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Torque control of a 5 KW, 220 V separately excited DC motor using microcomputer

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ABSTRACT

Fast torque control is crucial for various applications, including diesel-electric locomotives, electric automobiles, and steel plants. The purpose of this paper is to utilize a microcomputer to control the torque of a separately-excited DC motor fed from a single-phase semi-controlled converter. There are numerous strategies to determine torque using direct or indirect methods. The greatest issue of direct strategy using torque meters is that the measuring device must be installed between the motor and the load. In this paper, we avoid this challenge by employing the indirect approach, specifically by monitoring several DC machine-specific quantities such as voltage, current, and speed, which are easier to determine experimentally. This technology is unquestionably helpful in real-world applications since it eliminates any mechanical impact on the installation. This paper describes the system configuration and provides an explanation of the architecture and system features. The simulation of the proposed system using TUSTSIM dynamic simulation program which is capable of simulating the control system with a digital controller in the loop is presented. An implementation of microcomputer-assisted torque control of DC separately excited motor with proportional integral (PI) controllers is presented. A typical oscillography of the driving characteristics is provided along with the experimental results.

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1. INTRODUCTION

DC machines are widely used in a variety of industrial applications, including robots, electric vehicles, steel rolling mills, trains, and cranes due to their easy, wide, precise, and continuous control capabilities. In a direct DC drive system, controlling motor torque is frequently necessary. Numerous topologies exist for measuring torque using direct or indirect methods [1]–[5]. Each of these methods has its benefits and drawbacks [6]. The main difficulty with the direct method is that a measuring device, must be inserted between the load and the motor or between the driving motor and the generator, respectively, using a torque meters with strain gauges incorporated into a Wheatstone bridge [7], [8]. The indirect method is used to avoid this difficulty particularly by measuring some quantities of the dc motor itself. Dc motor parameters that are simpler to measure experimentally, like motor voltage, current, and shaft speed, are used to indirectly calculate the motor torque. This technology is unquestionably helpful in industrial settings because it avoids any mechanical impact on the actual installation. It is necessary to establish specific dc motor settings and characteristics before using indirect procedures [9], [10]. The accuracy and convenience with which the motor properties and parameters may be acquired generally define the success of this topology utilizing the indirect method [11], [12]. Separately excited dc motors are often used in applications needing precise control of speed and torque over a wide range [13]–[15]. In this paper, we concentrated on the study of microcomputer-based torque control of dc separately excited motor using the PI controller. A PC has been used to accomplish this method. The use of microcomputers to address real-time separately excited dc motor control issues is generally acknowledged to have benefits including fewer components, reduced cost, flexibility, and enhanced dependability [14], [16], [17]. This paper presents an experimental PC-based measurement and control torque for a dc motor that has been developed and tested in a laboratory environment. Additionally, this system can be utilized to conduct research in the fields of sample-data control, proportional integral derivative (PID) control, adaptive control, and modern control theory because these controllers are simple to create and modify through software functions. The system's control program is created in the C programming language. The armature voltage is adopted using the phase-controlled rectifier technology in order to keep the torque within the appropriate range. Results from simulations and experiments have demonstrated the viability of the suggested controlled system.

2. MATHEMATICAL MODEL OF THE SYSTEM

2.1. Mathematical model of DC separately excited motor

A separately excited DC motor with armature voltage control, as shown in Figure 1. The block diagram transfer function of DC motor torque control is shown in Figure 2. The voltage loop equation is (1):

$$e_a = e_g + R_a i_a + L_a \frac{di_a}{dt} \tag{1}$$

where:

$$e_g = k_a J n \tag{2}$$

the torque balance equation is (3),

$$T_D = T_L + Bn + J\frac{dn}{dt} \tag{3}$$

where:

$$T_D = k_a J i_a \tag{4}$$

using LaPlace transform, the (1) to (4) can be put in the form:

$$E_a(s) = E_g(s) + R_a I_a(s) + L_a I_a(s) \tag{5}$$

$$E_g(\mathrm{s}) = K_a \mathrm{a} J\, N(\mathrm{s}) \tag{6}$$

$$T_D(\mathrm{s}) = T_L(\mathrm{s}) + BN(\mathrm{s}) + J\, N(\mathrm{s}) \tag{7}$$

$$TD(s) = ka\, J\, Ia(s) \tag{8}$$

from (5),

$$I_a(s) = \frac{E_a(s) - E_g(s)}{R_a + sL_a} = \frac{[E_a(s) - E_g(s)]/R_a}{1 + \tau_a s} \tag{9}$$

were

$$\tau_a = \frac{L_a}{R_a}$$

in (7), can be put in the LaPlace form as (10).

$$N(s) = \frac{T(s) - T_L(s)}{B + Js} = \frac{[T(s) - T_L(s)]/B}{1 + \tau_m s} \tag{10}$$

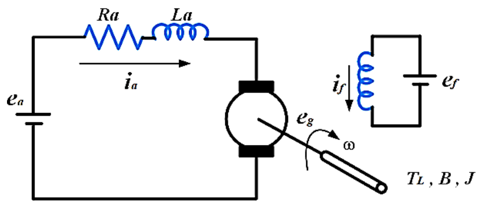

Figure 1. DC separately excited motor

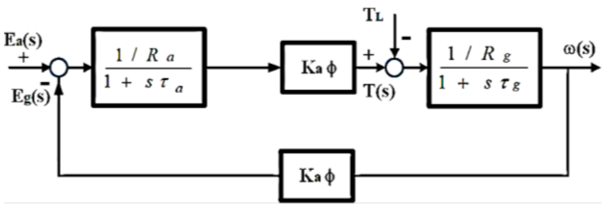

Figure 2. The block diagram transfer function of DC motor torque control

2.2. Measuring electromotive force

The equivalent circuit of a DC machine is given in Figure 3. The basic voltage is (11).

$$E_a = V - V_o - (R_1 + R_a) I_a \tag{11}$$

Where R_a: Resistance of the armature winding; R_1: Resistance of the compensation winding; V: Terminal voltage; and V_o: Brush voltage drop.

