

Software-Based Speed Control of a DC Motor Using Pulse-Width Modulation

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Abstract

Speed control of DC Motor is vital in many applications. In this paper, an effort has been made to control the speed of the DC motor using pulse-width modulation (PWM) based on LabVIEW (Laboratory Virtual Instrument Engineering Workbench) program. LabVIEW provides a graphical programming environment suited for high-level or system-level design. Because of the global tendency towards using PC-based data acquisition and control systems in industrial applications, and the high accuracy, reliability, and flexibility requirements to the control system, LabVIEW software is used. Experimental results show that the proposed control scheme provides soft start/ stop transient operations, which improves the dynamic performance of the drive system, and keeps the speed constant regardless of the changes in supply voltage or load torque.

Keywords: DC motor, Pulse-width modulation, Speed control, LabVIEW software, PC-based data acquisition

1. Introduction

DC motors have been popular in the industry control area for a long time, despite that DC power systems are rare, because they have many good characteristics, for example; high starting torque, high response performance, hard torque/ speed characteristics, easier to be linear control, wide range of speed regulation with high accuracy etc. DC motors are used with conveyors, elevators, extruders and in marine applications. They are also used in industry for material handling including paper, plastic, rubber, steel and textile (Salim *et al.* 2013, Aditya *et al.* 2013, Ruderman *et al.* 2008). Low-power DC motors are used in positioning systems in machine-tools, where high accuracy is required. In comparison with AC drive systems, DC drives are less and normally cheaper for low horsepower ratings. DC motors are identified as adjustable speed machines for many years and a wide range of options have evolved for this purpose. There are different control approaches and schemes, which depend on the desired performance of the used DC motors. The speed of DC motors can be controlled below base (nominal) speed for constant torque electric drives or above base speed for constant power drives. Different control methods and techniques are available. Open-loop and closed-loop control systems are used to control the speed of DC motors depending on the drive system requirements (Aditya *et al.* 2013, Atul Kumar *et al.* 2012).

The basic property of DC motor is that speed can be adjusted by varying the terminal voltage, inserting additional resistance into the armature circuit and weakening the magnetic flux. The first two methods are used for speed control below base speed, and the last method is used for speed control above the base speed. The control systems for DC motors are relatively simple because they use scalar control principle. The main advantage of DC motor speed control is that, the motor torque and magnetic flux can be independently adjusted. Therefore, the DC motor control is riper than other kinds of motors. Also, DC motor can be considered as a SISO (single-input single-output) compatible with most mechanical loads. By proper adjustment of the terminal voltage, the mentioned characteristic makes a DC motor controllable over a wide range of speeds (Nazanim *et al.* 2013, Ramesh *et al.* 2010, Nandkishor 2012).

Classic control has proven for a long time to be good enough to handle control tasks on system control; however its implementation relies on an exact mathematical model of the system (plant or process) to be controlled and not simple mathematical operations.

In this paper, pulse-width modulation PWM technique, based on LabVIEW software has been implemented to control the speed of DC motor below nominal speed by adjusting the average value of armature voltage and to perform soft start/ stop transition operations.

2. Speed Control of DC Motors

The equivalent electrical circuit of separately-excited DC motor is shown in Figure 1.

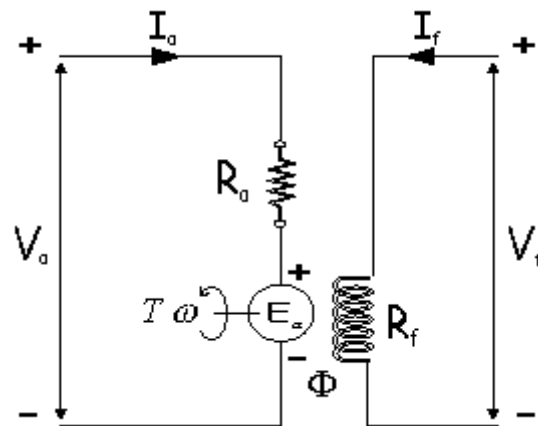


Figure 1. Equivalent Electrical Circuit of Separately-Excited DC Motor.

The instantaneous value of armature (terminal) voltage $v_a(t)$ is defined as:

$$v_a(t) = R_a i_a(t) + L_a \frac{di_a(t)}{dt} + e_a(t) \quad (1)$$

where R_a is the armature resistance, L_a is the armature inductance, $i_a(t)$ is the instantaneous armature current and $e_a(t)$ is the armature back emf.

The armature back emf $e_a(t)$ is expressed as:

$$e_a(t) = K\phi\omega \quad (2)$$

where K is a motor constant, ϕ is the magnetic flux and ω is the angular rotational speed.

The developed torque T is defined by:

$$T = K\phi i_a(t) \quad (3)$$

Neglecting the friction in the system, the equation of motion will be:

$$T - T_L = J \frac{d\omega}{dt} \quad (4)$$

where T_L is the load torque and J is the equivalent moment of inertia of the system.

