Practical Swarm Intelligent Control Brushless DC Motor Drive System using GSM Technology

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Abstract: - Sending written text messages are extremely popular among mobile phone users. Instant messaging allows quick transmission of short messages that allow an individual to share ideas, opinions and other relevant information. In this paper the same concept to design a system that acts a platform to receive messages is used. The designed control system which is based on the GSM technology allows control from a remote area to the desired location. The mathematical model and the design of PID speed controller for the brushless DC motor drive system are presented. A Practical Swarm Optimisation (PSO) algorithm is employed in order to obtain the controller parameters assuring enhanced step response performance criterion. Simulation results of the designed controllers are compared with that of classical controllers whose parameters are adjusted using Ziegler-Nichols technique. Results signify the superiority of the proposed technique over the classical method. The overall system is implemented and tested. The experimental results illustrate that the proposed system allows a greater degree of freedom to control and monitor the electric drive systems of a certain location is eliminated.

Key-Words: - GSM Technology, Brushless DC Motor, PID control, Practical Swarm Optimisation (PSO)

1 Introduction

Brushless Direct Current (BLDC) motors are one of the motor types which are gaining extraordinary reputation. BLDC motors are used in industries such as Appliances, Automotive, Aerospace, Consumer, Medical, Industrial Automation Equipment and Instrumentation. As the name indicates, BLDC motors do not use brushes for commutation; instead, they are electronically commutated. BLDC motors have many advantages over brushed DC motors and induction motors [1-3]. A few of these are [4]:

- Better speed versus torque characteristics
- High dynamic response
- High efficiency
- Long operating life
- Noiseless operation
- Higher speed ranges

In addition, the ratio of torque delivered to the size of the motor is higher, making it useful in applications where space and weight are significant factors.

The common communication technologies used today are SMS [5], WAP, MMS, GPRS, 3-G. Nokia grants a policy for wireless communication. The machine-to-machine, mobile-to-machine and machine-to-mobile (M2M) policy comprises hardware and software to employ wireless communication. Recently, the cost of log on to public wireless data networks has been reducing while the capabilities of these networks remain to increase. Wireless cellular networks have been highly developed in the last decades. The evolution of these networks moved from the 2G Global System for Mobile Communication (GSM), to 3G Networks. 3G Networks depend on Code Division Multiple Access technology (CDMA), and can provide high data rates. These Mobile networks are promising to provide flexibility, speed, and low cost. One of the major applications of mobile networks is remote monitoring systems. A system can be monitored by sending text massage (information) through these networks.

Short Message Service of GSM [6] is a value-added communication service based on data packet switching offered by mobile communication company using GSM network in addition to all types of telecommunication services and bearer services based on circuit-switching. GSM has some capabilities such as two-way data transmission function, stable performance and can be interfaced with microcontroller via RS232 adaptor. GSM network provides a strong platform for remote data transmission and monitoring the communication between equipments and it is an important method of wireless remote monitoring system [7].

Mobile phone users are sending written text messages regularly. Instant messaging, as it is also known, allows quick broadcast of short messages that permit an individual to share ideas, opinions and other related information [8-12]. In this paper the same concept is used to design a system that acts as a platform to receive messages. In fact, these messages are commands sent to control the speed of BMDC motor drive system. The designed control system is based on the GSM technology that effectively allows control from a remote area to the desired location.

Despite the rapid development of control theory during the last four decades, the majority of control systems in the world are operated by proportional-integral-derivative (PID) controllers. The proportional-integral-derivative (PID) controller is well documented in the literature since the classic Ziegler-Nichols method [13] was presented. This is because PID controller is simple, robust and well understood. To accommodate the high performance requirement of the modern industry, optimization of the PID parameters is so extensively studied, and many different tuning criteria and procedures have been proposed, or for example, decay ratio method [14], gain and phase margin method [15] and the internal model control (IMC) based PID tuning method [16, 17]. Recently, with the popularity of the interior point algorithm several PID design methods based on Linear Matrix Inequality (LMI) were proposed for the continuous-time systems [18, 19]. PID parameters tuning with state –feedback linear quadratic regulator (LQR) is given in [20].

In this paper a robust speed controller design method for PMBLDCM drive system is introduced. A simple algorithm is implemented to tune the parameters of PID. To measure the quality of system dynamic performance; the maximum overshoot performance index, settling time, rise time and steady state are minimized within the tuning procedure. This mini-max optimization problem is solved using Particle Swarm Approach. The designed algorithm is compared with the Ziegler-Nichols tuning technique.

This paper is organized as follows: Section 2 presents the BLDCM mathematical model. The problem formulation of the proposed system and the design of the PID speed controller are given in section 3. Results include simulation and experimental setup of the proposed system is established in section 4 and conclusions and system superior merits are introduced in section 5.

2 BLDCM Mathematical Model

The mathematical model of BLDCM drive is given in [4]. During two-phase conduction, the entire dc voltage is applied to the two-phases having an impedance of:

$$Z = 2[R_s + \frac{d}{dt}(L - M)] = R_a + \frac{dL_a}{dt} \tag{1}$$

where

R_s : stator resistance per phase.

L : self inductance per phase.

M : mutual inductance per phase.

$$R_a = 2R_s \qquad \text{and} \qquad L_a = 2(L - M) \tag{2}$$

The stator voltage equation is given by:

$$v_s = (R_a + \frac{dL_a}{dt})\, i_s + e_{as} - e_{cs} \tag{3}$$

Where the last two terms are back emfs in phases *a* and *c* respectively. During regular operation of the drive system, the back emfs are equal and opposite in direction therefore the back emfs are given by:

$$e_{as} = -e_{cs} = \phi_p\, \omega_m \tag{4}$$

Substitute by Eq.(4) on Eq.(3) the stator voltage become:

$$v_s = (R_a + \frac{dL_a}{dt})\, i_s + 2\phi_p\, \omega_m \tag{5}$$

The back emf constant for both phases can be written as:

$$K_b = 2\phi_p \tag{6}$$

then, the stator voltage in Eq.(5) become:

$$v_s = (R_a + \frac{dL_a}{dt})\, i_s + K_b\, \omega_m \tag{7}$$

The electromagnetic torque for two-phases is given by:

$$T_e = 2\phi_p\, i_s = K_b\, i_s \tag{8}$$

The electromechanical equation of the BLDCM is:

$$T_e - T_L = J\,\frac{d\omega_m}{dt} + B\,\omega_m \qquad (9)$$

The load torque is proportional to the motor speed, so it can be represented by:

$$T_L = K_T\,\omega_m \qquad (10)$$

Therefore, Eq.(9) can be rewritten as:

$$T_e - K_T\,\omega_m = J\,\frac{d\omega_m}{dt} + B\,\omega_m \qquad (11)$$

where:

