Design and Simulation of a Switched-Capacitor PID Control System using LabView Simulator

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Abstract
This paper presents a design and simulation of a switched capacitor PID controller to control the speed of DC motor. The work is divided into two parts which are hardware design for PID controller and software simulation. Basic operational amplifier circuit is used for design PID controller circuit. The PID parameters are calculated and used in LabView program (ver.10) for studying the response of the system. A crystal Oscillator circuit is used to generate two non-overlapping clocks for switching the MOSFET transistors with high accuracy and stability. The advantages of Switched Capacitor Circuits are Compatibility with CMOS technology, good voltage linearity and good temperature characteristics**.** Simulation results present a good performance for proposed design.
Keywords: PID Controller, Switched Capacitor, DC Motor, LabView

الخلاصة
يتطرق البحث الى تصميم ومحاكاة مسيطرتناسبي–تكاملي–تفاضلي ذو تقنية المتسعة المفتاحية للسيطرة على محرك تيار مستمر . يقسم العمل الى جزءين وهي تصميم الكيان المادي للمسيطروالمحاكاة البرمجية . تم استخدام دائرة مضخم عمليات اساسية لتصميم دائرة المسيطرنوع PID واحتساب قيم (K_p, K_i andK_d) التي استخدمت في برنامج LabView (ver.10) لدراسة استجابة المنظومة. تم استخدام دائرة المذبذب البلوري لتوليد نبضات غير متداخلة لفتح وغلق ترانزستورات نوع MOSFET بدقة واستقرارية عالية. ان من مزايا دوائر تقنية المتسعة المفتاحية هي التوافق مع تقنية CMOS، العلاقة الخطية الجيدة للجهد والخصائص الجيدة فيمايتعلق بدرجة الحرارة. قدمت نتائج المحاكاة أداء جيدا للتصميم المقترح.
الكلمات المفتاحية : مسيطر تناسبي–تكاملي–تفاضلي, المتسعة المفتاحية , محرك تيار مستمر , LabView

1. Introduction
Proportional Integral Derivative (PID) controller is one of the earlier control methods which is simple control structure that is understood by plant operators and easy to tune [Dingyu Xue, *et, al* , 2007] It is used in a wide range of applications in industrial control.

Resistors occupy a large amounts of area in integrated circuits (IC), particularly compared to MOS transistors. Switched-capacitor (SC) circuits are an elegant way to eliminate the resistors by replacing those elements with capacitors and switches [Richard *et. al,* 2011] a capacitor can be implemented on an integrated circuit more easily than can a resister. A large equivalent resistance can be simulated by using a small capacitance and an appropriate clock frequency. Capacitor also offers other advantages such as no power dissipation.

There are several methods for controlling the DC motor. Pratap S Vikhe et al [2015], presents a PID to control a DC motor. The ATmega Microcontroller is used in the design. The speed will be set by creating a Graphic User Interface for PID Controller in LabView. Panduranga Talavaru *et al* [2014] , used the microcontroller ATMEGA32 and LabView software to design and implementation of dc motor speed in two direction and position control system . The PWM signal generated by using microcontroller Atmega32 will drive the motor driver circuit...Saurabh Dubey and Srivastava [2013] present the analysis of control the speed of DC motor using PID controller. PID controller basics and different methods of tuning for PID controller are explained. The MATLAB/ SIMULINK used to build the mathematical modeling of dc motor. Salim *et al* [2013], present the process of controlling a PID temperature system of the electromagnetic oven using LabView program which aided to adjust the PID parameters to control the motor speed and temperature of electromagnetic oven S.Muruganandhan *et al* [2013], show the analysis with experimental results that the speed control of motor established with LabView can effectively control the speed. Data-Acquisition Toolbox is used for conversion signal. Jamal [2013], implements the design of control the speed of DC motor in two direction using Pulse Width Modulation technique based on the integrated circuit LM324. Neerparaj and Bijay [2013] present the Neural Network and PID controller to design and implementation of DC motor speed control system. Firas [2013] designed and implemented an electronic interface circuit for controlling the speed of DC motor with the aid of a personal computer. The basic operation of the proposed circuit is based on the pulse width modulation. Dipti and Deshmukh [2013] implemented a Pulse Width Modulation with the help of LM3524 for control the speed of PMDC motor. Vinod and Pandey [2013], describe a Pulse Width Modulation technique to control the speed of PMBLDC motor. The speed is regulated by proportional integral controller. SIMULINK was utilized with MATLAB.

In this research, the switched capacitor technique is used to implement the PID controller for controlling the speed of DC motor. The values of PID parameters (K_p, K_i and K_d) are calculated and used a LabView program version 10 for studying the response of the system.

2. Theory

2.1 Switched-capacitor circuit

Figure (1) shows a general model of a switched-capacitor circuit.