Based on Equations (1) to (4), the dynamic model of DC drive system in state-space form can be derived as:

$$\begin{cases} \frac{d}{dt} \begin{bmatrix} \omega \\ i_a(t) \end{bmatrix} = \begin{bmatrix} 0 & \frac{K}{J} \\ -\frac{K}{L_a} & -\frac{R_a}{L_a} \end{bmatrix} \begin{bmatrix} \omega \\ i_a(t) \end{bmatrix} + \begin{bmatrix} 0 \\ \frac{1}{L_a} \end{bmatrix} v_a(t) \\ \omega = [1 \quad 0] \begin{bmatrix} \omega \\ i_a(t) \end{bmatrix} \end{cases} \quad (5)$$

For steady-state ($\frac{d}{dt} = 0$) operation, the following two equations can be obtained:

$$\omega = \frac{V_a}{K\phi} - I_a \frac{R_a}{K\phi} \quad (6)$$

$$\omega = \frac{V_a}{K\phi} - T \frac{R_a}{(K\phi)^2} \quad (7)$$

where V_a and I_a are the steady-state values of armature voltage and armature current, respectively.

Equation (6) is called electromechanical characteristic of the drive system and Equation (7) is called torque/speed (mechanical) characteristic of the drive system.

The first term in Equations (6) and (7) represents the no-load speed ω_0 of the drive system and the second term represents the drop in speed $\Delta\omega$ due to the load.

The relationship:

$$\beta = \frac{dT}{d\omega} = \frac{\Delta T}{\Delta\omega} \quad (8)$$

is called the hardness of mechanical characteristic of the drive system, which represents the sensitivity of the system to the change in load torque.

From Equation (6) it is clear that the speed of DC drive system can be controlled by weakening the magnetic flux below its nominal value, by inserting additional resistance into the armature circuit and by reducing the armature voltage below its nominal value. The first two methods are rarely used because they increase the heat losses in the system and reduce the hardness of the mechanical characteristic, which may cause instable steady-state operation of the drive system. The third method is widely used to control the speed of constant load torque DC drives below base speed because it does not affect the hardness of mechanical characteristic and does not increase the heating losses in the motor. Variable armature voltage for speed control of DC drives can be obtained by different methods, such as Ward-Leonard schemes, transformer with taps and an uncontrolled rectifier bridge, static Ward-Leonard scheme or controlled rectifiers and chopper control. Usually controlled rectifiers are used in applications requiring slow response in high power systems. The main disadvantage of controlled rectifiers is that, they can't change their state immediately by inverting the polarity of applied voltage. For this reason, pulse-width modulation is recently used to adjust the armature voltage of DC motors, especially for small power motors fed from limited power sources.

3. Pulse-Width Modulation with LabVIEW

Laboratory Virtual Instrument Engineering Workbench LabVIEW is new graphical development software with built-in functionality for data acquisition, instrument control, measurement analysis, and data presentation. LabVIEW delivers extensive acquisition, analysis, and presentation capabilities, so it is possible to create applications, simulations and presentations of systems and processes in a single environment without utilizing for other software. LabVIEW uses a graphical programming language called the G language. This language represents programs in a symbolic form called block diagrams, which reduces a lot of syntactical details, so the user will concentrate on the flow of information than the procedure. Also, the graphical form of the programs eliminates syntax errors as in text-based language and this saves time.

LabVIEW ties the creation of user interfaces, called front panels, into the development cycle. LabVIEW programs (subroutines) are called virtual instruments VIs. Each VI has three components: block diagram, front panel and connector pain. The last is used to represent the VI in the block diagrams of other VIs. The front panel is built using controls and indicators. Controls are inputs: they allow a user to supply information to the VI. Indicators are outputs: they indicate, or display, the results based on the inputs given to the VI. The (back panel), which is a block diagram, contains the graphical source code. All of the objects placed on the front panel will appear on the block diagram as terminals. The block diagram also contains structures and functions which perform operations on controls and supply data to indicators. The structures and functions are found on the functions palette and can be placed on the block diagram. The LabVIEW programming environment makes it simple to create some applications. The available Virtual Instruments VIs and sub VIs with National Instruments hardware can be developed to obtain PWM to control the speed of DC motors (LabVIEW 2009).

