to handle the presentation of primary reinforcement, while the orbitofrontal cortex is involved in the detection of omission of reinforcement. The mechanism behind the BELBIC is based on sensory inputs and emotional cues.

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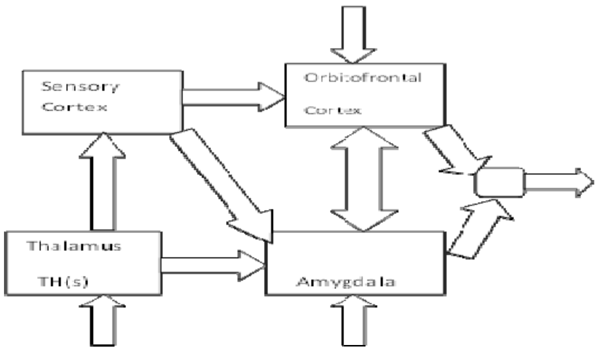

Figure-10. Limbic system of brain.

In the IPMS motor the speed error signals are taken as sensory inputs. Emotional cues are depends on the performance objectives, here the objective is to minimize the speed error. Sensory input signals are realized as a PI controller.

SI=K1.e+ k2 ∫e.dt (13)

Emotional cues are realized by the following equation

Ec= MO [w1 (e.é) +|e|.w2] (14)

where, k1,k2,w1,w2 are the gains to be tuned to get desired controller output.

MO is the model output of BELBIC, which is obtained by the equation 15.

$$MO = \sum A_i - \sum O_i \tag{15}$$

where A is sum of Amygdala's node output,

O is sum of Orbitofrontal Cortex node output are obtained by eqn 16 and 17 respectively.

Ai=ga.SI (16)

Oi=go.SI (17)

ga is the learning rate of amygdala connection and go is the controlling factor in orbitofrontal connection.

The amygdala and the orbit frontal cortex have a network-like structure; they have connection with each sensory input. Based on the above equations mathematical model of BELBIC is formed. Since BELBIC is purely formed by the arithmetic equations it is ease to implement and converges fast.

SIMULATION RESULTS AND DISCUSSIONS

IPMSM dive is simulated using MATLAB/Simulink. IPMSM dive is analyzed using Anti windup PI controller. Then the same system is analyzed with BELBIC. For the analysis load is changed during run time. Reference speed and load are same for all Anti windup PI controller and BELBIC. The results of IPMSM drive system using proposed Anti windup PI controller for 1000rpm speed is shown in Figure-11 and Figure-12.

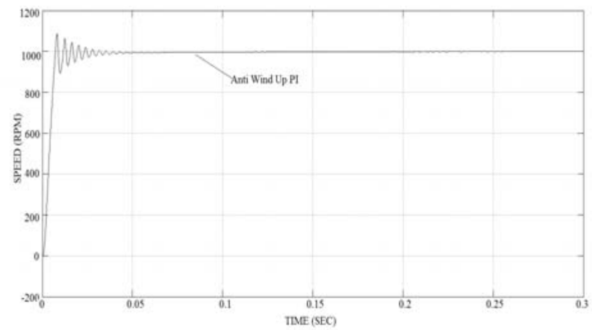

Figure-11. Anti windup PI controller speed response.

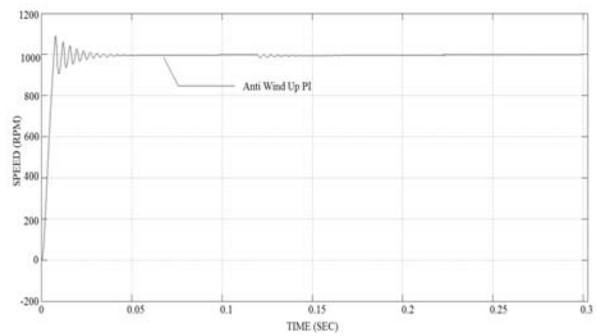

Figure-12. Speed response of IPMSM drive using Antiwindup PI controller with change in load.

The results of IPMSM drive system using proposed Anti windup PI controller for Torque is shown in Figure-13.