To measure the E.M.F. "E_a" and to avoid simultaneously a measurement of the temperature, an E.O.M. bridge is used as shown in Figure 4. From this figure, we can get the (12):

$$V_{12} = (E_a + V_b)\left(\frac{R_1}{R_a+R_1}\right) + V\left(\frac{R_{e2}}{R_{e1}+R_{e2}} - \frac{R_1}{R_a+R_1}\right) \tag{12}$$

when the bridge is equilibrated.

$$R_{e1} = K R_a \tag{13}$$

$$R_e = KR_1 \tag{14}$$

$$V_{12} = (E_a + V_b)\left(\frac{R_1}{R_a+R_1}\right) = C_1(E_a + V_b) \tag{15}$$

From the experimental C_1 is found (16).

$$C_1 = 1.99 \times 10^{-3} \tag{16}$$

Finally, E_a of the machine is given by (17).

$$E_a = \frac{1}{C_1} V_{12} - V_b \tag{17}$$

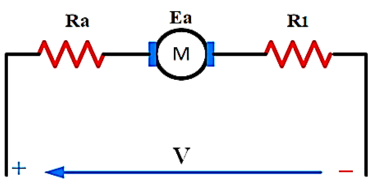

Figure 3. Equivalent circuit of DC machine

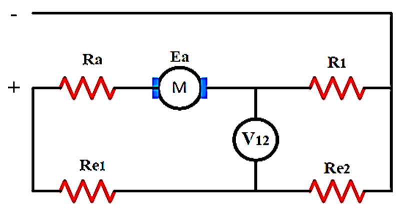

Figure 4. EMF bridge measurement

2.3. Indirect method to measure the torque

The mechanical output power P_{mech} is given by (18).

$$P_{mech} = T\omega \tag{18}$$

The electrical input power P_{el} is given by (19).

$$P_{el} = VI \tag{19}$$

The power loss ΔP is given by (20).

$$\Delta P = P_{el} - P_{mech} \quad (20)$$

The electromagnetic power P_{em} are used instead of the supply voltage V and the electrical input power P_{el}, respectively.

$$P_{em} = E_a I_a \quad (21)$$

The power loss,

$$\Delta P = P_{em} - P_{mech} = \Delta P_{fric} + \Delta P_{iron} \quad (22)$$

the electrical power at no load is:

$$\Delta Po \approx \Delta P_{fric} + \left(C_2 + \frac{C_3}{n}\right) E_a^2 \quad (23)$$

from experimental results, the constants C_2 and C_3 are given by:

$C_2 = 6.11 \times 10^{-3}$, and $C_3 = 1.5$

3. SYSTEM SIMULATION

The simulation language used in this paper is the TUTSIM dynamic simulation program [18]. A brief summary of TUTSIM commands, model specification input, and simple examples of using TUTSIM are presented [19]. The system equations from 1 to 23 generate a TUTSIM program, the block diagram of the system is shown in Figure 5. The controller design problem consists of choosing the parameters KP, KI, and KD to produce a desired system response to the step forcing function. This is achieved by using the parameter estimation PE facility in TUTSIM which is designed to estimate model parameters by minimizing some measure of the difference between a reference response and a simulated response using the model. The situation is illustrated in Figure 6. Parameter optimization for controller design is implemented by generating a design response as the reference and allowing the PE feature to iteratively vary the control parameters until the objective function F in Figure 6 is suitable small.

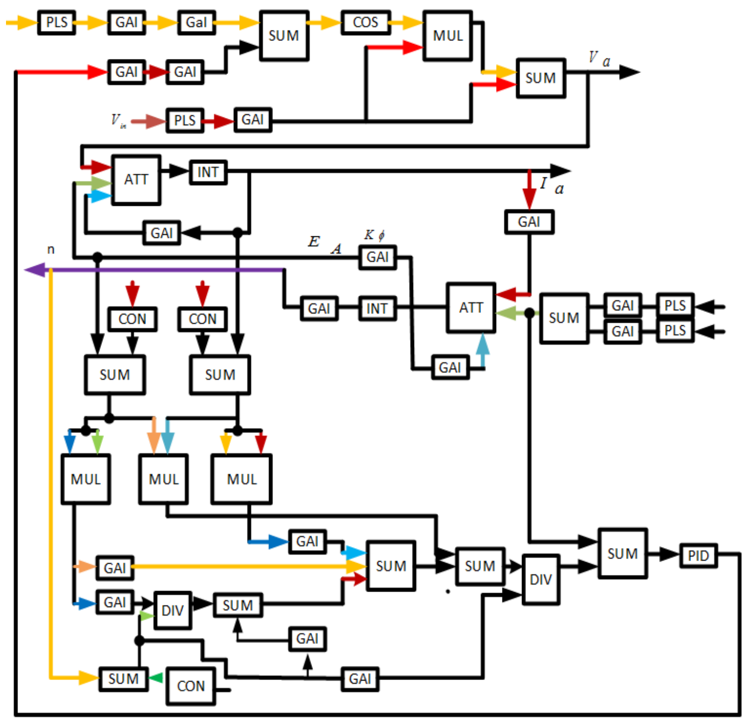

Figure 5. TUTSIM block diagram of the system

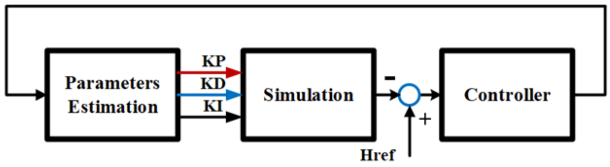

Figure 6. Objective function F to control parameter

3.1. Simulation of the system with P-controller

The proportional gain was selected as the parameter in the optimization routine. The system simulation with different P-controllers is shown in Figures 7 to 10. Several interesting properties can be read according to the motor shaft torque-time simulation with the different values of KP. A low value of proportional gain at KP = 0.9 leads to the presence of a sensible steady-state error and a small settling time. In contrast to that, a high value of gain minimizes the steady state error which isapproximately equal to zero in the case of KP = 1.5 and increases the settling time.