R_s	: stator resistance per phase.
L	: self inductance per phase.
M	: mutual inductance per phase.
ϕ_p	: flux linkage per phase.
ω_m	: rotor speed.
v_s	: stator voltage.
i_s	: staor current.
T_e	: electromagnetic torque.
T_L	: load torque.
K_T	: load torque constant.
K_b	: flux constant (volt/rad/sec).
B	: motor friction.
J	: moment of inertia of BLDCM.

3 Problem Formulation

The objective of this paper is to develop a user-device that allows remotely to control and monitor BLDCM drive system using a smart phone. This system will be a powerful and flexible tool that will offer this assistance at any time, and from anywhere with the constraints of the technologies being used. The proposed approach for designing this system is to employ a microcontroller-based control module that receives its instructions and command from a smart phone over the GSM network. The microcontroller then will carry out the issued commands, do the control algorithm and then communicate the status of BLDCM back to the smart phone. The overall block diagram of the proposed system is given in Fig. 1.

The designed system has two major tasks. The first task is to monitor the BLDC motor current and the temperature. The feedback signals measured from the sensors connected to the motor is feed to the microcontroller to decide if these values are within the rated accepted value or not. If it is more than the accepted value a warning signal is given and displayed by the smart phone with the present values. The processor will wait for 1 min, if it is still increasing operation shutdown warning message is given to the smart phone and wait for a decision command from the operator via the smart phone. If nothing is received by the microcontroller within a certain period of time, a shutdown signal is given to the motor for protecting it from further degradation.

The second task is to control the speed of the BLDC motor. The speed command is given by the operator via the smart phone. The microcontroller receives both the command coming from the smart phone and the feedback signal from the speed sensor. The PID controller is designed using PSO-algorithm OFF-line by MATLAB Software package. These parameters are selecting to tune and optimize four control terms; percent overshoot (M_p), settling time (t_s), rise time (t_r) and steady state error (E_{ss}). These controller parameters are used in implementing the C-language PID controller and then downloaded into the microcontroller. The microcontroller fed the derivers of the DC-DC converter by the proper period pulses. The feedback speed signal is also monitored by the system. When the command speed is executed by the system and the BLDC motor is running by this speed a confirmation message is sent for verification to the smart phone.

3.1 Design PID Speed Control Loop

The block diagram of the speed control loop of PMBLDCM drive system is given in Fig. 2.

The BLDCM contains three inner loops creating a complexity in the development of the model. Mason’s rule is used to reduce the block diagram as shown in Fig. 3.

$$G_{sys} = \frac{\omega_m(s)}{I^*{}_s(s)} = \frac{P}{1 + (L_1 + L_2 + L_3) + L_1\,L_2} \qquad (12)$$

where the forward path ,loop gins are respectively given as ,

$$P = \frac{k_p\,K_r\,K_b\,(1 + T_i\,s)}{T_i\,s\,(1 + T_r\,s)\,(R_a + L_a\,s)\,(B + J\,s)} \qquad (13)$$

$$L_1 = -\frac{k_p\,K_r\,K_c\,(1 + T_i\,s)}{T_i\,s\,(1 + T_r\,s)\,(R_a + L_a\,s)\,(1 + T_c\,s)} \qquad (14)$$

$$L_2 = -\frac{K_T}{(B + J\,s)} \qquad (15)$$

$$L_3 = -\frac{K_b^2}{(R_a + L_a\, s)(B + J\, s)} \tag{16}$$

The open loop transfer function of the speed control loop is:

$$G_{speed\_openloop} = \frac{k_{p_{PID}}\, P\, K_w\, (T_{i_{PID}}\, T_{D_{PID}}\, s^2 + T_{i_{PID}}\, s + 1)}{T_{i_{PID}}\, s\,(1 + (L_1 + L_2 + L_3) + L_1\, L_2)(1 + T_w\, s)} \tag{17}$$

where,

K_w : Gain of speed transducer.
T_w : Time constant of speed transducer.
$k_{p_{PID}}, T_{i_{PID}}, T_{D_{PID}}$: Parameters of the PID controller.

To assess the quality of system dynamic performance the maximum overshoot performance index, settling time, rise time and steady state error are to be minimized within the tuning procedure. This mini-max optimization problem is solved using PSO given next.

3.2 Mini-max Optimization Problem for Speed Control Loop

Problem: Given the system in Fig. 3, find PID parameters with minimum overshoot, settling time, and rise time

$$u = G_{PID}(s) \cdot (\omega_m^* - \omega_m),$$

$$G_{PID}(s) = k_{p_{PID}} \left[\frac{T_{i_{PID}} T_{D_{PID}} s^2 + T_{i\,PID}\, s + 1}{T_{i_{PID}}\, s} \right] \tag{18}$$

The tuning of the PID controller parameters can be done by using PSO. The evolutional computing tools give optimal solution. To have a well designed controller based on tuned parameters, four control terms have to be optimized. These terms are; percent overshoot (M_p), settling time (t_s), rise time (t_r) and steady state error (E_{ss}). The optimization function is given by:

$$\underset{k_{PID}, T_{D_{PID}}, T_{i_{PID}}}{Minimize}\; f(k_{PID}, T_{D_{PID}}, T_{i_{PID}}) = (1 - e^{-\beta})(M_p + E_{ss}) + e^{-\beta}(t_s - t_r) \tag{19}$$

where β is a weighting factor ($\beta < 0.7$ to reduce t_s and t_r and $\beta > 0.7$ to reduce M_p and E_{ss}). The BFO fitness function (J) is the reciprocal of the optimization function given by Eq. (19).