PWM is a digital technique used for speed control of DC motors by varying the armature voltage below its nominal value. The principle of PWM is illustrated in Figure 2. PWM is characterized by duty cycle q , which is defined as:

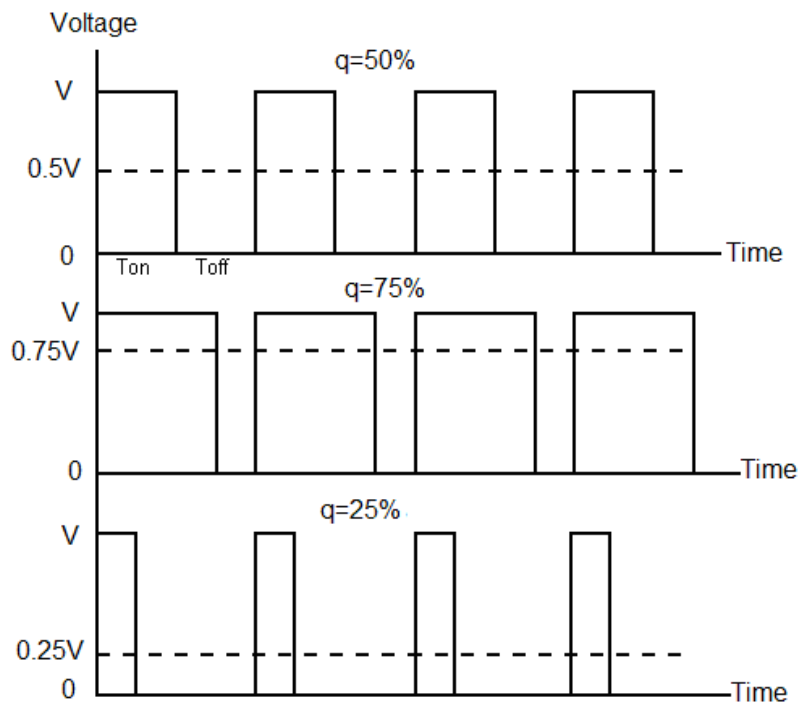


Figure 2. Principle of PWM.

$$q = \frac{T_{ON}}{T_{ON} + T_{OFF}} 100\% = \frac{T_{ON}}{T_{CYC}} 100\% \quad (9)$$

where T_{ON} is the duty (turned-on) interval, T_{OFF} is the turned-off period, and T_{CYC} is the cycle time (period).

The average value of voltage applied to the armature V_a equals:

$$V_a = \frac{1}{T_{CYC}} \int_0^{T_{ON}} V dt = qV \quad (10)$$

The equations for electromechanical and mechanical characteristics can be rewritten as:

$$\omega = \frac{qV}{K\phi} - I_a \frac{R_a}{K\phi} \quad (11)$$

$$\omega = \frac{qV}{K\phi} - T \frac{R_a}{(K\phi)^2} \quad (12)$$

The natural characteristic of the motor is obtained when $q = 1$. The regulated characteristics are obtained for $0 < q < 1$ keeping $T_{CYC} = const$ (pulse frequency =const). Usually the pulse amplitude V is not sufficient to operate the motor, thus it should be amplified.

PWM technique is considered as an efficient method for smooth speed control of DC motors.

To realize PWM technique in LabVIEW environment, the following VIs and sub VIs were used:

1. Speed stabilizer (using counter), as shown in Figure 3. This VI uses counter 0 on DAQ board to generate pulse trains to feed the motor. The pulse frequency can reach $10kHz$. By varying the duty cycle of generated pulses, the speed can be controlled smoothly. Speed stabilizer VI enables the motor to operate on three linear characteristics before reaching the desired speed. This action is illustrated in Figure 4.
2. Increment sub VI which provides the speed stabilizer VI with the duty cycle needed for increasing the average voltage fed to the motor.
3. Decrement sub VI which provides the speed stabilizer VI with the duty cycle needed for decreasing the average voltage fed to the motor.
4. Write to file sub VI, which is used to record particular data, such as speed, duty cycle and frequency in an external document.