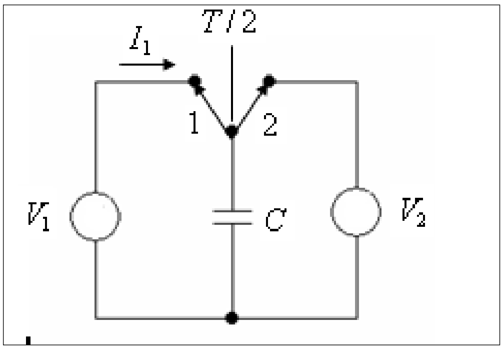

Figure (1): Basic operation of a switched-capacitor circuit

Assuming that the source voltage V_1 and discharge voltage V_2 are constant during the time period T and V_1 larger than V_2,the average current produced by V_1 is I_1 and the capacitor rapidly discharges to the voltage V_2, then the average current is [Floyd,2009]:

$$current = I_{1(avg)} = \frac{q_{1(T/2)} - q_{1(0)}}{T} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots.. (1)$$

Where $q_{1(0)}$ is the charge at $t = 0$ and $q_{1(T/2)}$ is the charge at $t = T/2$ Therefore, when the switch at position (1), $q_{1(T/2)} - q_{1(0)}$ is the net charge transferred.

By substituting $q = C * V$ in the previous equation:

$$I_{1(avg)} = \frac{C(V_{1(T/2)} - V_{2(0)})}{T} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{(2)}$$

Because V_1 and V_2 are constant during T, the average current became as follows:

$$I_{1(avg)} = \frac{C(V_1 - V_2)}{T} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{(3)}$$

Figure (2) shows a conventional resistive circuit with two voltage sources.

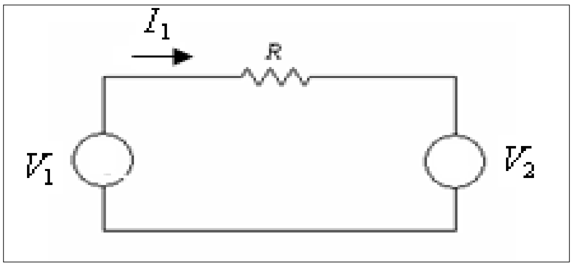

Figure (2): Conventional resistive circuit

From Ohm's law, the current is:

$$I_1 = \frac{V_1 - V_2}{R} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{(4)}$$

For the switched-capacitor circuit eq. (3) equal eq. (4):

$$\frac{C(V_1 - V_2)}{T} = \frac{V_1 - V_2}{R} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{(5)}$$

Solving equation (5) for R and canceling the $V_1 - V_2$ terms,

$$R = \frac{T(V_1 - V_2)}{C(V_1 - V_2)} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{(6)}$$

$$R = \frac{T}{C} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{(7)}$$

From equation (7) the value of resistor can be determined by the time period T and the capacitance C. Figure (1) shows the two-pole switch which is used in each position for one-half of the time period T that varies by varying the frequency. The MOSFETs transistors in figure (3) acting as the switch with their (ON) and (OFF) times are controlled by timing signals with programmable the frequencies. The two square waves are turning the MOSFETs transistors (ON) and (OFF) that are 180° out of phase so that when one transistor is (ON) the other transistor is (OFF) with no overlap.

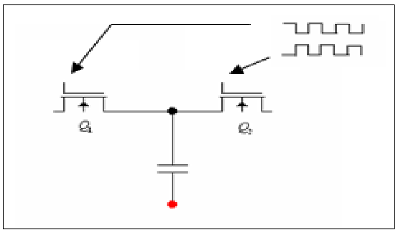

Figure (3): A switched-capacitor circuit with MOSFET switches

2.2 Proportional-integral-derivative (PID) controller

Figure (4) shows the schematic model of a control system. Control signal $u(t)$ is a linear combination of error $e(t)$, its integral and derivative [Karl Johan Astr¨om, 2012] as shown below:

$$u(t) = K_P e(t) + K_I \int e(t)dt + K_D \frac{de(t)}{dt} \quad \text{.......................................} \ (8)$$

$$u(t) = K_P (e(t) + \frac{1}{T_I} \int e(t)dt + T_D \frac{de(t)}{dt}) \quad \text{...................................... ....} \ (9)$$

Where

K_P =proportional gain

K_I =integral gain

K_D =derivative gain

T_I =integral time

T_D =derivative time

Where the derivative term is may be replaced with a backward difference and the integral term may be replaced with a sum for a small constant sampling time T_S if the controller is digital, then equation (9) can be approximated as follows:

$$u(n) = K_P (e(n) + \frac{1}{T_I} \sum_{j=1}^{n} e(j)T_S + T_D \frac{e(n) - e(n-1)}{T_S}) \quad \text{........................} \ (10)$$