3.3 PID Speed Control Design via Swarm Optimization

The PSO is one of the techniques of evolutionary approach for optimization. Such approach is biologically inspired and is based on the natural evolution of populations to Darwin's principle of natural selection "Survival of the fittest". PSO is a novel optimization method [21]. It is a multi agent search technique that traces its evaluation to the emergent motion of a flock of birds (agent, particle) searching for food. Each bird traverses to the search space looking for the global minimum (or maximum). The PSO technique is computationally simple since it does not require gradient calculations. The function to be optimized does not have to be convex. It is a stochastic optimization technique with large number of agents, so it is unlikely to be trapped at a local minimum.

While the agents in the PSO algorithm are searching the space, each agent remembers two positions. The first is the position of the best point the agent has found (self-best). The second one is the position of the best point found among all agents (group-best). The equations that govern the motion of each agent are,

$$\vec{S}_{new} = [\vec{S} + \vec{v}]_{old}$$

$$\vec{v}\big|_{new} = [\omega \vec{v} + a\, r(0,1)(\vec{S}_{self-best} - \vec{S}) + b\, r(0,1)(\vec{S}_{group-best} - \vec{S})]_{old} \tag{20}$$

where ($\vec{S}$) is a position vector of a single particle, ($\vec{v}$) is the velocity of this particle, (a, b) are two scalar parameters of the algorithm, (ω) is an inertia weight, $r(0,1)$ is a uniform random number between 0 and 1, group-best is the best solution of all particles and self-best is the best solution observed by the current particle. A maximum velocity ($v_{\max}$) that cannot be exceeded may also be imposed.

The parameters of the PID controller are tuned using PSO by minimizing Eq. (19). To reach the optimization goal, proper adjustment of the PSO parameters is needed [21-24]. Table 1 shows the parameters of PSO that provide best results.

Table 1: PSO-PID speed controller design parameters.

No. of swarm birds (particles)	30
Particle dimension	3 ($k_{p\,PID}, T_{i_{PID}}, T_{D_{PID}}$)
Max. particle speed, v_{max}	0.065
ω, a, b	0.65, 0.47, 0.53

The parameters $k_{p_{PID}}, T_{i_{PID}}$ and $T_{D_{PID}}$ of the PID controller are randomly initialized. Figure 4 shows the global best value of the optimization function vs. iteration. The optiimisarion problem is achieved in 24 iterations.

The resulting PID controller is:

$$G_{PID}(s) = 4.324\ \frac{(0.01402\, s^2 + 0.0572\, s + 1)}{0.0572\, s} \qquad (21)$$

The results showing the merits of the PID controller with minimal overshoot, settling time, rise time and steady state error designed by PSO is given in the next section.

4. Results

The PSO-PID speed controller parameters are designed off-line using MATLAB software package. To have a well designed controller based on tuned parameters; four control terms have to be optimized. These terms are; percent overshoot (M_p), settling time (t_s), rise time (t_r) and steady state error (E_{ss}). The optimization function is given in Eq. (19). To verify the capability of the proposed controller, it has been designed with the will known Ziegler-Nichols tuned technique. The transfer function of PID speed controller Ziegler-Nichols is given by:

$$G_{PID\_Ziegler} = 156\ \frac{(314.3x10^{-6}\, s^2 + 3.54x10^{-3}\, s + 1)}{3.54x10^{-3}\, s} \qquad (22)$$

Simulation and experimental results of the PSO-PID controller are compared with that of classical controller whose parameters are adjusted using Ziegler-Nichols technique. Results of system performance which validate the proposed technique and highlight its practicability are given in the next subsections.

4.1 Simulation Results

The PID speed controller for the BLDC motor drive system is designed off-line using PSO. The PSO algorithm is achieved by using MATLAB software. The PSO optimize the controller parameters ($k_{p\,PID}, T_{i_{PID}}, T_{D_{PID}}$) to enhance the controller response. Hence, the maximum degree of system stability is obtained by solving the minimize optimization problem via PSO. The proposed PID controller is compared with the conventional PID controller tuned by Ziegler-Nichols technique. A comparison between the proposed and classical technique is presented in Fig. (5). The control parameters of the two PID controllers with PSO and Ziegler-Nichols for BLDCM drive system are given in Eq. (21 and 22) respectively. The output voltage controller step response performance parameters for BLDCM drive system (M_p, t_r, t_s, and E_{ss}) are shown in Table 2.

Table (2): A comparison between PSO and Ziegler and Nichols PID-parameters

Type of PID Controller	**M_p (percent overshoot)**	**tr (rise time)**	**ts (settling time)**	**E ss (steady state error)**
Ziegler-Nichols	38 %	0.036 sec	0.23 sec	0.142 %
PSO	0 %	0.045 sec	0.063sec	0.0023%

In Fig. 6, the system is tested by applying multi step responses. At t= 0 sec a speed step response from 0% to 100% of the speed, at t= 1 sec another speed step response is applied from 100% to 50% of the speed, and at t= 2sec a step response is employed from 50% to 100% of the speed.

Through the two simulations tests, Results signify the superiority of the proposed technique via PSO over the classical method using Ziegler-Nichols technique.