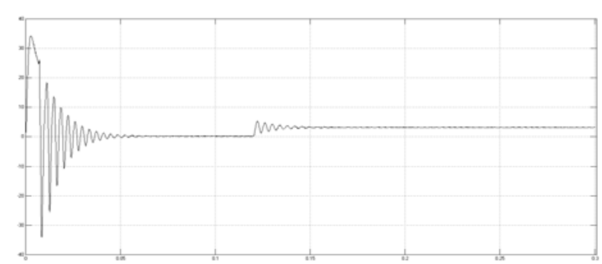

Figure-13. Torque response of IPMSM drive using Anti windup PI controller with change in load.

The results of IPMSM drive system using the proposed BELBIC controller for speed is shown in Figures 14 and 15.

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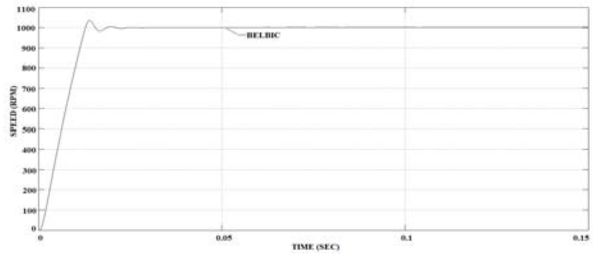

Figure-14. Speed response of IPMSM drive using BLEBIC.

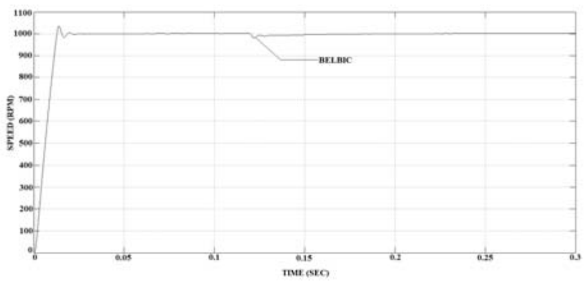

Figure-15. Speed response of IPMSM drive using BLEBIC with change in load.

Speed response of IPMSM drive using BLEBIC at various speed references such as rated speed, above rated speed and below rated speed is shown in Figure-16.

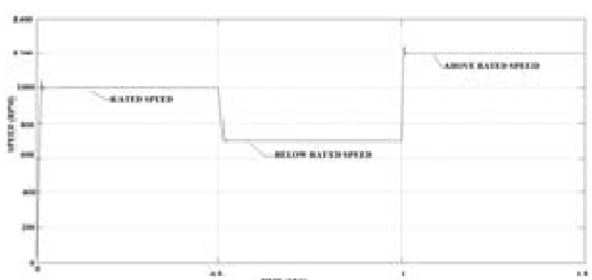

Figure-16. Speed response of IPMSM using BELBIC at various speed references.

Figure-17 and Figure-18 shows the Id and Iq response of IPMSM drive using BELBIC

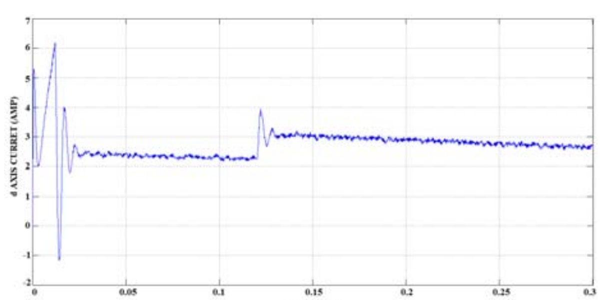

Figure-17. Id of IPMSM Drive Using BLEBIC at 1000rpm.

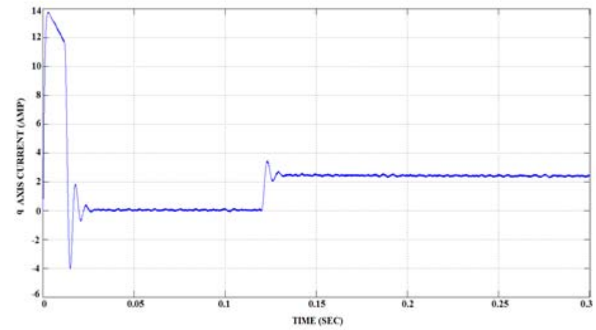

Figure-18. Iq of IPMSM Drive Using BLEBIC at 1000rpm.