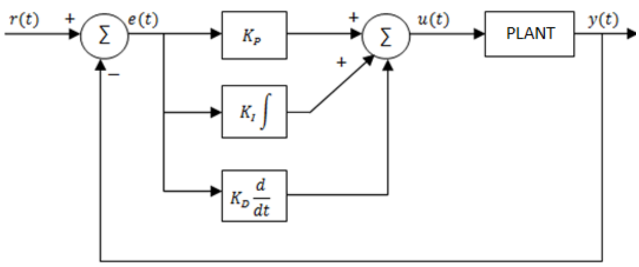

Figure (4): PID control system

3. Proposed System Design

Transfer functions of PID controllers can be realized using electronic circuits. Figure (5) shows a simple operational amplifier circuit with input voltage $V_i(s)$, output voltage $V_o(s)$, input impedance $Z_i(s)$, and feedback impedance $Z_f(s)$.The transfer function of the circuit can be written as follows:

$$G(s) = \frac{V_o}{V_i}(S) = -\frac{Z_f(s)}{Z_{o(}(s)} \quad \text{..............................} \ (11)$$

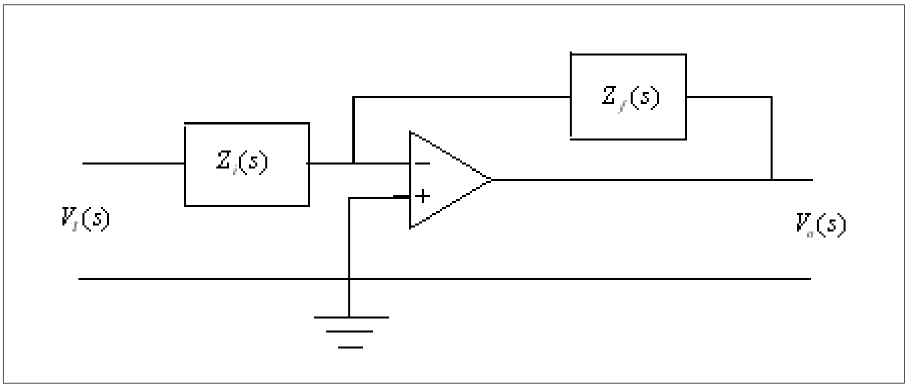

Figure (5): Basic Operational Circuit

If PI and PD controllers are joined in parallel then PID controllers can be implemented. But this is expensive. Instead, the usual implementation is shown in figure (6).The transfer function is [Karl Johan Astr¨om, 2012]:

$$\frac{V_o(s)}{V_i(s)} = -\frac{(RCs+1)(R_2C_1S+1)}{Cs(R_1+R_2+R_1R_2C_1s)} \quad \text{.........................} (12)$$

$$\frac{V_o(s)}{V_I(s)} = -(\frac{RC+R_2C_1}{R_2C} + \frac{1}{R_2Cs} + RC_1s)\frac{\beta}{(\beta R_1C_1s+1)} \quad \text{........} (13)$$

$$\frac{V_o(s)}{V_I(s)} = -(K_P + \frac{K_I}{s} + K_DS)\frac{1}{\beta R_1C_1S+1)} \quad \text{....................} (14)$$

$$v_o = -(K_Pv_i + K_I\int_0^t e_idt + K_D\frac{de_i}{dt}) - \beta R_1C_1\frac{de_o}{dt} \quad \text{.............} (15)$$

Where

$$\beta = \frac{R_2}{R_1+R_2} \quad \text{..........................} (16)$$

$$K_P = \beta\frac{RC+R_2C_1}{R_2C} \quad \text{.........................} (17)$$