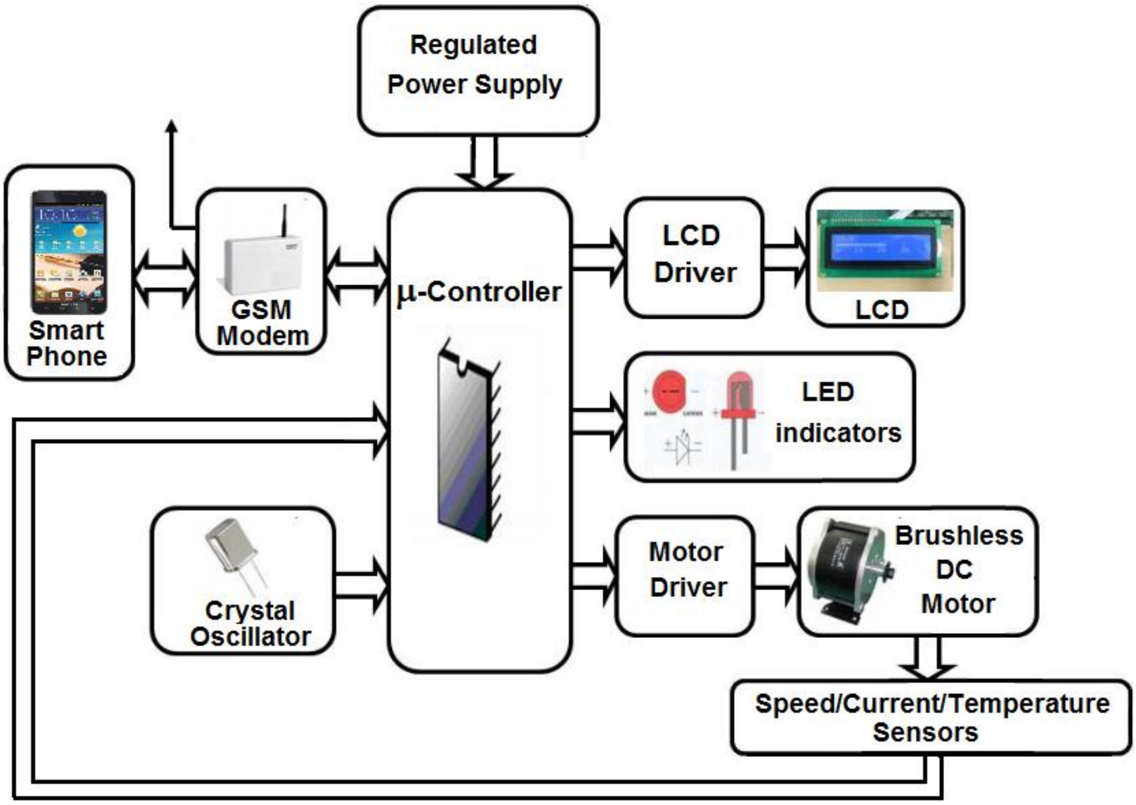


Fig. 1. The overall Block diagram of the proposed system.

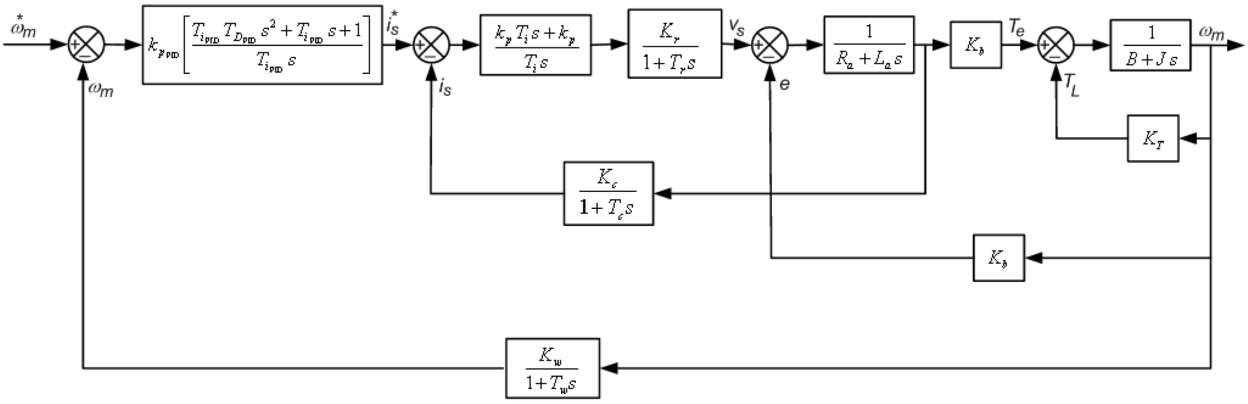


Fig. 2. Block diagram of the speed control loop for PMBLDCM.

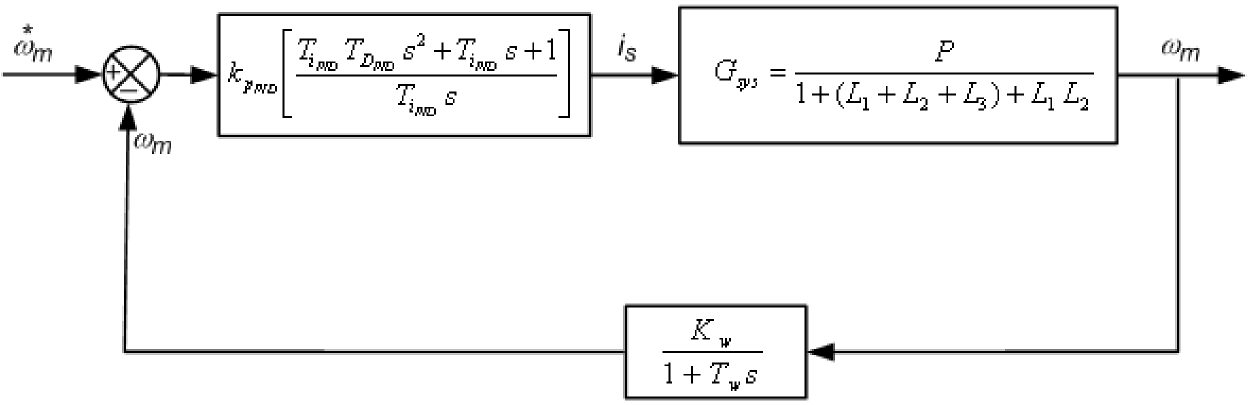


Fig. 3. Reduced block diagram of the speed control loop for PMBLDCM.