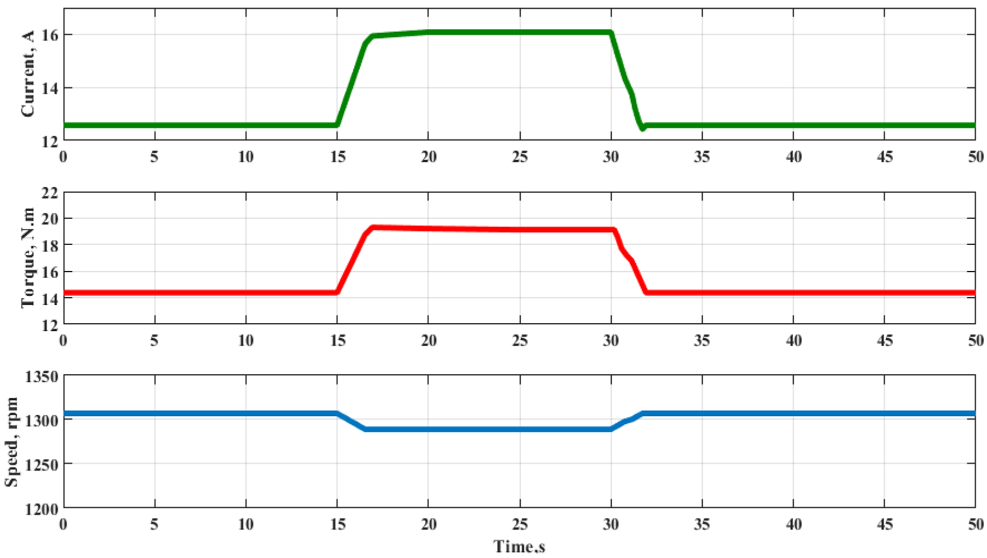

Figure 7. System simulation waveform with P-controller (KP = 0.9)

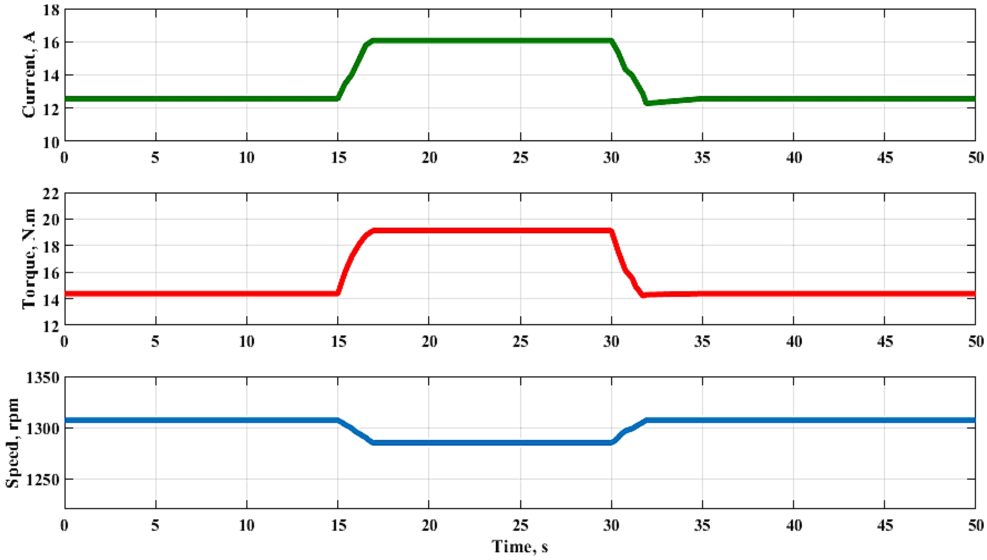

Figure 8. System simulation waveform with P-controller (KP = 1)

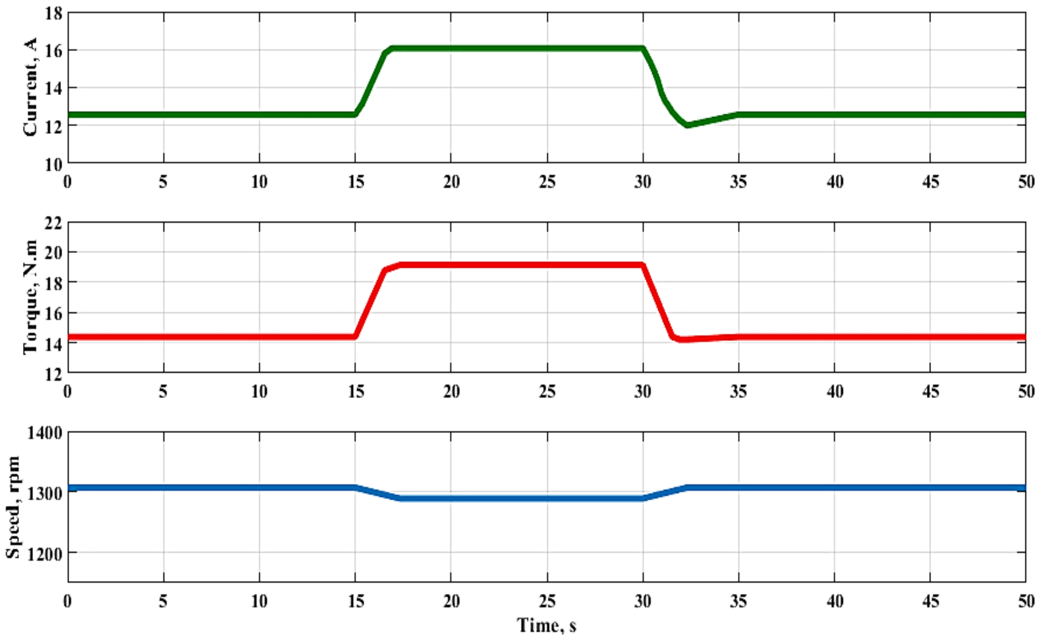

Figure 9. System simulation waveform with P-controller (KP = 1.2)