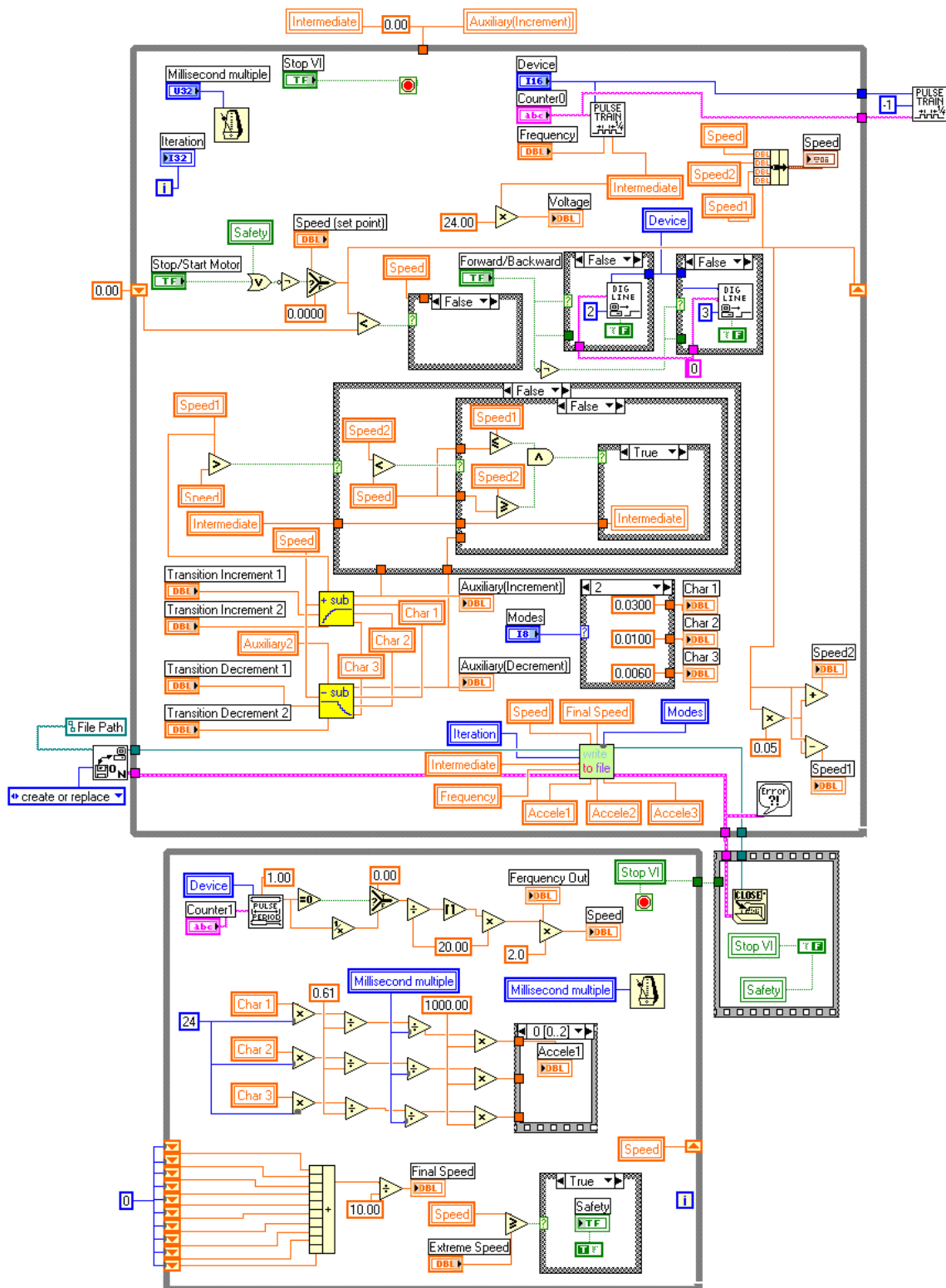


Figure 3. Block Diagram of Speed Stabilizer VI.

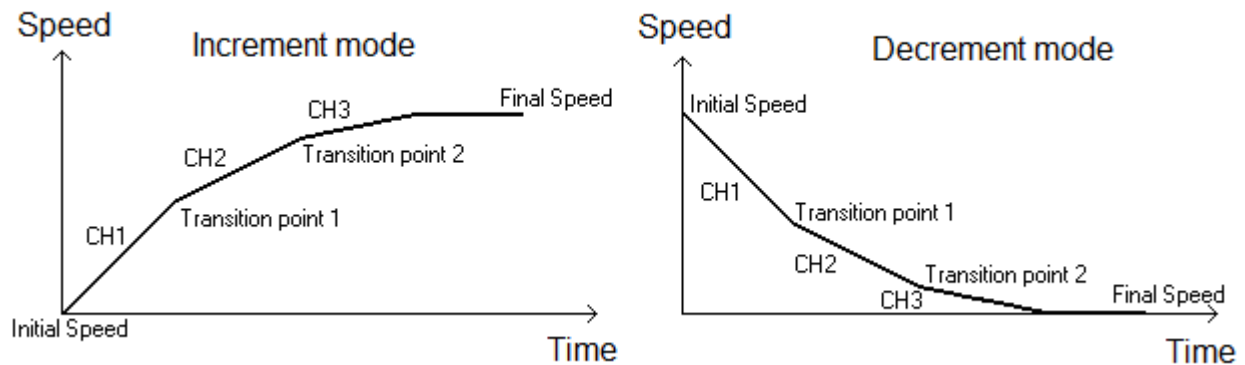


Figure 4. Increment and Decrement Characteristics of the Motor.

5. Saw-tooth VI, to generate continuous saw-tooth signal, which can be modified in slope and amplitude.
6. Programmable counter sub VI, which provides the saw-tooth VI with the number of generated pulses.
7. Mono-stable VI, to produce pulses as a response to an input signal.
8. Start-stop VI, which forms pulses according to a certain algorithm with a frequency up to 500Hz .

The block diagram of start-stop VI is shown in Figure 5. Examples of start-stop operations are illustrated on Figure 6 for different selected settings. In general, the start-stop VI enables to operate the motor at three modes, which are represented on Figure 6.