$$K_I = \frac{\beta}{R_2C} \quad \text{........................} (18)$$

$$K_D = \beta RC_1 \quad \text{.......................} (19)$$

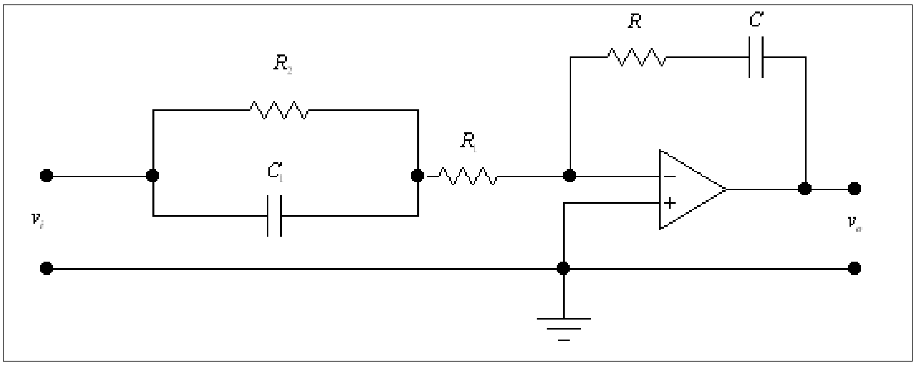

Figure (6): Implementation of operational amplifier circuit as PID Controller

4. The Simulation of Proposed Circuit and its Results

Figure (7) shows the implementation of operational amplifier circuit as PID Controller. The circuit of Clock Function Generator is shown in Figure (8). The design depends on the crystal oscillator circuit that generates two non-overlapping clocks by using the two independent comparators of the LM741. The oscillator circuit is used to drive a switching transistor. *C*1 oscillates and *C*2's output will toggle at different times. The clocks control the operating of two switching transistor of type 2N700.

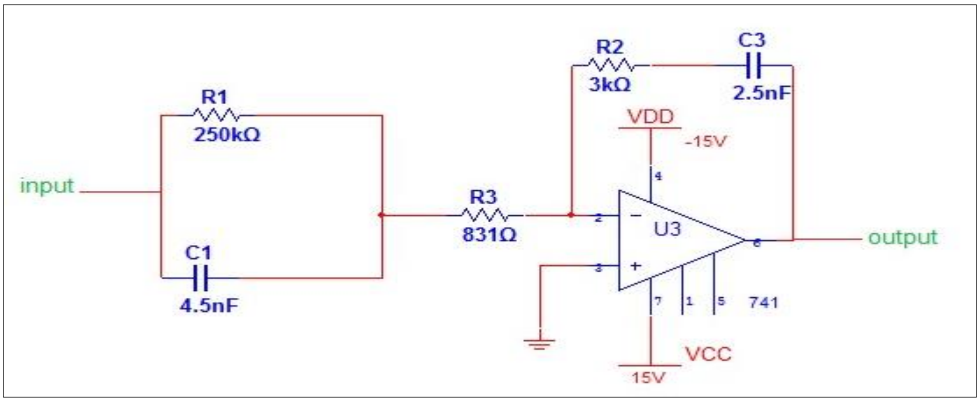

Figure (7): PID controller design

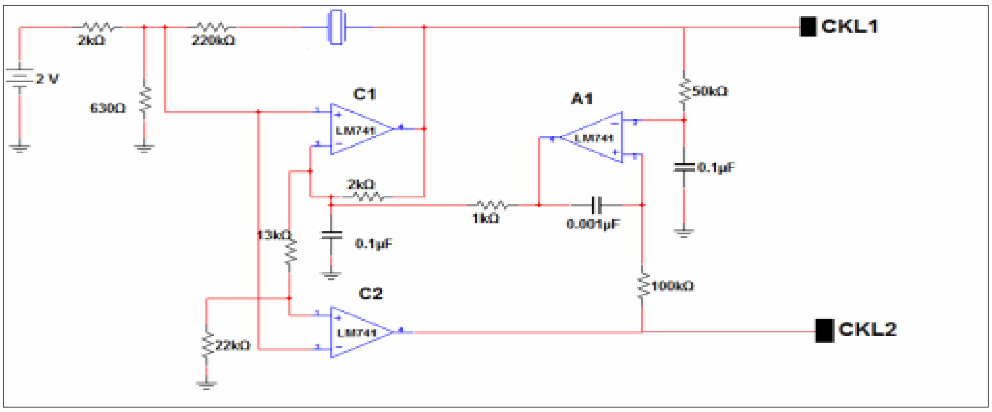

Figure (8): Clock Function Generator

Figure (9) shows a PID controller circuit with switched-capacitor. Figure (10) shows the implementation of closed loop PID controller in LabView. Figure (11) represents the Front panel in LabView which indicates step response graph, impulse response graph, Bode magnitude, Bode phase with parameters of PID and motor(Figures 12,13,14 and 15 respectively).