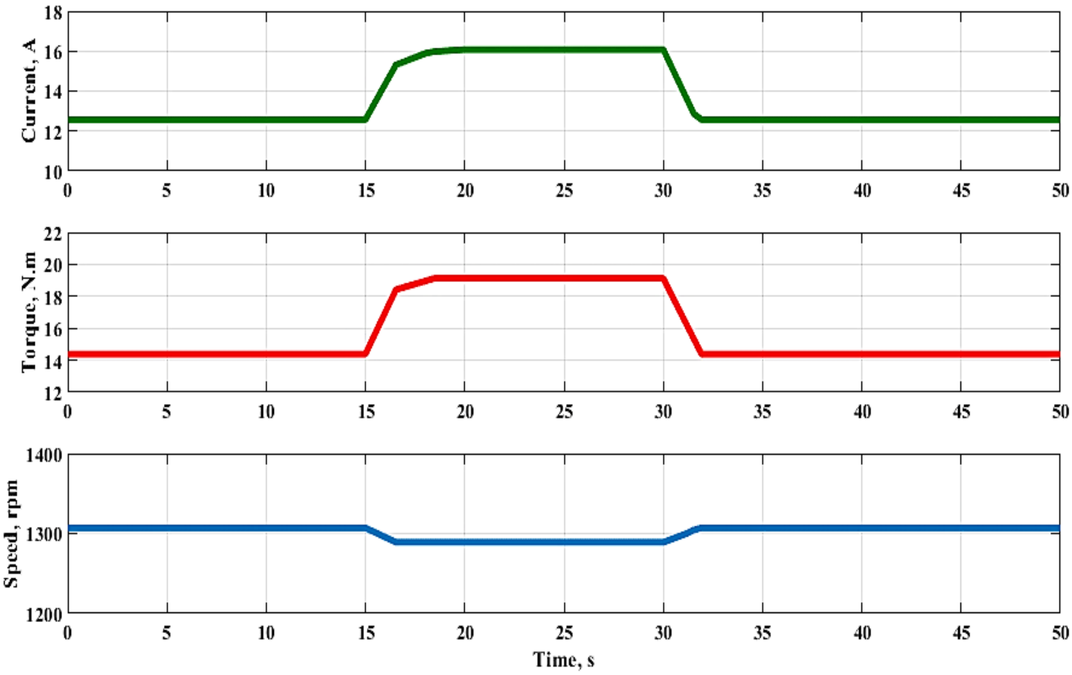

Figure 10. System simulation waveform with P-controller (KP = 1.5)

3.2. Simulation of the system with PI-controller

According to the motor shaft torque-time simulation with different PI-controllers, several interesting properties can be noticed. The most important property of the PI-controller when included in a system, is the elimination of steady-state error. Also, the variation of the controller parameters KP, and KI, has a considerable effect on the system behavior. A high value of KP = 0.9, and KI equal 0.022, and 0.025 leads to an increase in the settling time as shown in Figures 11 and 12 respectively. A low value of KI at constant KP leads to more system oscillations after removing the disturbance are made and not printed in this paper to limit the length of the paper.

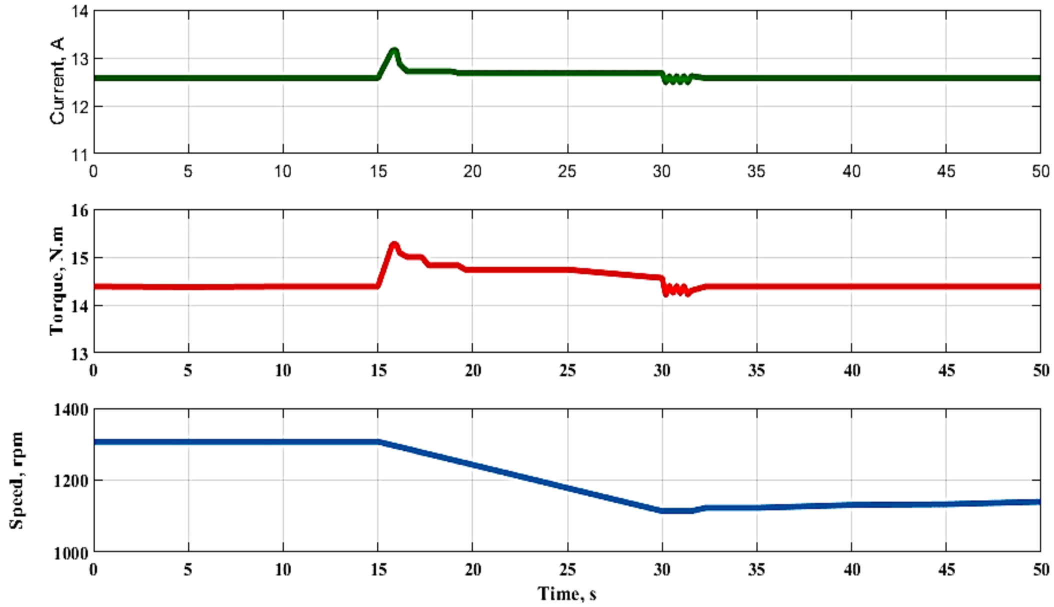

Figure 11. System simulation waveform with PI-controller (KP = 0.9, KI = 0.022)

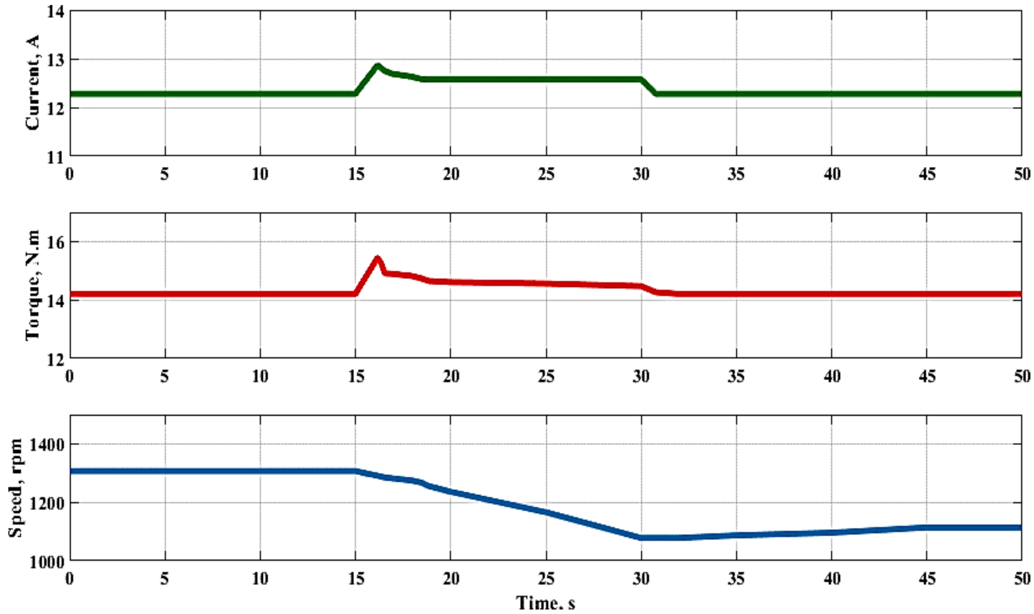

Figure 12. System simulation waveform with PI-controller (KP = 0.9, KI = 0.025)

4. SYSTEM DESCRIPTION

The primary function of a torque control system is to allow the motor shaft torque to follow a reference setting or to minimize its divination from the reference in case of a disturbance acting on the motor shaft. Figure 13 depicts an example of a PC-based data acquisition control system for the various controller structures P and PI implementation. The driving system comprises of a single-phase full wave half-controlled converter feeding a separately excited DC motor with a "5 KW maximum power". The motor is coupled with an eddy current brake as a load. Using a "DAS16 interface card," the "PC 80386-33MHZ" is connected to the drive system to implement various control algorithms. Three voltage signals that represent the motor speed, armature current, and E.M.F. of the motor are the input to the card. The computational result of the controlled algorithm is fed to the interface card internally in the “PC” by means of a software program, the output of the interface card is a DC motor armature voltage. Each component of the suggested hardware design is analyzed in the following section.