The Id value varies with respect to speed reference to produce desired speed. The Iq value is maintained at zero irrespective of reference speed. It varies during transient period and settles back to zero during steady state.

EXPERIMENTAL RESULTS

Effectiveness of the proposed controller performance is analyzed using experiments to confirm the simulation result. An IPMSM of rating 41w, 24v, 1500 RPM is experimented using the 16F877A PIC microcontroller. It is a 40 Pin, enhanced flash-based 8-Bit CMOS Microcontrollers with NanoWatt Technology. It has a High performance RISC CPU makes programming simple. BELBIC algorithm is programmed in PIC. It is built with the PWM module produces triggering pulses for the inverter as per BELBIC program. The hex bridge inverter is designed with MOSFETs. The speed of the machine is sensed using an inductive proximity sensor. The USART port in microcontroller supports the communication with the computer. A computer customized program is developed using LabVIEW. VISA tool in LabVIEW software is used to interface with PC instead of DAQ card. It minimizes the cost of hardware. The experimental setup of IPMSM drive is shown in Figure-19. The power and control circuit of the BELBIC based IPMSM drive is portrayed in Figures 20 and 21. The Labview program and results are illustrated in Figures 22 and 23, respectively.

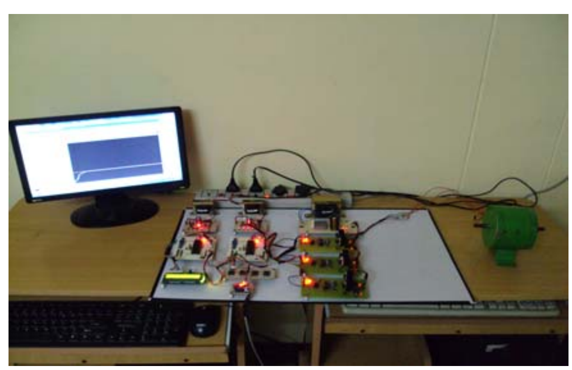

Figure-19. Image of experimental setup.

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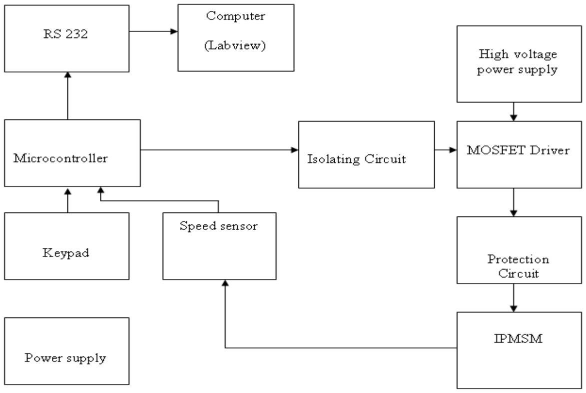

Figure-20. Block diagram of controller unit.

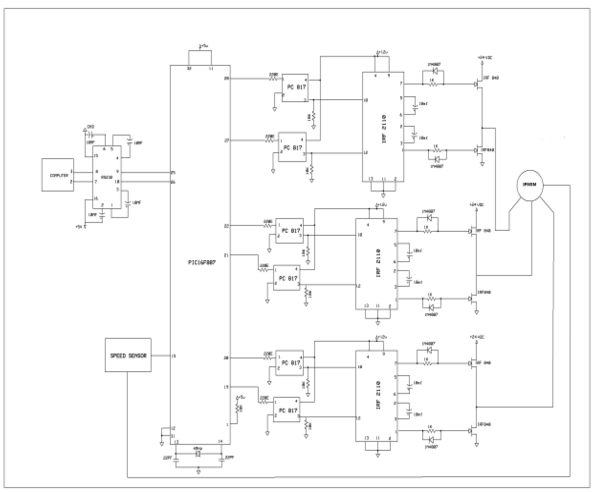

Figure-21. Circuit diagram.

