FPAA BASED DC MOTOR SPEED CONTROL [+]

استخدام المصفوفات المتشابهة في السيطرة على سرعة محرك تيار مستمر

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Abstract:

This paper presents design, modeling, simulation and hardware implementation of a separately excited Direct Current (DC) motor speed control using Field Programmable Analog Array (FPAA) technology. The hardware consists of a DC motor system, Proportional-Integral-Derivative (PID) controller using FPAA kit, power module, and tacho-generator. The results show that there is a reduction in overshoot, settling time, rising time and steady-state error compared with the conventional PID controlled system. The proposed system has been simulated using MATLAB software to study the effect of adding a PID controller on the factors affects the DC Motor speed. The model results show enhancement in the overshoot, settling time and improve the steady-state and transient response of the system.

ألمستخلص:

يهدف البحث الى تصميم، نمذجة، محاكاة، والتطبيق العملي للسيطرة على سرعة محرك تيار مستمر منفصل الاثارة باستخدام بطاقة المصفوفات المتشابهة (FPAA). تتكون المنظومة المقترحة من محرك تيار مستمر ومسيطر من نوع تناسبي–تكاملي–تفاضلي (PID) مصمم باستخدام بطاقة المصفوفات المتشابهة. اظهرت النتائج ان هناك انخفاض في قيمة القفزة الزائدة (overshoot) بالاضافة الى تقليل الزمن اللازم للوصول لحالة الاستقرار، زمن النهوض وخطا الحالة المستقرة مقارنة مع مسيطر (PID) التقليدي. تم محاكاة المنظومة المقترحة باستخدام برمجيات المخبر الرياضي (MATLAB) لدراسة تاثير اضافة منظومة السيطرة من نوع التناسبي–التكاملي–

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التفاضلي (PID) من عدمه على العوامل المؤثرة على سرعة المحرك. اظهرت نتائج الاختبار حالة تحسن في نسبة القفزة الزائدة، زمن الاستقرار وخطا الحالة المستقرة.

Introduction:

Direct current motors hold the very important status in the electric driving automatic control system. Relative to the alternating current motor, the performance of DC motor's speed control is much better. It is the first choice in the applications which require wide range of speed regulation and high-precision speed, and it has been widely used in Computerized Numerical Control machine tools and process control. It has great significance to study the direct current motor's velocity control [1]. The objective of a control system design is to make a physical system behave in a useful fashion, causing its output to track a desired reference input even in the presence of noise, modeling error and disturbances. In the control system, one of the main components is the controller which generates the appropriate control signal for the physical system to regulate the system performance. The Proportional-Integral-Derivative (PID) controller is one of the most common types of feedback controllers that are used in dynamic systems .It is used in a wide variety of control systems due to its simple structure and robust performance [2]. PID controllers are undoubtedly the most adopted controllers for industrial plants, mainly because, despite their simplicity, they can assure satisfactory performances for a wide range of processes. Thus, the cost/benefit ratio they provide which is difficult to achieve by other controllers. To simplify the operators work, many tuning formulas have been devised in the last 60 years. Three parameters of a PID controller must be determined and tuned to obtain a satisfactory closed-loop performance. Thus methods to tune the parameters of PID controllers are very important for the process industries. There are two main classes of methods for tuning the PID controller: traditional methods and intelligent methods. Traditional methods such as Ziegler Nichols often do not provide good tuning and are easy to produce surge and big overshoot. On the other hand, several intelligent approaches have been suggested to improve PID tuning, for instance, the fuzzy self-adjusting, artificial neural network method (Tao, Y. H. et al., 1998). An intelligent algorithm also has been widely used to tune the parameters of PID controller [3].

Conventional PID Controller:

PID controller is a traditional linear control method that used commonly in industrial applications. PID letter is stand for the calculation (algorithm) that involves three separate parameter, the proportional, the integral and derivatives. A PID and PI controllers are designed for buck converter for operation during a startup transient and steady state, respectively [4].

The block diagram of PID controller of conventional PID control is shown in Fig. (1). the model in time domain is as follows:

$$u(t) = K_p \left[e(t) + \frac{1}{T_i} \int_0^t e(t) + T_d \frac{de(t)}{dt} \right] \qquad (1)$$

Where K_p denotes proportional gain, K_i ($K_i = K_p / T_i$) denotes integral constant and T_i is the Integral time. While K_d ($K_d = K_p T_d$) denotes differential constant and T_d is the derivative time. The increased K_p enhances the speed response of the system and improves control precision, but the over much of K_p will results in instability of the system. K_i can remove steady-state error of the system. And K_d can improve dynamic performance of system [5].