Figure 14 shows the thyristor zed power circuit of the single-phase half-controlled bridge converter fed separately excited DC motor [20]. It consists of two diodes D1, and D2, and silicon-controlled rectifiers SCR1, and SCR2. It is necessary to generate synchronizing firing pulses for the positive and negative half cycles. The signal processor of the recommended operational amplifier firing of the positive half cycle is divided into four stages as shown in Figures 15 and 16 respectively.

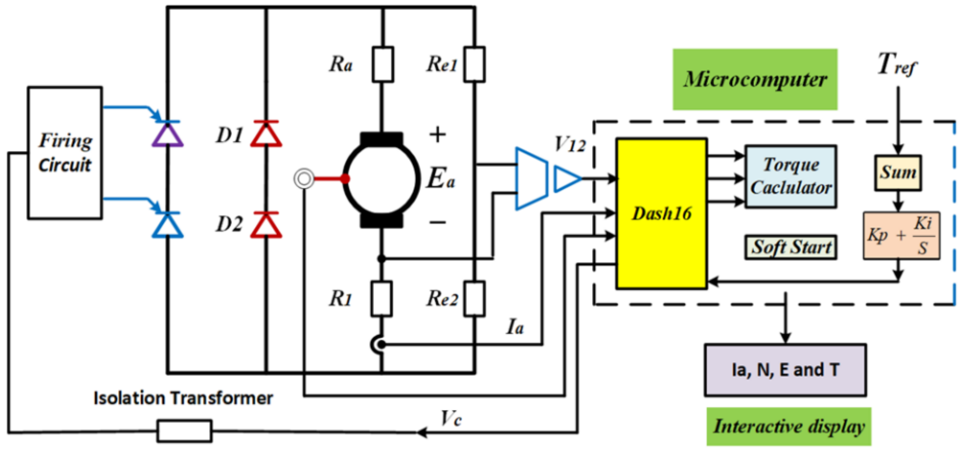

Figure 13. Block diagram of PC-based torque controller for DC motor

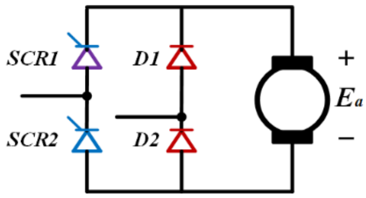

Figure 14. Single phase half-controlled bridge

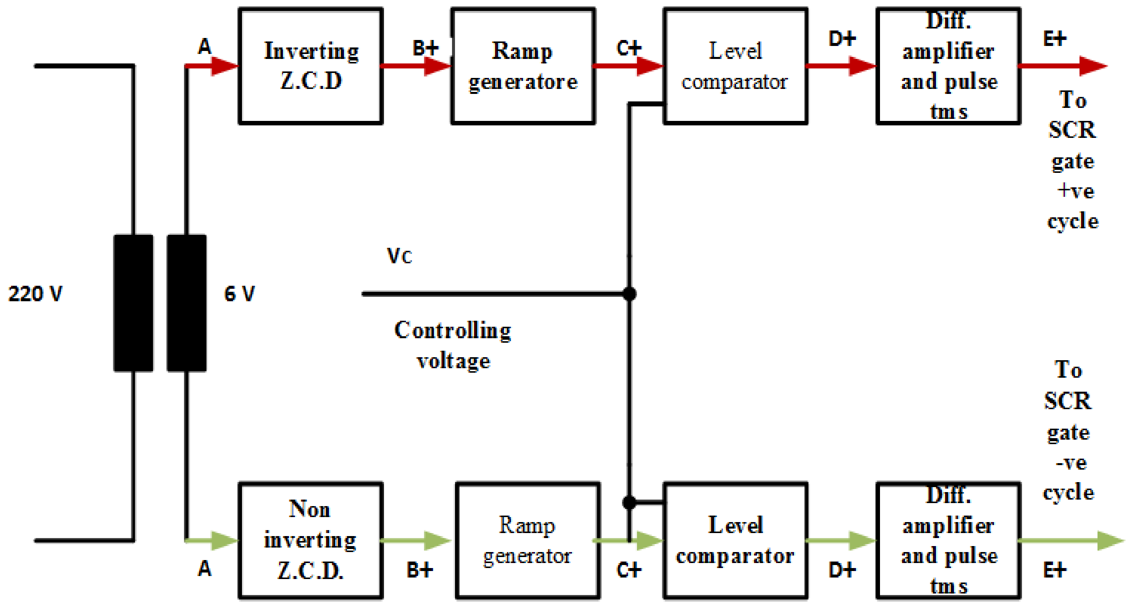

Figure 15. Block diagram of the firing circuit

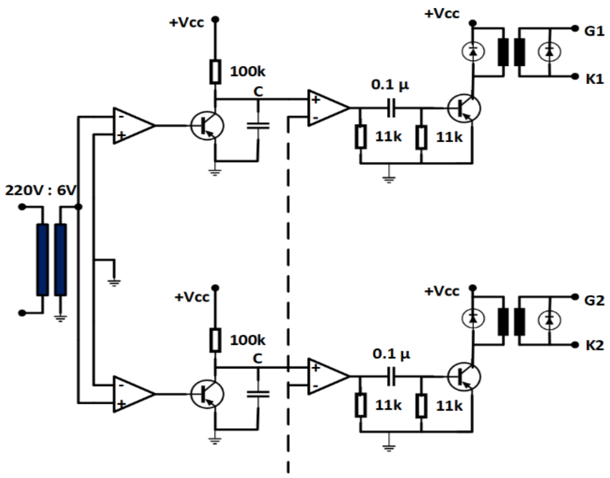

Figure 16. The firing circuits

4.1. The eddy current brake

Compared to conventional mechanical brakes, eddy current braking has many advantages. Due to the lack of physical contact between components, eddy current brakes require very little maintenance and are suited for a wide range of machinery [20]. It is incorporated to provide smooth loading of the DC motor. It is made out of a thick, solid aluminum disc connected to the motor shaft that travels between magnetic poles and is powered by a full wave DC voltage [21].