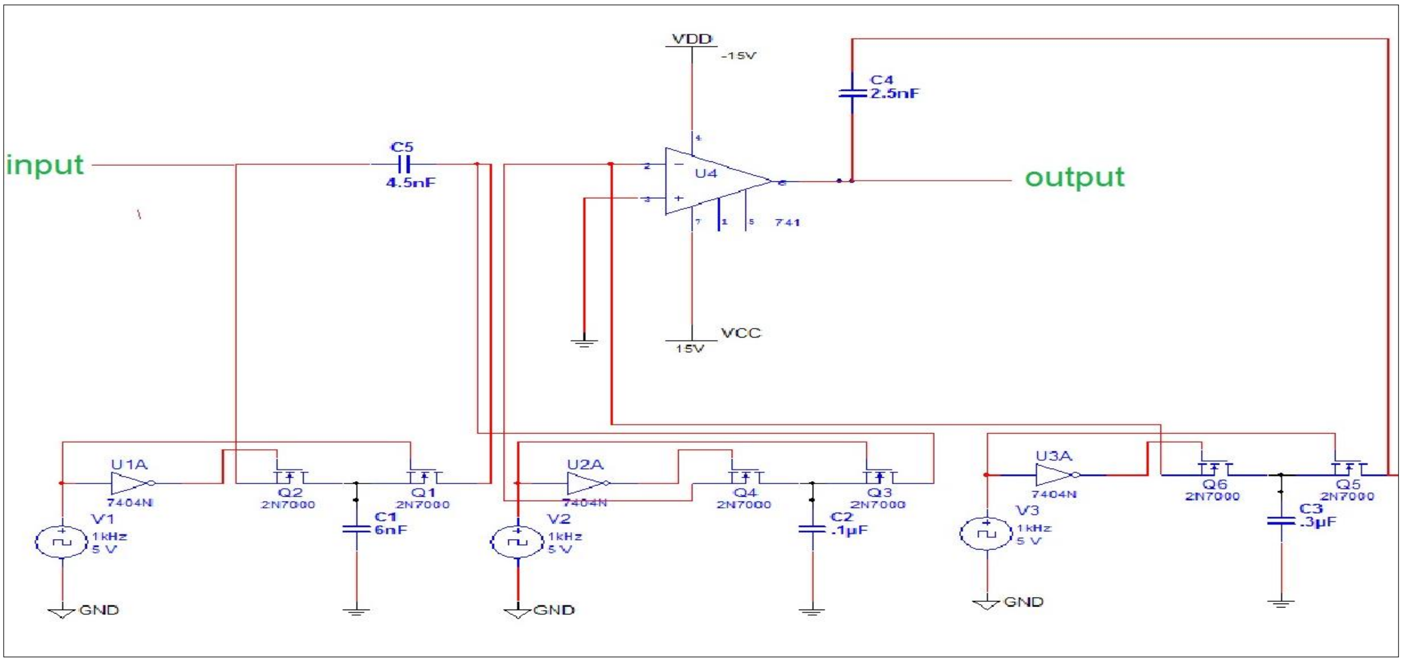

Figure (9): PID controller circuit with switched- capacitor

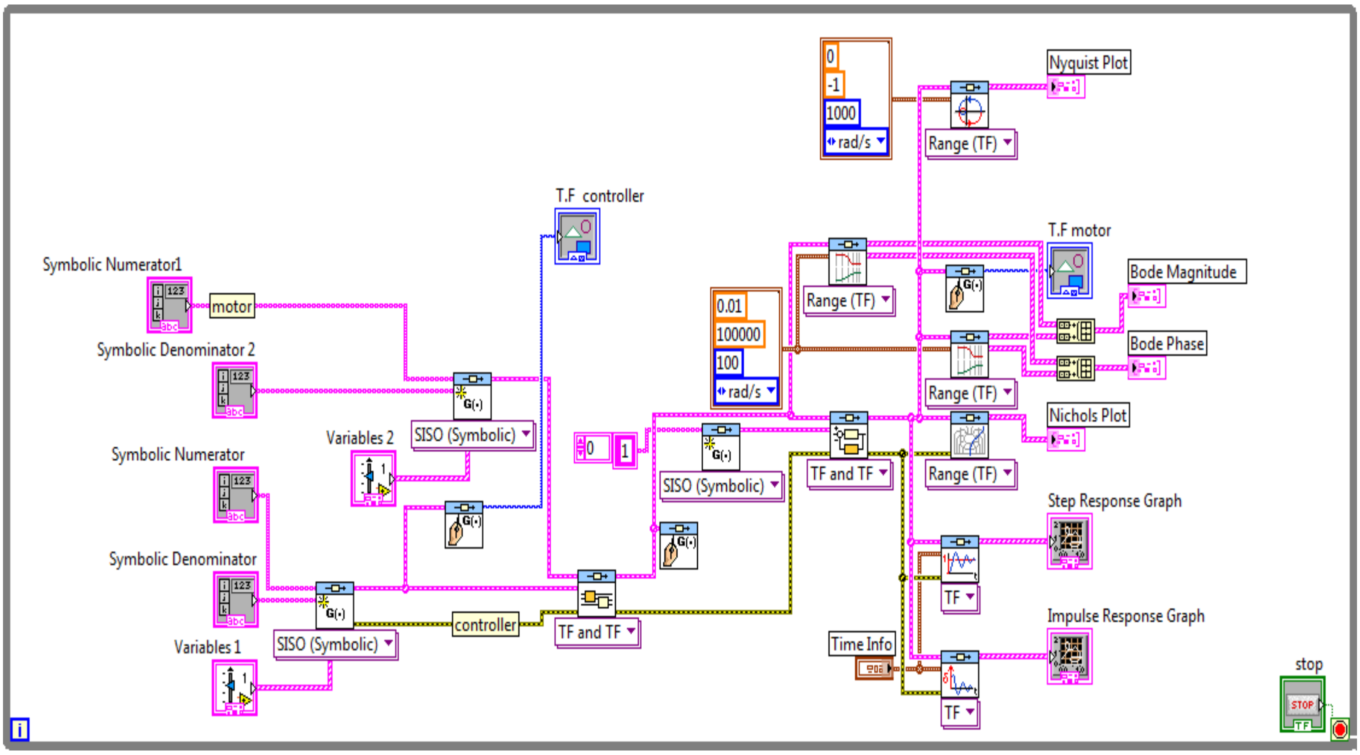

Figure (10): Blok Diagram Closed loop PID controller in LabView