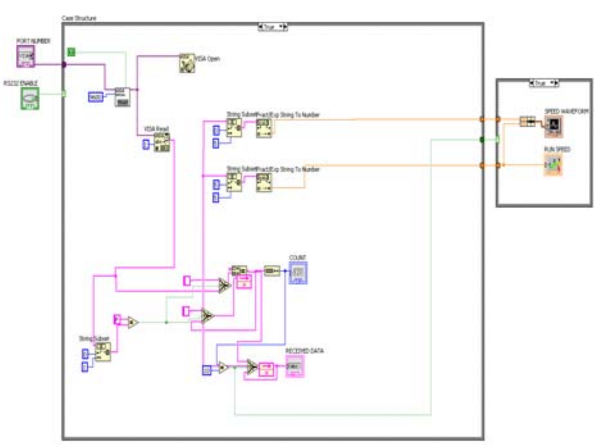

Figure-22. LabVIEW front panel diagram.

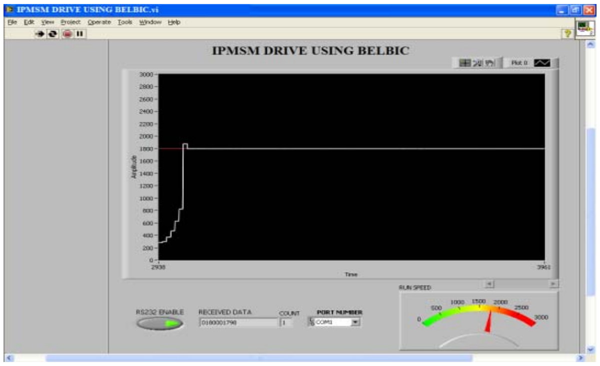

Figure-23. Speed performance at 1800 RPM.

The performance of Anti windup controller for various speeds is tabulated in Table-1 the performance of simulation results of IPMSM drive using BELBIC with various speed and load is tabulated in Table-2. Experimental results of prototype IPMSM drive using BELBIC is tabulated in Table-3.

Table-1. Anti windup controller Performance.

Speed (rpm)	**Peak over shoot** (%)	**Steady state error** (%)	**Rise** time (s)	**Peak** time (s)	**Settling** time (s)
800	12.25	0.313	0.00070	0.00081	0.0087
1000	8.9	0.4	0.00703	0.00795	0.009
1200	6.62	0.333	0.00072	0.00078	0.0057
1500	4.55	0.467	0.00077	0.00083	0.0035
1800	3.03	0.44	0.00087	0.00092	0.003

Table-2. Performance of BLEBIC-Simulation Results.

Speed (rpm)	**Peak over shoot** (%)	**Steady state error** (%)	**Rise time** (s)	**Peak time** (s)	**Settling** time (s)
800	4.86	0.125	0.01	0.0112	0.036
1000	2.75	0.1	0.0159	0.0171	0.028
1200	1.8	0.01	0.0123	0.0225	0.04
1800	1.05	0.04	0.0279	0.0292	0.042

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Table-3. Performance of BLEBIC-Experimental results.

Speed (rpm)	**Peak over shoot** (%)	**Steady state error** (%)	**Rise time** (s)	**Peak time** (s)	**Settlin g time** (s)
800	5.1	0.15	0.014	0.013	0.04
1000	3	0.12	0.017	0.019	0.03
1200	1.9	0.01	0.015	0.024	0.055
1800	1.2	0.05	0.029	0.03	0.058

CONCLUSIONS

The essential characteristics of traction motors are accurate speed and stability during load change. From the simulation and experimental results, it is clear that the BELBIC has the ability to control the nonlinear dynamic systems. The BLEBIC controller improves the speed response compared to Anti windup PI controller in terms of the overshoot, steady state error, insensitive to parameter variations and less restoration time. The BLEBIC controller based IPMSM drive is suitable for traction to operate in a wide speed range and frequent load changing condition.

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