4.2. The interface card "DAS16"

The key component in our control system is the interface card that manages the flow of control signals between the drive system and the software in the PC microcomputer. The DAS16 offers three 16-bit down counters, 8 digital I/O lines, 16 single-ended or 8 differential analogue inputs, 16-bit A/D resolution, and 16-bit resolution. An onboard pacer clock, or an external pacer input, or software polling can trigger A/D conversions [22]. It is possible to configure the digital channels eight inputs, eight outputs, or four inputs and four outputs using software, enabling you to perceive and manage discrete events.

4.3. Torque, speed, and current measurements in DC drive using the indirect method

The microcomputer-controlled device uses some preliminary stored values of parameters and characteristics to calculate the torque from a voltage, current, and speed signal [23]. An AC alternator is used to measure the motor speed. The output of the alternator is a sinusoidal AC waveform having frequency and amplitude proportional to shaft speed. The AC output is rectified using a 3 F rectifier bridge. The output of the bridge is adjusted to give +5 V, which corresponding to a maximum speed of 1500 rpm by using a potentiometer [24].

Current sensors come in two varieties. Resistive current sensing is a traditional method where the desired current is determined by measuring the voltage drop across a shunt resistor. High current measurements cannot be done with this method since it does not offer galvanic isolation. The second technique is based on the hall effect. A hall effect current transducer is used to measure the armature current and to provide galvanic isolation between the control circuit and the motor power circuit [25].

4.4. Isolating amplifier

The input and output of the isolation amplifier are either electrically or optically isolated, and it has numerous stages of amplification. The ISO 120 G is a precision isolation amplifier that amplifies low-power signals and isolates the side of the microcomputer control circuit from the side of the motor power circuit using a revolutionary duty cycle modulation-demodulation process. To avoid any connections between the amplifier input and output, the isolation amplifier's DC power source needs to be isolated [26].

4.5. System flowchart

The flow chart for the microcomputer-based torque control in DC drives is shown in Figure 17, control begins by initializing the interface card and selecting both of a reference torque and firing angle (α). The monitoring for protection against abnormal conditions such as overcurrent, and open field is done during the starting of the DC drive system also, is done regularly in every cycle.

The microcomputer is programmed to out the control voltage necessary for the firing circuit from one D/A channel of the interface card, and adjusted to set the firing angles to be 180 degrees at the moment of starting. An important feature of the system discussed in this section is that the soft start/stop control is taken care of completely by the software. The start command will be valid only at the time of starting. Prior to the enabling of firing pluses to the thyristors, the program checks for the closed status of the field circuit. If not, it will loop back and wait until the field is closed. The stop command is monitored every cycle and when the signal is sensed the firing pulses will be inhibited and control is transferred to the start of the program instructing the system to wait for a fresh start command.

The torque error and integral error (summated error) are multiplied by the appropriate constants KP and KI and then added to the starting value of firing angle "α". The DC motor speed, armature current, E.M.F, and shaft torque values are displayed during the running condition, where is the motor may run in any one of the control modes during the running condition. Also, the control parameters can be displayed by pressing the "1" key to see the present values and they can be altered as wished by the user. These parameters changing don't affect the normal running of the motor. After the parameters has been changed, when the 'Enter' key is pressed the motor continues to run by taking into effect the changed parameters values.

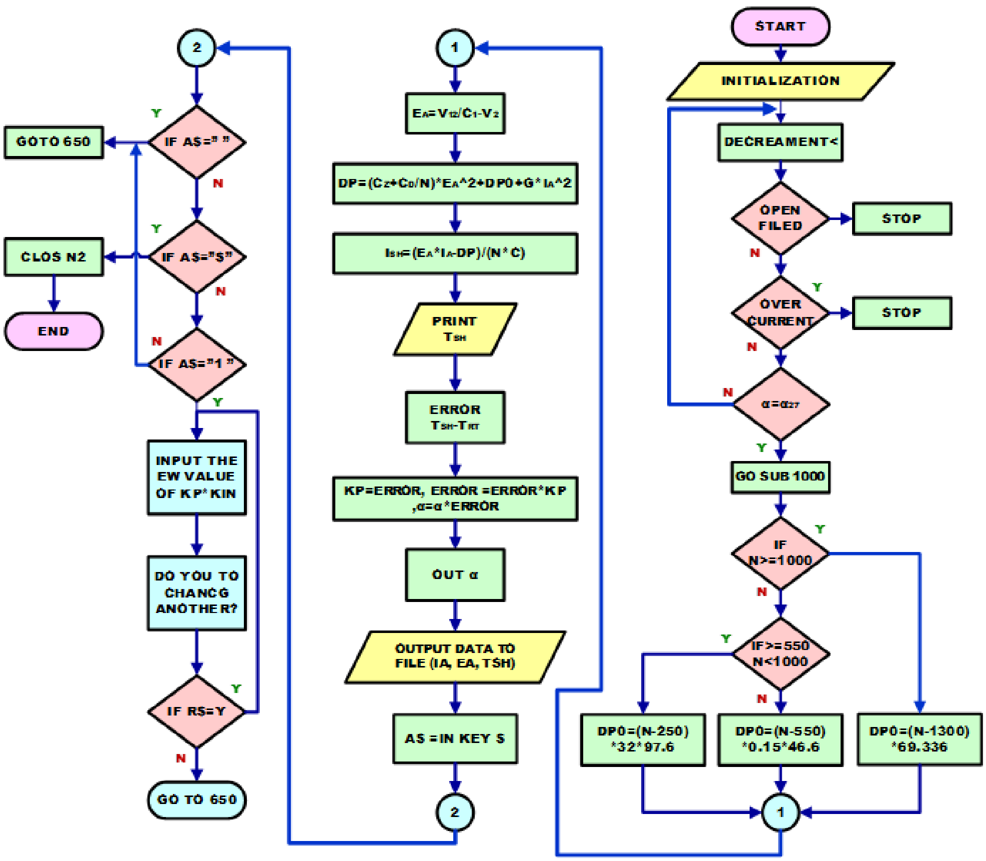

Figure 17. Flow chart for the microcomputer-based torque control

5. EXPERIMENTAL RESULTS

In this section, the implementation of the microcomputer-based torque controller for the proposed DC drive system with proportional and proportional plus has been described. The quick BASIC language is utilized for the implementation of the necessary software required to control the interface card (DAS16). The values of the controller parameters are chosen according to the simulation results. Real-time torque, speed, and armature current against time plots are included to demonstrate the effectiveness of the implemented system.