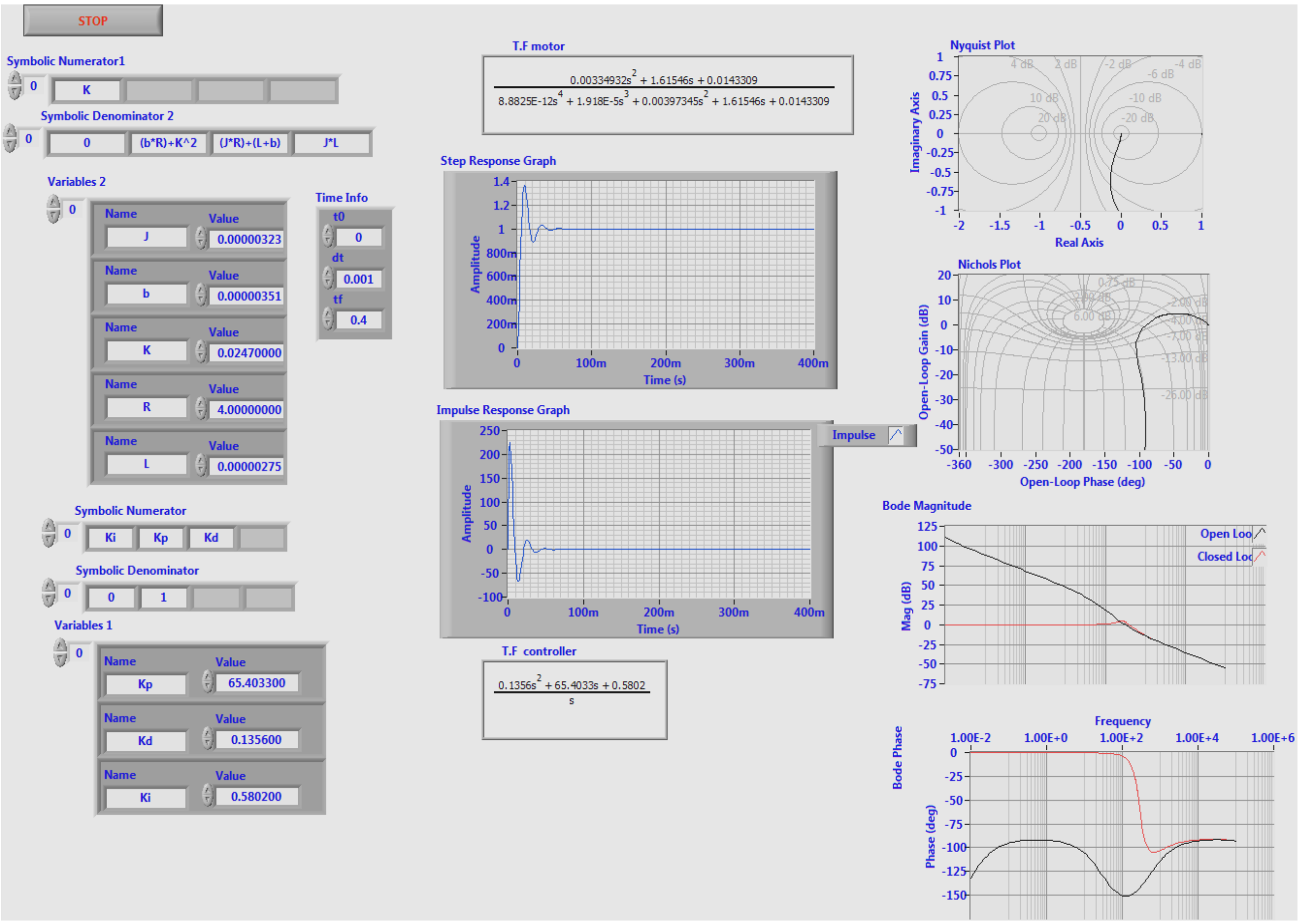

Figure (11): The Front panel closed loop PID controller in LabView

By using the equations (17, 18, and 19), we calculate the values of K_p, K_i, K_d as follows:

K_P=65.4033 , K_i=0.5802, K_d =0.1356

The above parameters are used in LabView program which gives the transfer functions of controller as follows:

$$T.F. = \left[\frac{0.1356S^2 + 65.4033S + 0.5802}{S} \right] \quad \text{.......... (20)}$$

The equation of the motor is [Payal P.Raval, 2012]:

$$G_v(s) = \frac{w(s)}{V(s)} = \frac{K}{(R + L_s)(J_s + b) + K^2} \quad \text{............. (21)}$$

The transfer function from the input voltage, V(s), to the angular velocity, w, the parameter of the motor used in this proposed design is:

J=0.00000323

b=0.00000351

k=0.02470000

R=4.00000000

L=0.00000275

Also, by using LabView program, we obtained the transfer function of motor as follows:

$$T.F.=\frac{0.00334932S^{2}+1.61546S+0.0143309}{8.8825E-12S^{4}+1.292E-5S^{3}+0.00397345S^{2}+1.61546S+0.0143309}$$

From figure (12) the following parameters are calculated:
Overshot=1.3
Steady state error=1.0
Settling time=30ms

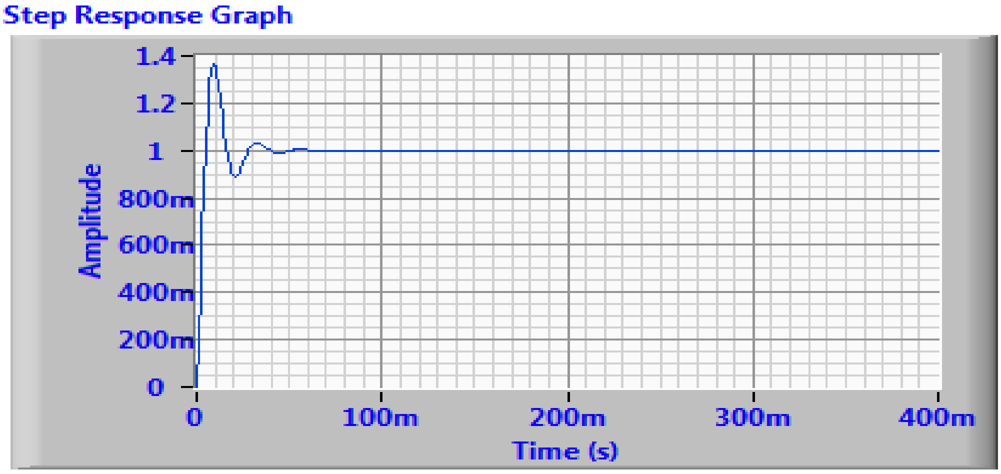

Figure (12) Step response graph

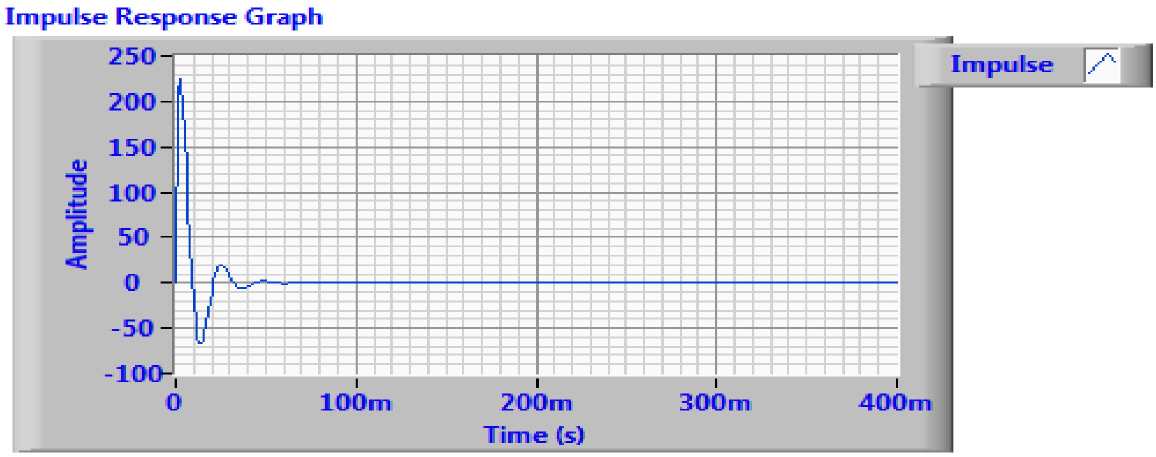

Figure (13) Impulse response graph

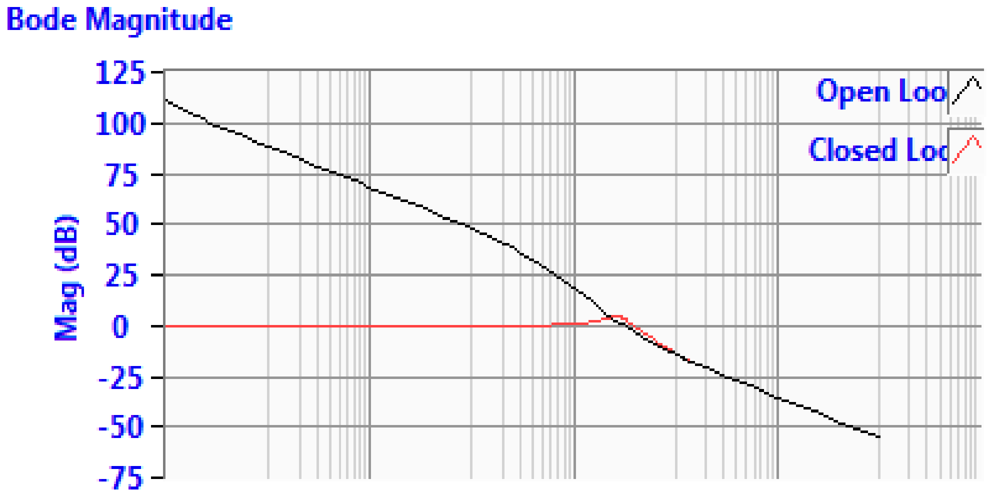

Figure (14): Bode Magnitude