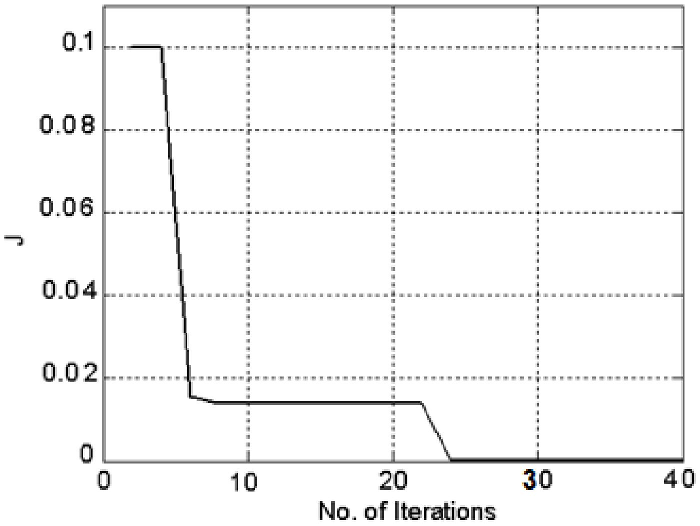


Fig. 4: Objective function global best values vs. iterations for PID controller.

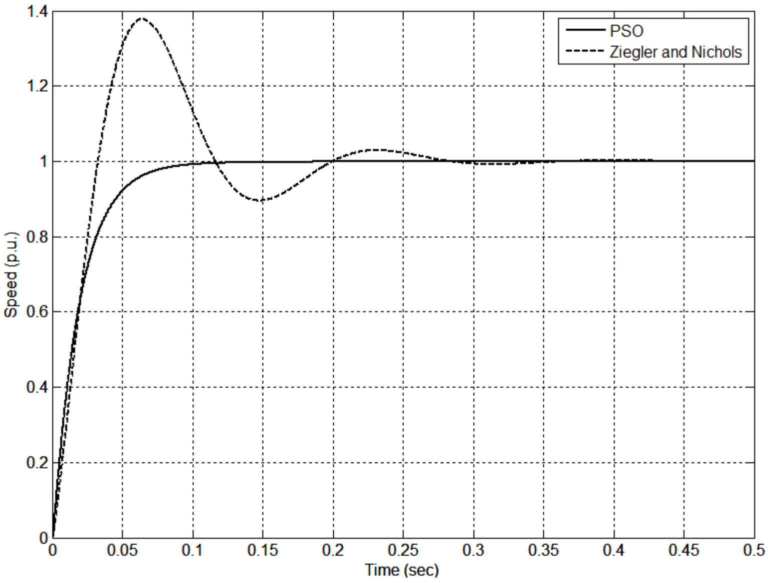


Fig. 5. A step response for the speed PID controller using PSO and Ziegler-Nichols techniques.

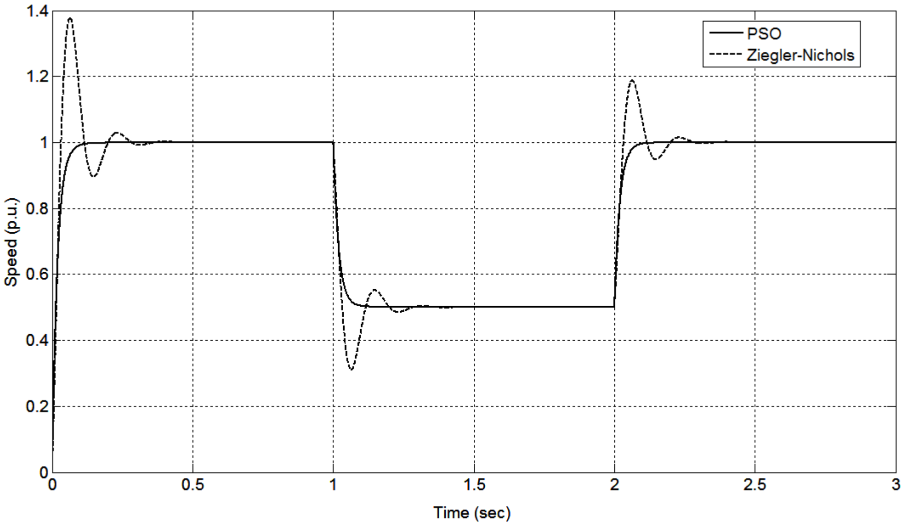


Fig. 6. A multi step response for the speed PID controller using PSO and Ziegler-Nichols techniques.

4.2 Experimental Results

The GSM system has been selected as the communication medium. The main issue to select GSM system is the worldwide recognition of the system. The GSM is wireless system. It helps the system to be used in area where wiring is impossible or for temporary/field usage. It offers high speed wireless communication. It is connected to the data adaptor RS232. Through the RS232, it can be connected to a personal computer or a microcontroller. The PMBLDCM drive, converter and transducers parameters are given in Tables 3 and 4.

The GSM modem is used as short message server (SMS) device. It can send and receive messages containing 160 characters. It supports call forwarding, call transfer, multiparty calling and security options such as call barring. In this application, the GSM modem is interfaced with the PIC18F4420 microcontroller via RS232 adaptor [10]. The modem receives a message from a mobile phone as an SMS that contains the speed command of the BLDCM. It will then transmit the information to the microcontroller via RS232 serial interface. This information is then stored in the built-in Flash memory of microcontroller. The microcontroller in-turn sends the information to the GSM modem after the BLDCM reaches the desired speed by the aid of PID controller. This information is sent as reply through an SMS to the mobile phone.

PIC18F4420 is an 8-bit microcontroller that has built-in 13 channels A/D converter module with 10-bit resolution [11]. The built-in Flash memory is used to host the embedded software algorithm that takes care of the parameters acquisition, processing, transmitting and receiving. The RS232 is utilized for the GSM modem communication to upload and download messages that contain the speed command of the BLDCM drive system.

The experimental setup of the proposed system is given in Fig. 7. In the designed system, BLDCM parameters can also be monitored and the data is send to the mobile and a LCD screen. The speed, current and temperature are the parameters are selected to be monitored in the designed system. Fig. 8. Shows the parameter selected to be monitored in the LCD screen when the command speed is executed by the microcontroller.