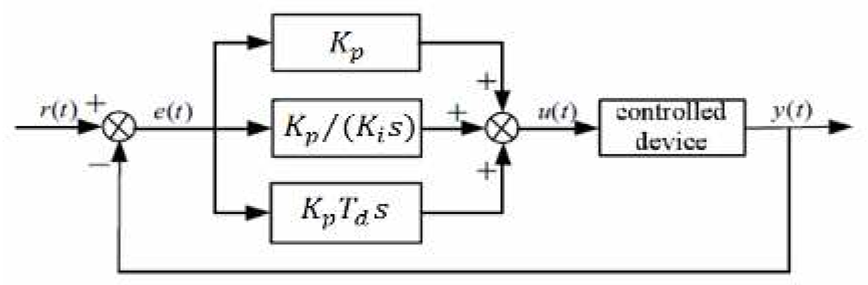

Figure. (1) Block diagram of PID controller

The PID controller can be implemented using analog circuits or software (discrete PID controller algorithm) with microcontrollers. Both implementations have advantages and disadvantages:

1. The classical analog implementation has the advantages of continuous operation, but the disadvantage that it is difficult to tune the constants, and this process can be done manually and which is time consuming.
2. Software implementation of the PID controller presents the advantage of easily tuning and adjusting the controller parameters, with the possibility of auto-tuning or self-tuning. This implementation is more flexible, but has the disadvantages that it is not continuously and the microcontroller resources are mostly used for PID algorithm than for other activities. Also, there are some difficulties for fast time response applications [6]. In the industry control, PID is the most commonly used method, Because of their immediately perceptive, simple structure robust performance and good features. PID parameters tuning, however, was a complex work traditional. PID parameters tuning method was artificial Trial, But it could not achieve the optimal controller [7].

The implementation of PID controllers using microprocessors and DSP chips are well understood, whereas very little work was reported in the literatures on how to implement the PID controllers using FPAAs as FPAA is relatively new technology.

FPAA Structure:

FPAAs can be used for the realization of different functional units, circuits, circuit elements. These circuits can be used effectively in applications where the low electric power, the lower development and component cost, the effective electronic of Computer Aided Design (CAD) possibility are important. The advantage of FPAAs in the field of faster and more economical circuit planning is significant [8]. The general architecture of FPAA circuit made by Anadigm is presented in Fig. (2), and it is composed of four Configurable Analog Blocks (CABs) each with two operational amplifiers capacitor array, interconnection resources, memory cells and some additional elements. The most advantage of the FPAAs is the possibility of dynamically reconfiguration of the CABs, which is a very important feature, making possible the tuning of the characteristics of analogue section to the design requirements. This is very useful in applications like sensor conditioning where dynamically tune and adapt the signal characteristics to the front end specification can improve the sensor performance. Another advantage of using the FPAAs is offered by the switched capacitor technique that replaces the dissipative components and reduces the power consumption of the circuit [9].