5.1. The system torque time response with proportional (p) controller

According to offline torque time simulations for the drive system model utilizing the P controller for the closed loop torque control, a range of suitable gains has been selected. The proportional gain has been selected to be 0.9 and 1.5. The online torque time plots have been plotted according to the real-time values of torque versus time recorded during the motor's online operation. Also, the plots of the armature current and speed versus time are included. The system responds with the proportional controller of values 0.9 and 1.5 is shown in Figures 18 and 19 respectively. Several interesting properties can be read according to the motor shaft torque time responses with the different values of KI. A low value of proportional gain KP = 0.9 leads to the presence of a sensible steady state error and a minimum settling time. In contrast to that, a high value of gain minimizes the steady state error which is approximately equal to zero in the case of KP = 1.5, and also increases the settling time.

5.2. System torque time response with proportional integral controller

Based on off-line torque time simulations for the drive system model utilizing PI-controller for the closed loop torque control, a range of suitable gains has been selected. The proportional gain has been selected to be 0.6 or 0.9, also the constant KI has been selected to be between 0.01 and 0.0161. The online torque time plots with KP = 0.9, and different values of KI = 0.01 and 0.0161 are shown in Figures 20 and 21.

According to the motor shaft torque time response with PI-controllers, several interesting properties can be noticed. The most important property of the PI controller when included in a system, is the elimination of the steady state error. A high value of constant KI at constant KP leads to increase in settling time. Also, the increase in KI leads to more system oscillations in which if KI incases than a certain limit, the system may be blowing up. Then the PI controller have been succeeded in solving the most important problem which is the steady state error. The best performance of the system is verified at KP 0.6 and KI 0.02 as shown in Figure 22.

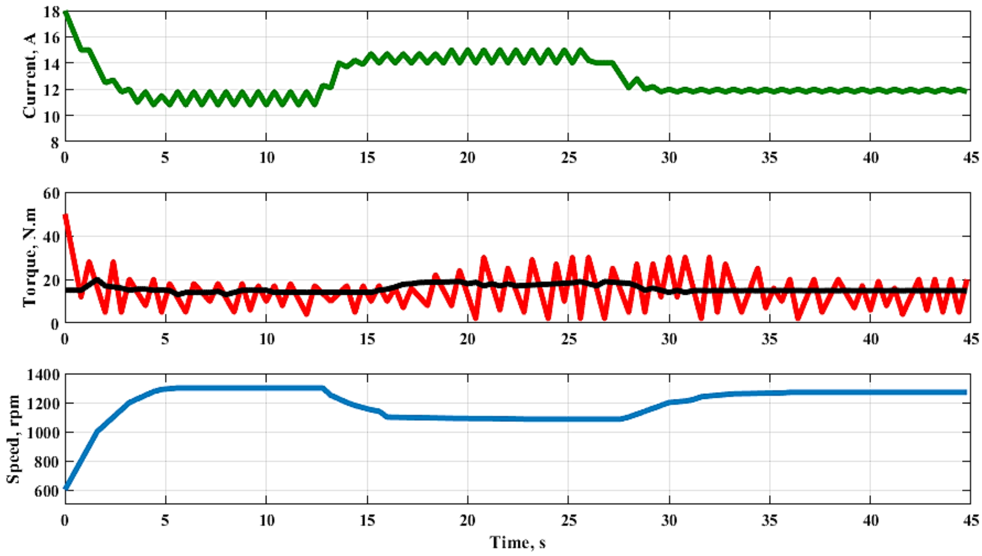

Figure 18. System waveform with P controller (KP = 0.9)

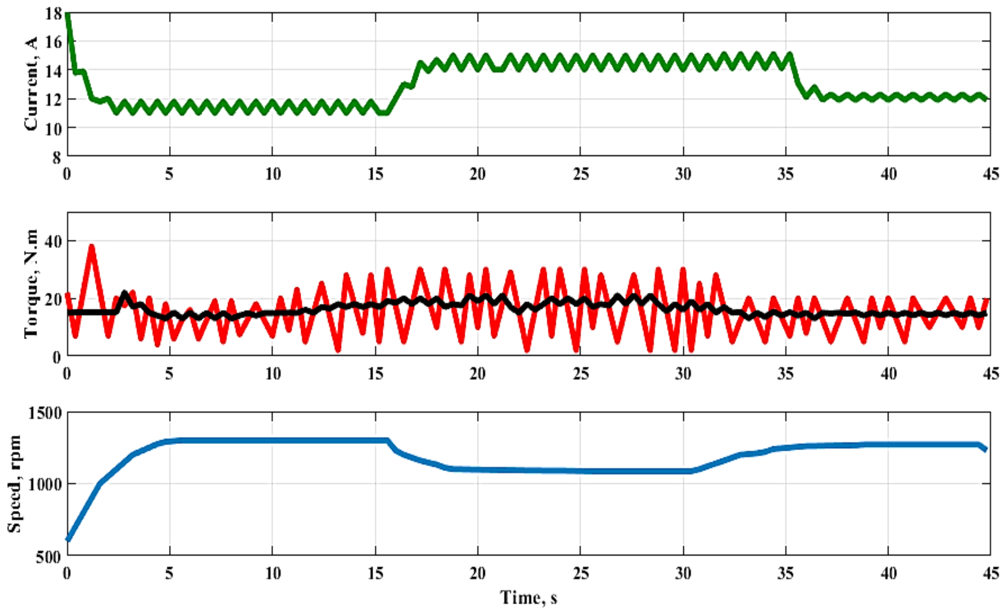

Figure 19. System waveform with P controller (KP = 1.5)