The layout of the hardware of the proposed system is given in Fig. 9. The overall software algorithm of designed C-program which is downloaded into the microcontroller is illustrated in Fig. 10. The on/off pulses generated by the microcontroller for different speed commands are illustrated in Fig. 11. The on/off pulses for 15%, 30%, 50% and 80% of the rated speed (450, 900, 1500, 2400 rpm) is given in Fig. 11 (a, b, c and d) respectively. A step change of the speed commands from 0rpm to 2400rpm and back to 0rpm is given in Fig. 12and 13. In Fig. 12, step change on the motor speed command of the PSO-PID speed controller is applied and in Fig. 13, Step change on the motor speed command of the Zeigler-Nichols-PID speed controller is employed. It is clear shown that the proposed PID controller is follow the speed command precisely optimizing the four control terms; percent overshoot (M_p), settling time (t_s), rise time (t_r) and steady state error (E_{ss}). Moreover, the experimental results illustrate that the proposed system allows a greater degree of freedom to control and monitor the BLDCM drive systems of a certain location is eliminated.

Table 3: The PMBLDCM drive parameters.

Power	1.2 kW
Current	7.5 A
Voltage	160 V
Torque	3 N.m
Phase resistance (R_a)	1.9 Ω
Phase inductance (L_a)	1.24 mH
Moment of inertia (J)	0.00035 kg m^2
Motor friction (B)	0.00323 N.m/rad/sec
EMF constant (K_b)	0.358 Vs

Table 4: converter and transducers parameters.

Converter gain (K_r)	16 V/V
Converter time constant (T_r)	50 µs
Current transducer gain (K_c)	0.288 V/A
Current transducer time constant (T_c)	0.159 ms
Speed transducer gain (K_w)	0.0239 Vs
Speed transducer time constant (T_w)	1ms

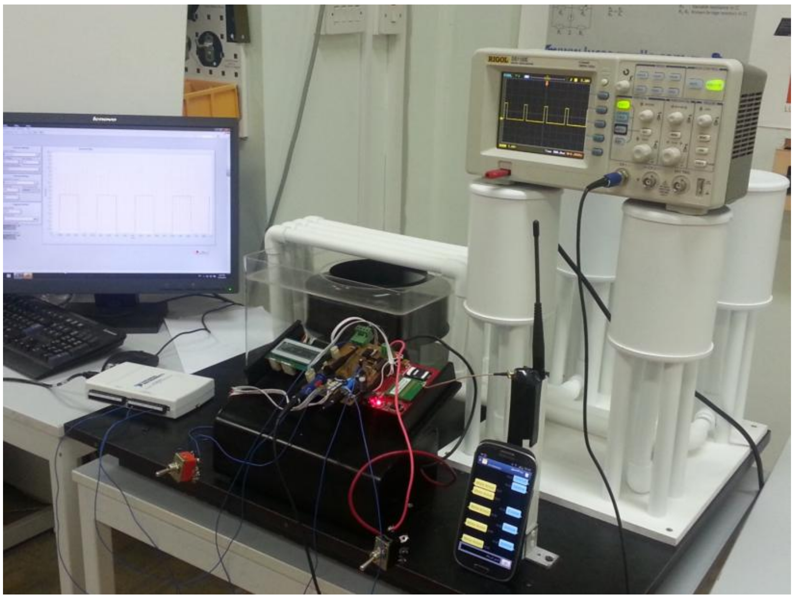


Fig.7. Experimental setup of the proposed system.

Fig.8. The motor parameters read by the system after the command speed is executed.