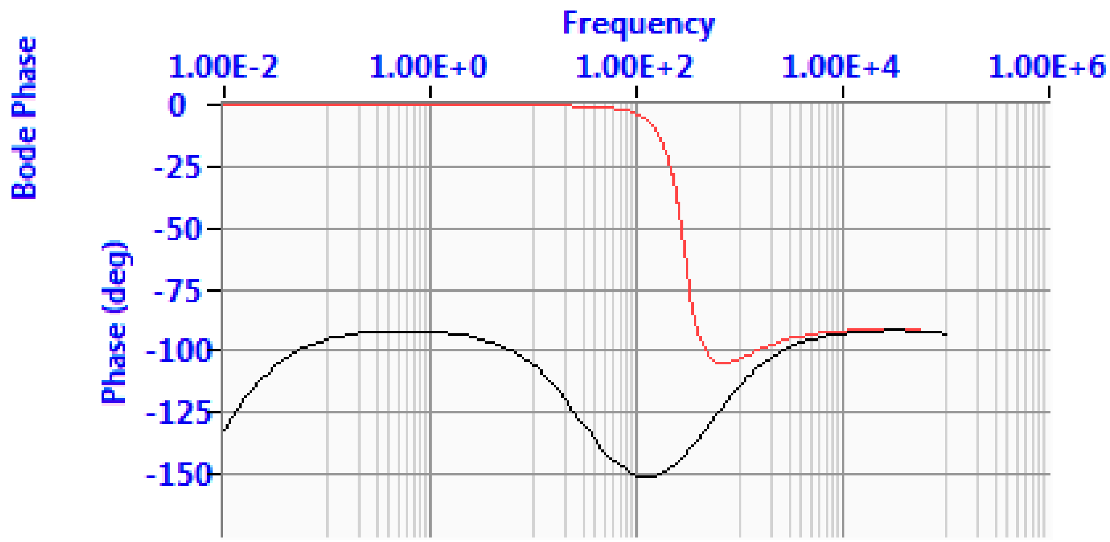

Figure (15): Bode Phase

5. Conclusions

1. The paper presented a new design for controlling the speed of DC motor by using a switched capacitor technique to PID controller. The main advantage of SC circuit is that the capacitor ratios determined the operation of the circuit; hence it is less sensitive to mismatch errors. Thereby the cicuit is mostly very linear. Another advantage is accuracy. Since the capacitor ratio can be accurately controlled and since the clock frequency can be generated from an external crystal, the accuracy of integrated SC filters can be very good.
2. A Switched-Capacitor (PID) Controller for the DC motor speed control was successfully implemented with LabView program which is proven to be an excellent tool for studying the characteristic of the system (fig.11).
3. The results and the graphs (figures12, 13, 14 and 15) indicated a good performance for proposed PID Controller design.
4. Bode plots (figures 14, 15) are graphs of the steady-state response of stable continuous-time LTI systems, plotted as change in magnitude and phase versus frequency.

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