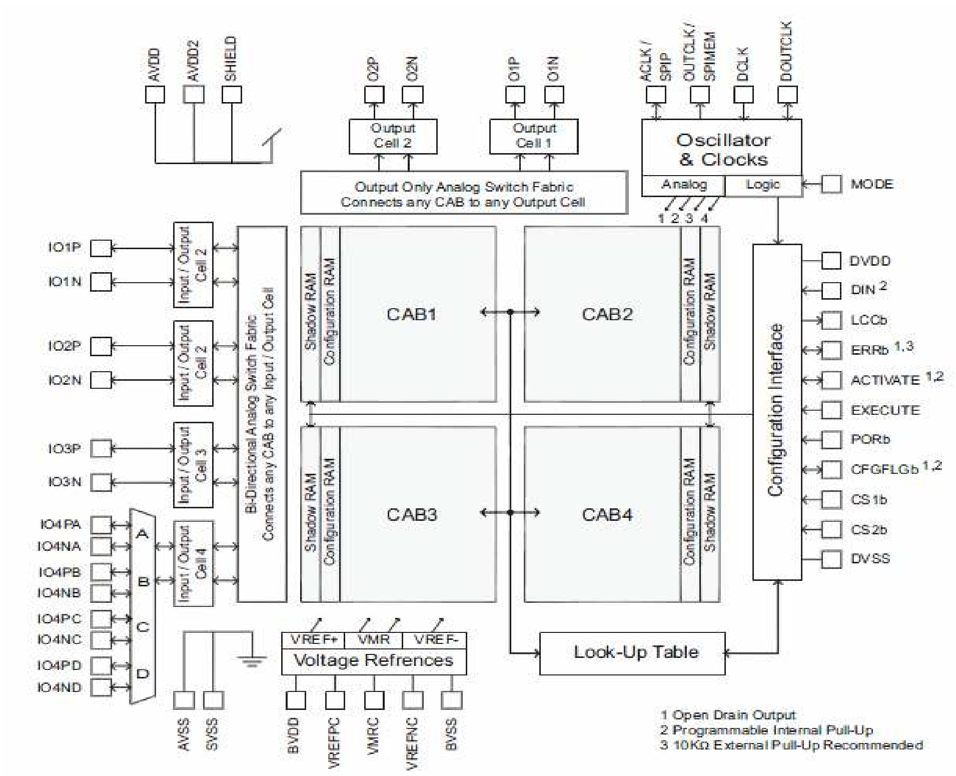

Figure. (2). Block diagram of AN221E04 FPAA.

Buck Converter:

Buck converter is a typical reduction voltage DC/DC topology, which has been used widely in DC regulated power supplies such as photovoltaic system, DC motor regulated speed, LED illumination, and other electrical power and electronics systems. The topology of Buck converter is shown in Fig. (3). T is switch, L is inductance, C is capacitance, D is freewheel diode, R is load resistance. i_L is the current of inductance L , V_i is input voltage, V_o is output voltage [10].

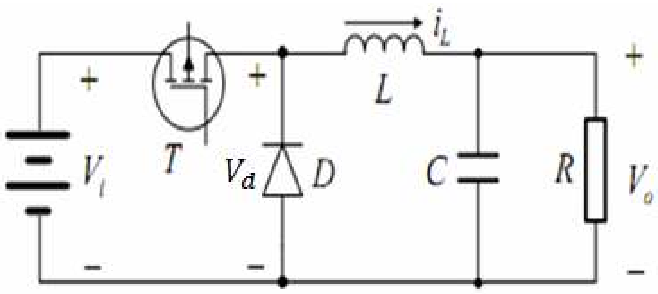

Figure. (3) Buck converter topology.

The DC-DC converter can operate in two distinct modes, which are either in Continuous Conduction Mode (CCM) or Discontinuous Conduction Mode (DCM). The term continuous and discontinuous is referred to induction current [11].

However the DC-DC converters that operates in CCM is only considered for this paper. The circuit operation can be divided into two modes. First mode (mode 1) begins when the controlled switch is switched on, the input current rises, through filter inductor (L), filter capacitor (C), and load resistor (R). During this mode, the diode (D) is reversed biased resulted from flowing current, and the input provides energy to the load as well as to the inductor. The result is a positive inductor voltage, $V_L = V_d - V_o$. It causes linear increase in inductor current.

Mode 2 begins when the controlled switch is switched off, and the freewheeling diode (uncontrolled switch) conducts due to energy stored in the inductor (L) and the inductor current continues to flow through L, C, R, and D. During this interval, $V_L = -V_O$ for time duration (1-d)T where (d) is the Duty cycle and (T) is the Time for one cycle period until the switch is turned on again [4].

Without considering any harmonics, the transfer function of Buck converters in continuous mode conduction is represented by the following equation:

$$\frac{V_o(s)}{V_i(s)} = \frac{\frac{d}{L.C}}{S^2 + \frac{S}{R.C} + \frac{1}{L.C}} \tag{2}$$

Where (S) is Laplace operator and (d) is duty cycle. Assuming constant DC input voltage, equation (2) can be further transformed as:

$$\frac{V_o(s)}{d} = \frac{\frac{V_i}{L.C}}{S^2 + \frac{S}{R.C} + \frac{1}{L.C}} \tag{3}$$

As a result, one can dynamically control the duty cycle d to achieve the desired output voltage. Since equation (3) is a second order system, a PID controller is normally selected to reduce transient overshoot and eliminate steady state error. Correspondingly, the closed loop block diagram of the control system is represented by Fig. (4) [12][13].