4. Investigation of the Proposed Control System

The schematic diagram of proposed control system is shown in Figure 7. The system consists of the following components:

1. 24V, 1.5A, 600rpm, 0.02hp DC separately-excited motor.
2. L6203 H-bridge, to provide 4-quadrant control of the DC motor.
3. Two PC817 opto-couplers to isolate the DAQ pulses and direction signals from the motor circuit.
4. 7805 regulator to produce 5V-signal.
5. Incremental encoder, to measure the speed.
6. CD4017B frequency divider to match the frequency of feedback signal with the DAQ VI frequency.
7. DAQ VI, which includes DAQ card, cable and terminal block.

The control system operates as follows: firstly, the driving pulses and direction signals are generated and extracted from the PC using LabVIEW and DAQ system respectively. After that, these signals enter two AND gates to determine the direction the motor rotation. The direction signals are generated in a way that one AND gate is activated at a certain moment. Opto-couplers isolate between the DAQ and the motor circuit. The outputs of the opto-couplers are connected to the motor circuit through H Bridge. To get a speed feedback signal, encoder is used to produce pulses with a frequency proportional to the speed of the motor. The controller (PC) changes the duty cycle of the pulses as the value of the final speed changes to keep the speed of the motor constant.

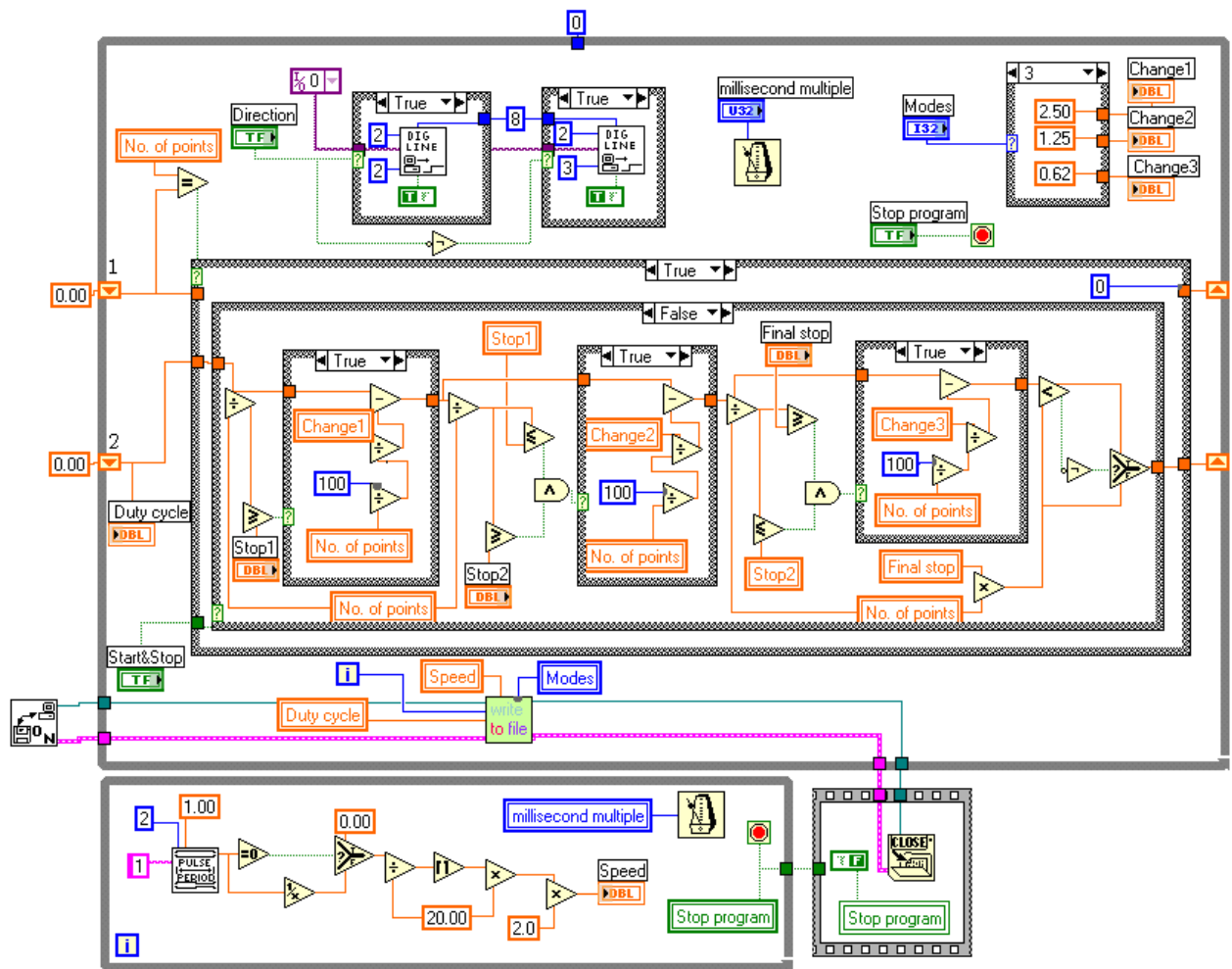
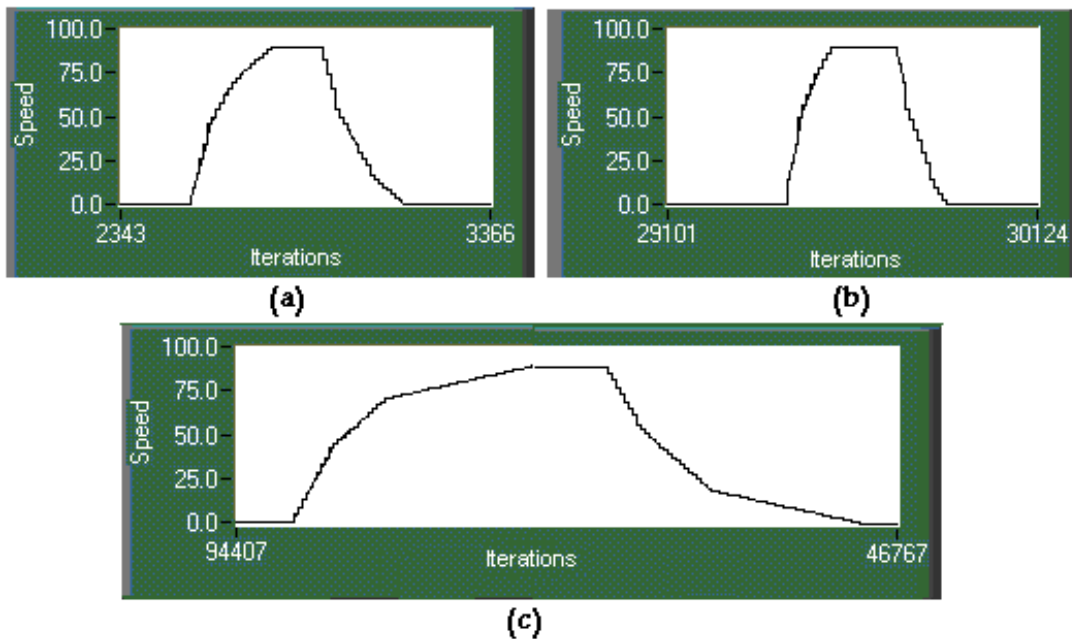