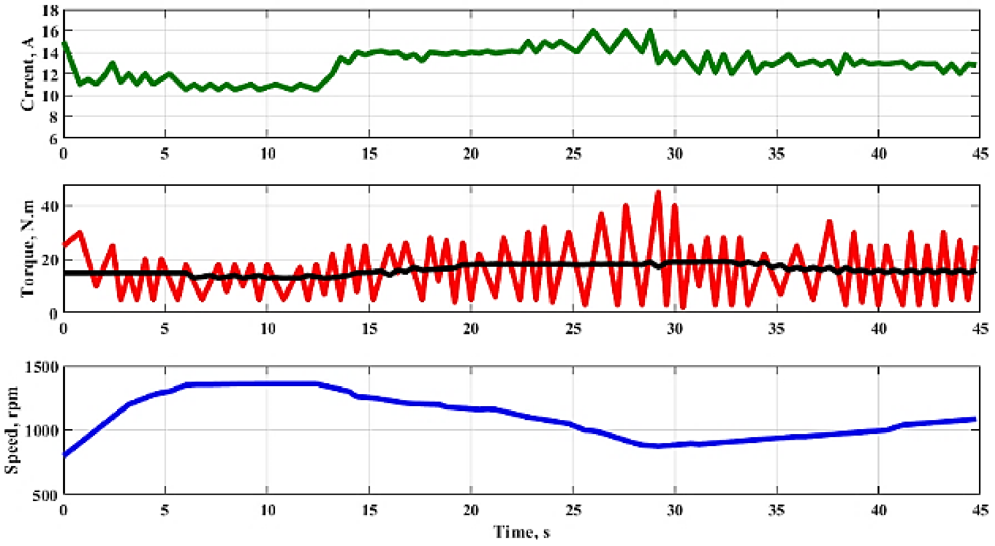

Figure 20. System waveform with PI controller (KP = 0.9, KI = 0.01)

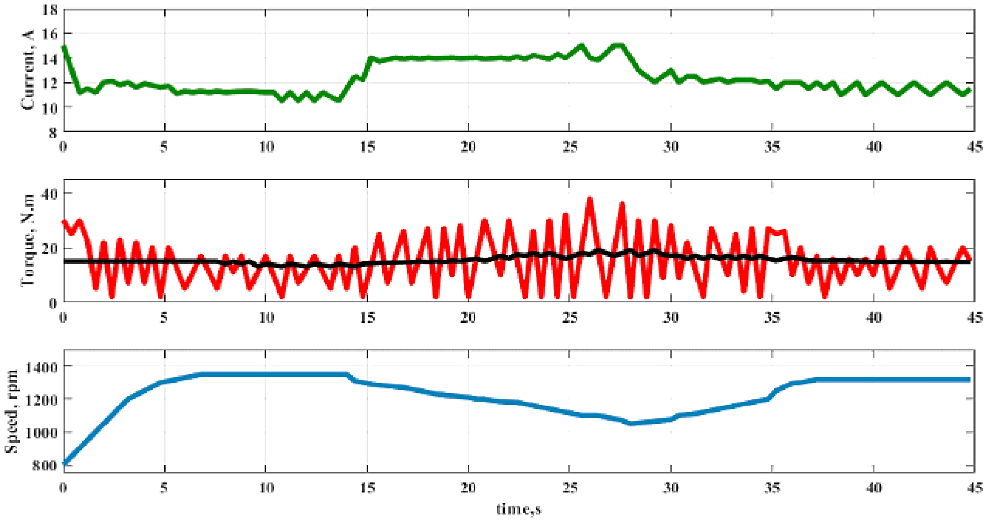

Figure 21. System waveform with PI controller (KP = 0.9, KI = 0.0161)

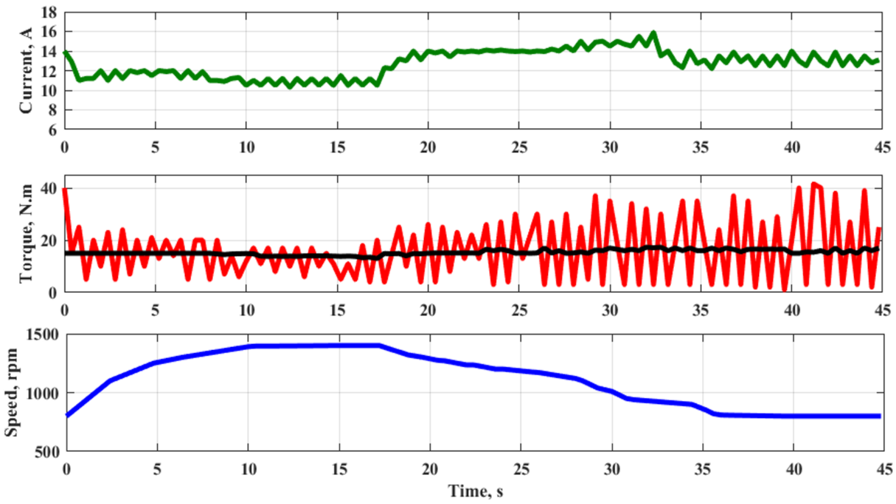

Figure 22. System waveform with PI controller (KP = 0.6, KI = 0.02)

6. CONCLUSION

This paper presented the development of a microcomputer torque control system for a separately excited DC motor with a rating of 5 KW, 220 V, 1450 rpm and that eddy current brakes have been used to load the motor. The most significant merit of the microcomputer-based DC motor torque control system is flexibility and versatility when all the control algorithms are implemented in software which can be changed very easily to suit changes in operating conditions.

The most important advantage of the microcomputer-based DC drive torque control system is flexibility and versatility when implementing all control algorithms in software, which can be changed very easily to suit changes in operating conditions. The motor torque is indirectly measured with good accuracy using motor voltage, current, and speed signals. This method is unique in that it does not require any mechanical modifications to the practical system.

The TUTSIM Dynamic simulation program has been presented to simulate the control system with a digital controller in the loop, and the optimal parameter for controller design has been implemented to achieve control parameter optimization. The control parameters of the algorithms, such as the change in the proportional constant KP, and integral constant KI, or the change in the reference torque setting can easily be done without disturbing the control process under running conditions. A good correlation exists between the experimental and simulation results, which validate the effectiveness and simplicity of the proposed motor torque control scheme.

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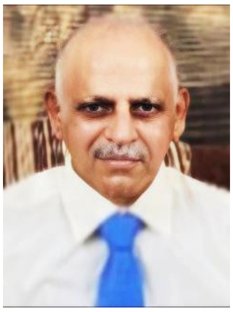

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