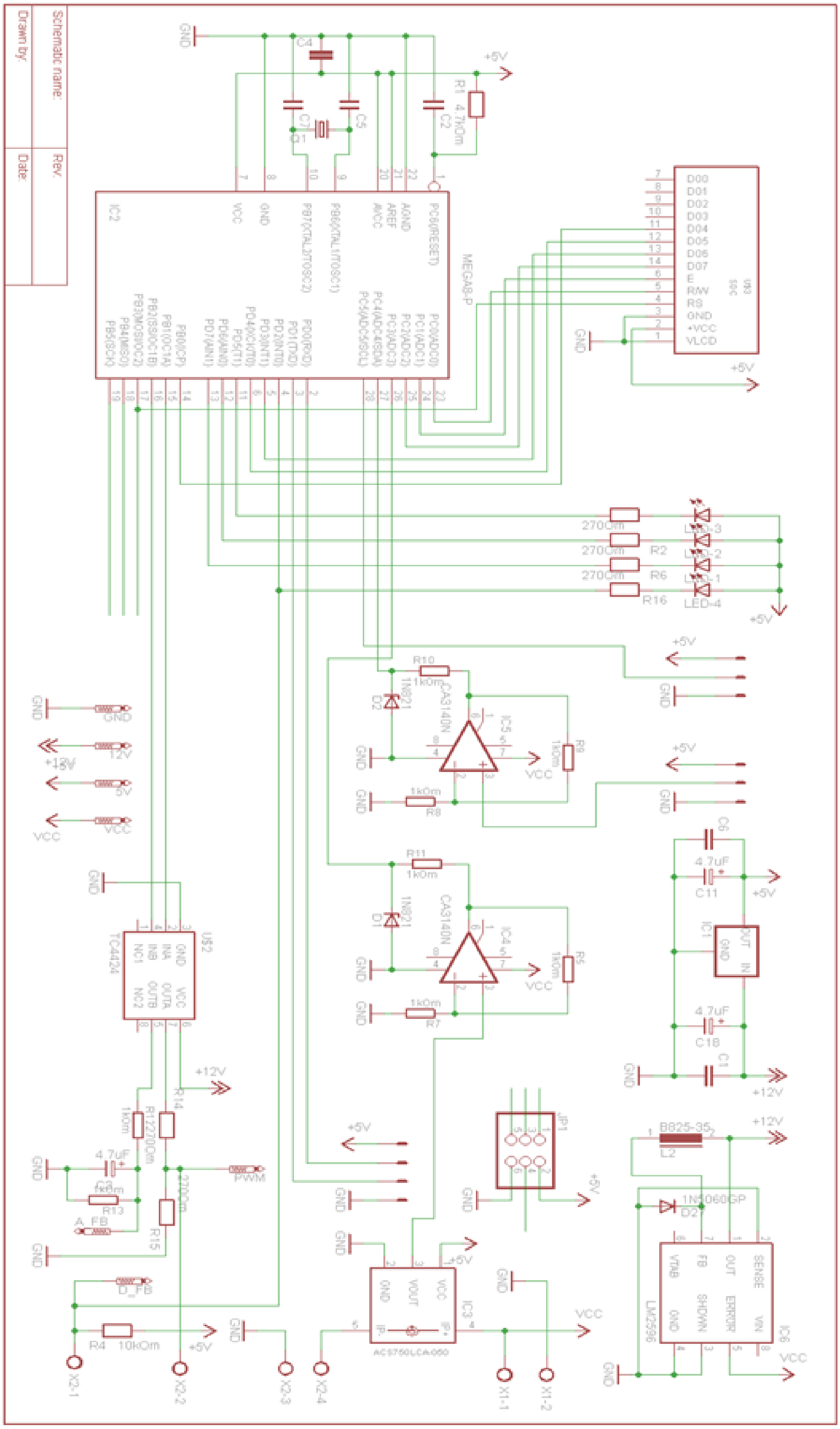


Fig. 9. The overall layout of the hardware for the proposed system.

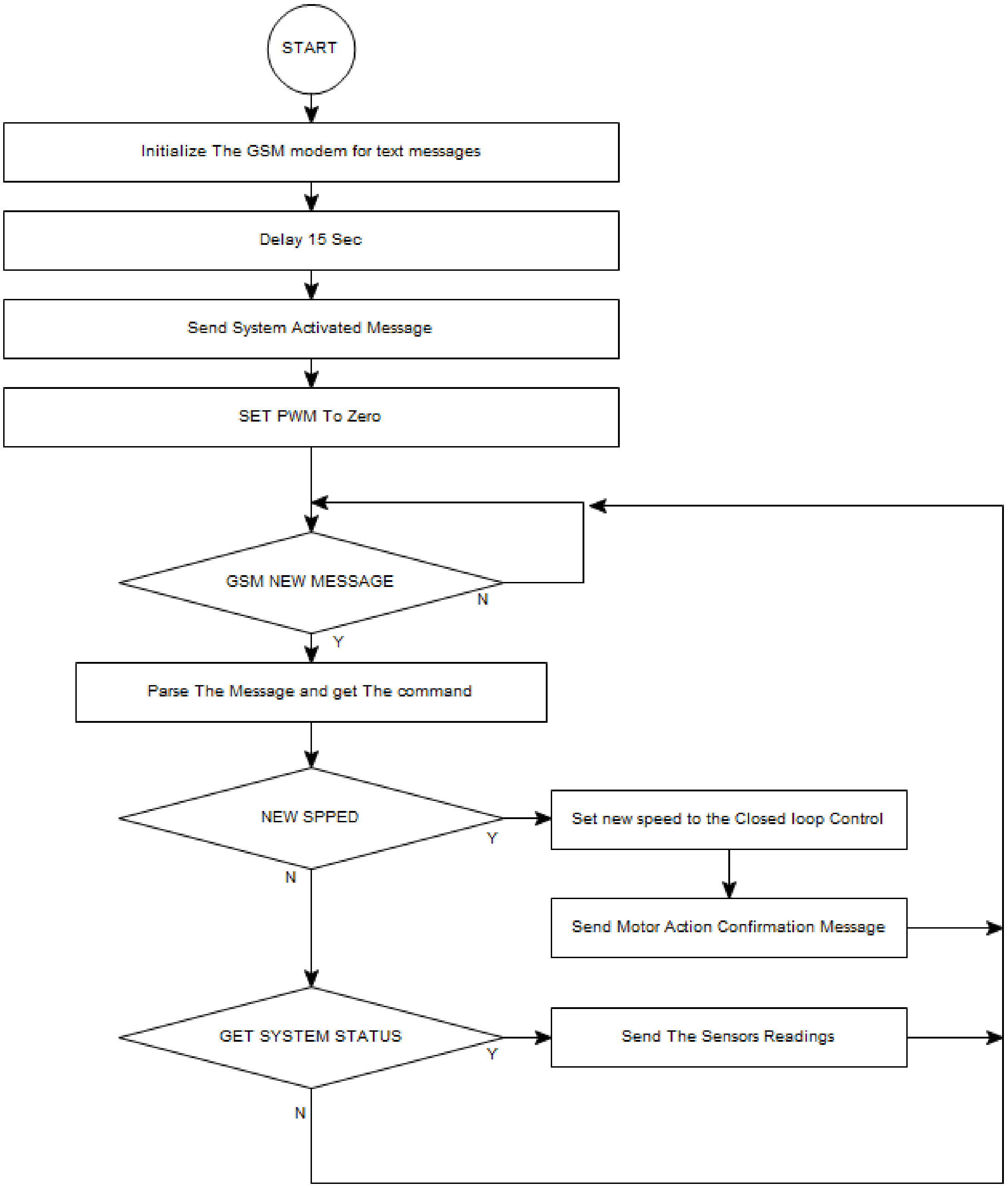
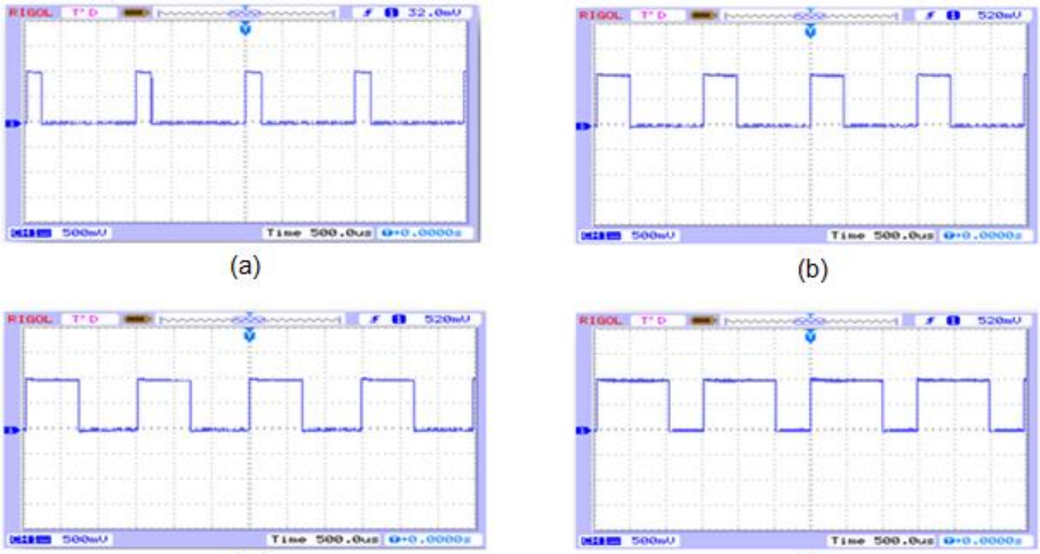