Figure 5. Block Diagram of Start-Stop VI.



Time = No. of Iterations * 100 (ms)
 Figure 6. Examples of Start-Stop Operations.

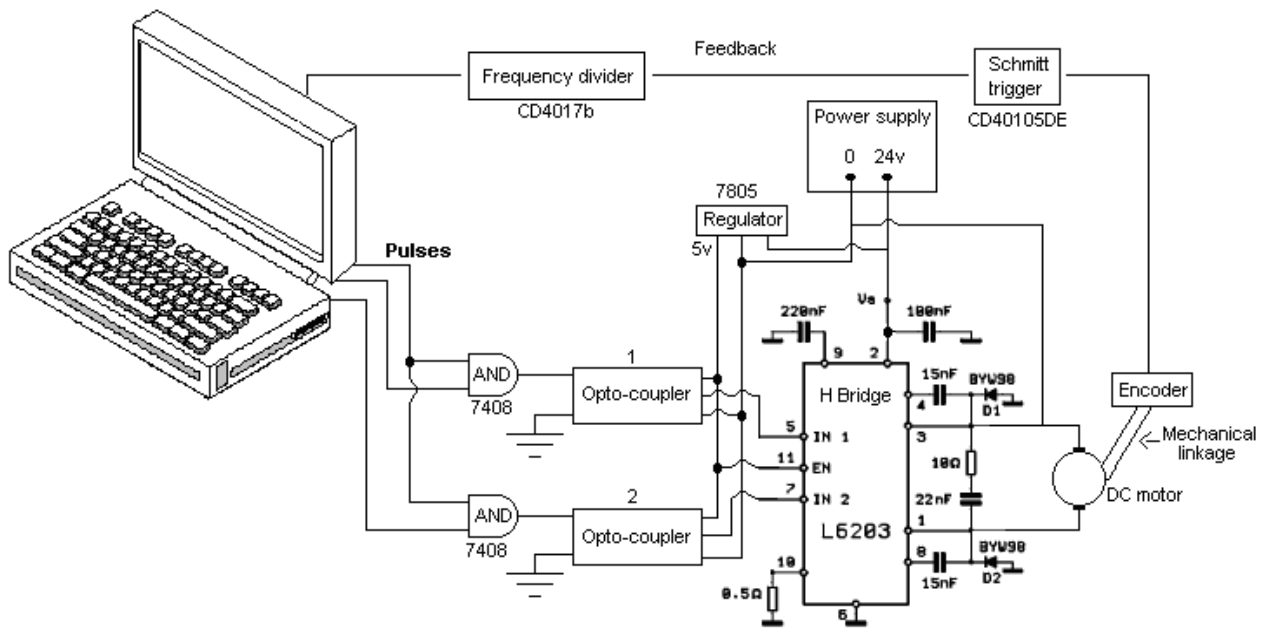


Figure 7. Schematic Diagram of Proposed Control System.

The control system has been experimentally tested for different operating modes. Figure 8 shows the response of the system at no-load for three accelerating modes.

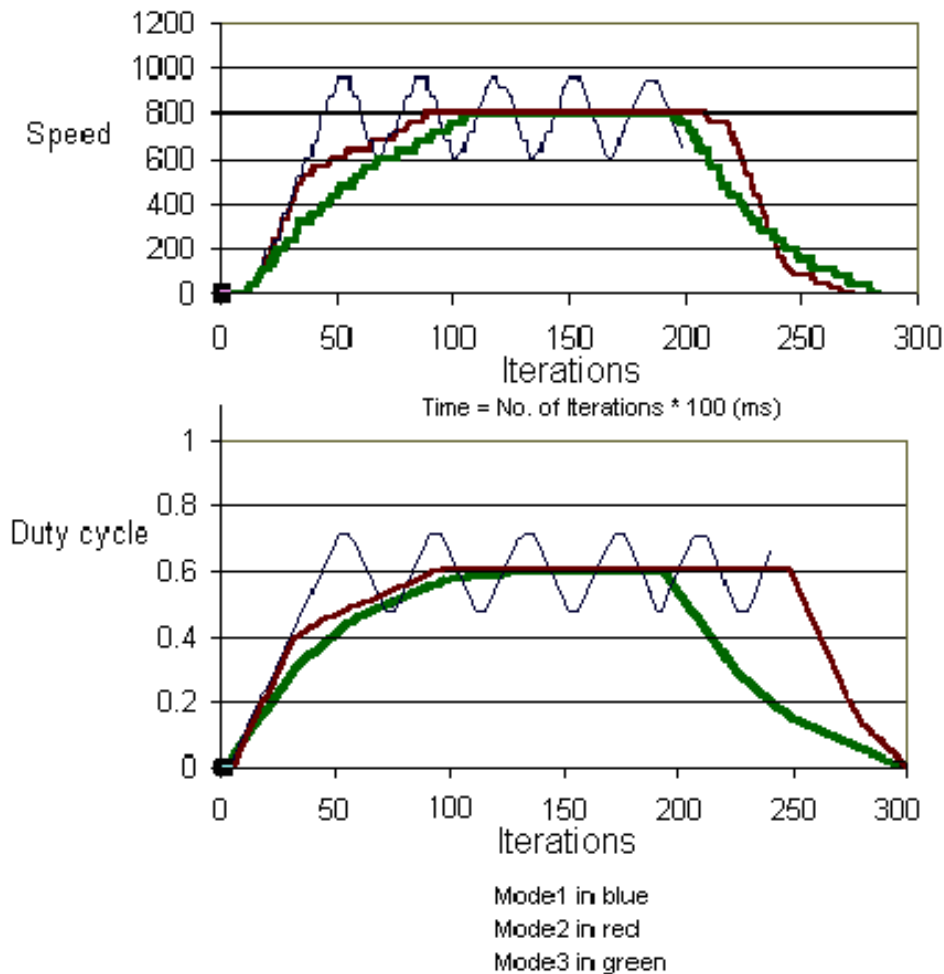


Figure 8. Dynamic Response of the System at No-load Operation.

The system response due to applying external load for a short time is shown in Figure 9. As known, when a torque is affecting a motor, its speed decreases; consequently, according to this VI tries to remain its value (set point) by increasing the duty cycle in order to compensate the speed drop.