Fig.10. The overall software algorithm of the proposed system.



(a) (b)

(c) (d)

Fig. 11. On-off pulses generated from the microcontroller for different speed commands.
(a) for 15 % of the rated speed (450 rpm), (b) for 30% of the rated speed (900rpm),
(b) for 50% of the rated speed (1500 rpm), and (d) for 80% rated speed (2400 rpm).

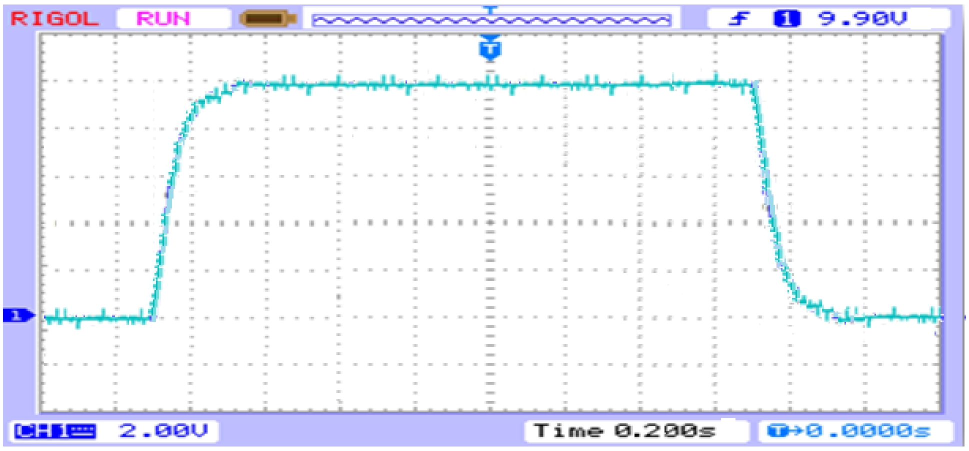


Fig. 12. Step change on the motor speed command of the PSO-PID speed controller from 0 rpm to 2400 rpm and from 2400rpm to 0 rpm at 80% load.

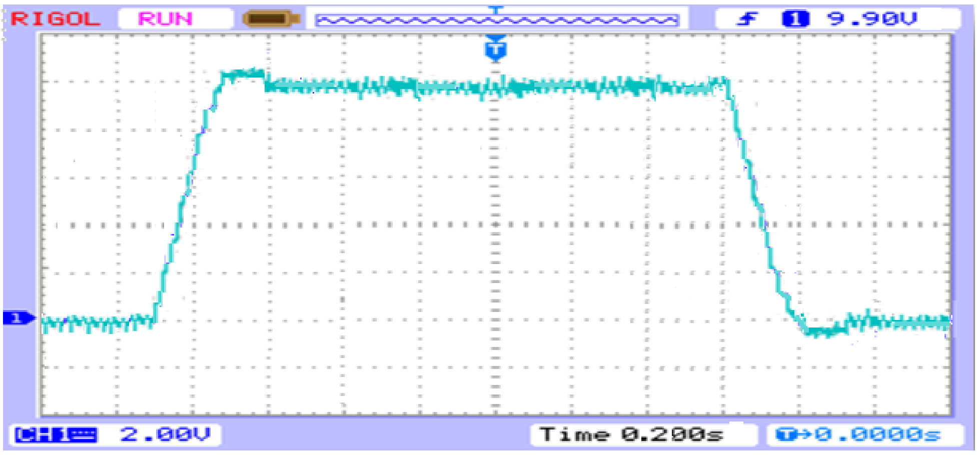


Fig. 13. Step change on the motor speed command of the Zeigler-Nichols-PID speed controller from 0 rpm to 2400 rpm and from 2400rpm to 0 rpm at 80% load.

5 Conclusion

A prototype for monitoring and control BLDCM drive system using GSM network. The BLDCM drive system model is given. The speed PID controller is designed. The overall derive system using the GSM network in conjunction of the RS232 serial interface adaptor and microcontroller. The GSM modem receives a message from a mobile phone as an SMS that contains the speed command of the BLDCM. It will then transmit the information to the microcontroller via RS232 serial interface. The microcontroller in-turn sends the information to the GSM modem after the BLDCM reaches the desired speed by the aid of PID controller. This information is sent as reply through an SMS to the mobile phone. The overall system is simulated, implemented and tested. The speed PID controller parameters are designed by using PSO algorithm. To have a well designed controller based on tuned parameters, four control terms have to be optimized; percent overshoot (M_p), settling time (t_s), rise time (t_r) and steady state error (E_{ss}). The proposed controller is compared with the classical controller; the proposed introduce a fast, accurate and will tuned response. The experimental results show the flexibility of this technique which allows the drive system to be monitored and controlled precisely and remotely.

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