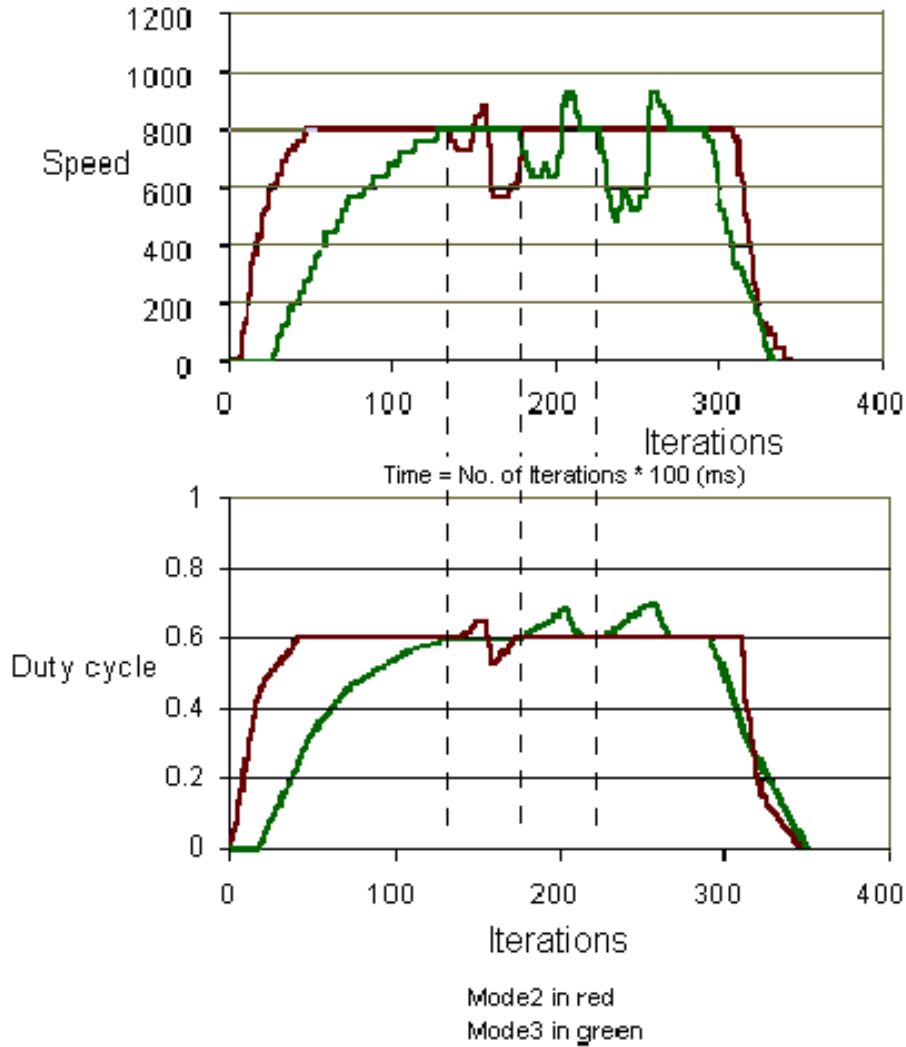


Figure 9. Dynamic Response of the System due to Applying Load.

The dynamic response of the system due to the reduction in supply voltage is shown in Figure 10.

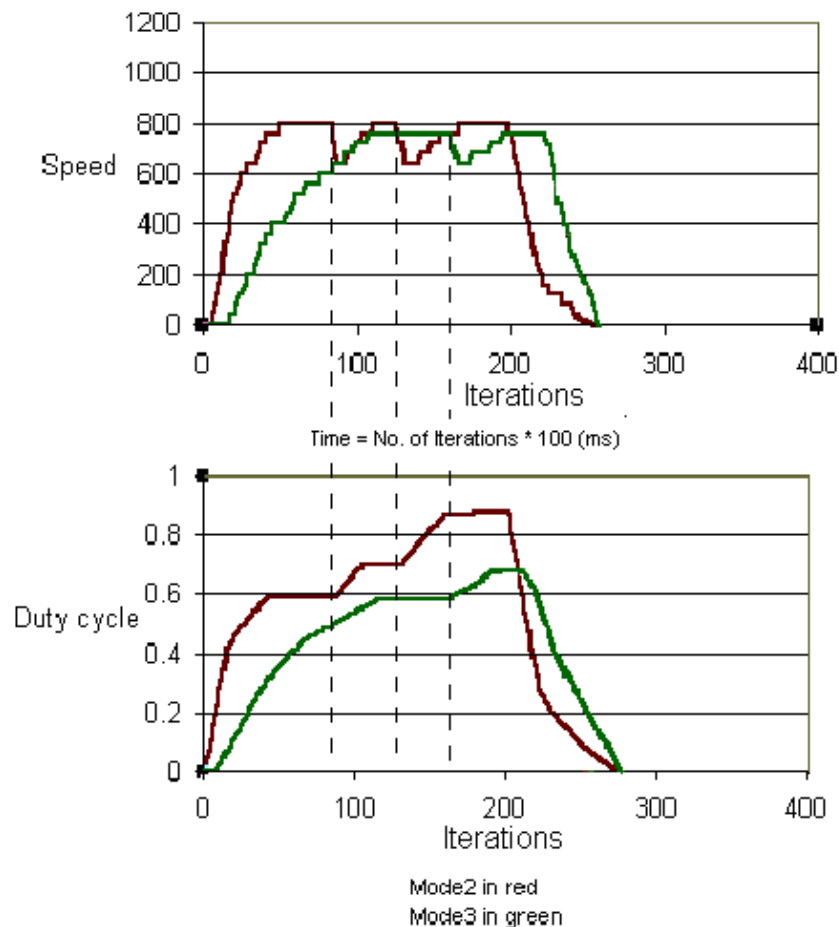


Figure 10. Dynamic Response of the System due to Reduction in Supply Voltage.

5. Conclusions

In this paper, the use of LabVIEW as a graphical and programming language has been demonstrated to build a control scheme to maintain the speed of a DC motor constant regardless of the load or supply voltage variations. Also, the proposed system provides soft start/ stop transient operations, which improves the system dynamic performance.

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- Using the LabVIEW PWM Toolkit with the LabVIEW control

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