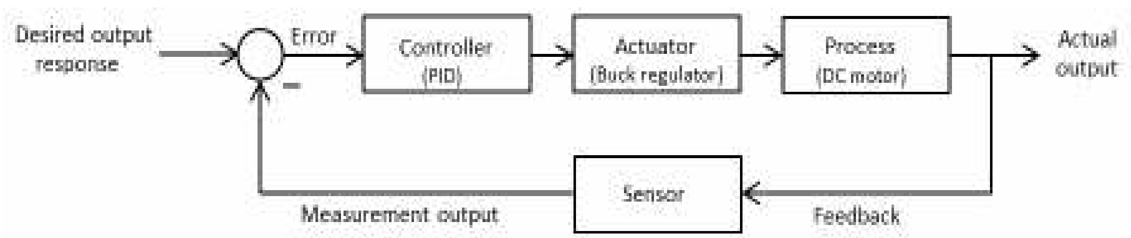

Figure. (4) Closed loop control block diagram.

The package like the Matlab/Simulink is a very useful environment for simulation of switching converters, the system stability and transient behavior analysis can also be performed. In this paper, MATLAB Simulink package is chosen as software platforms [11].

In this paper, the adaptive control architecture is described and implemented by the field programmable analog arrays (FPAAs). The proposed adaptive control scheme for interleaved DC-DC converters is described in section **4**, the Transfer function and mathematical formulation of the system is described in section **5**, the hardware circuits and simulation are separately presented in section **6** and section **7** respectively.

Transfer function of the system:

The transfer functions of the system shown in fig. (4) is formed of :

1. Transfer function for PID controller [14].

Time-domain PID controller formula

$$u_c(t) = k_p e(t) + k_I \int^t e(\tau)d\tau + k_D \frac{de}{dt} \tag{4}$$

Transfer function PID controller formula

$$U_c(s) = \left[k_p + \frac{k_I}{s} + k_D s\right] E(s) \quad (5)$$

2. Transfer function for buck converter [12].

$$\frac{V_O(s)}{V_i(s)} = \frac{\frac{d}{L.C}}{S^2 + \frac{S}{R.C} + \frac{1}{L.C}} \quad (6)$$

3. Transfer function for DC motor [15].

T_m: Motor torque

R_a: Armature resistance (Ω)

L_a: Armature inductance (H)

e_b: back emf

J_m: Rotor inertia (kg.m^2)

∅: Magnetic flux=constant

K_i: Torque constant ($N.m/A$)

i_a: Armature current (A)

e_a: applied voltage (V)

K_b: back emf constant (V/rad/sec)

B_m: Viscous-fraction coefficient (N.m/rad/sec)

θ_m: angular position (rad)

W_m=$\ddot{\theta}_m$=angular speed (rad/sec)

The torque developed by the motor is proportional to the armature current

$$T_m = K_i i_a \quad (7)$$

The circuit equation for the armature

$$e_a = R_a i_a + L_a \frac{di_a}{dt} + e_b \quad (8)$$

$$e_b = K_b \frac{d\emptyset_m}{dt} = K_b W_m \quad (9)$$

The torque about fixed axis is equal to the product of the inertia and the angular acceleration about the axis

$$T_m = J_m \frac{d^2\emptyset_m}{dt^2} + B_m \frac{d\theta_m}{dt} \quad (10)$$

$$\frac{d}{dt} = s \quad , \quad \frac{d^2}{dt^2} = s^2$$

Sub (1) in (4) and (2), (3) in (4) we get

$$T.F = \frac{\ddot{\theta}_m(s)}{E_a(s)} = \frac{W_m(s)}{E_a(s)} = \frac{K_i}{L_a J_m s^2 + (R_a J_m + B_m L_a)s + (K_b K_i + R_a B_m)} \quad (11)$$

Output: speed ($\ddot{\theta}_m$)

Input: voltage (E_a)

<u>Design of Controller with Hardware Circuits:</u>

The hardware components of the system consist of firing circuit, Buck converter, DC motor, tacho-generator, reshaping circuit (AC to DC converter with low-pass filter) and the FPAA as shown in Fig. (5). the experiment set is from Terco Instruments Limited. It is contained of DC motor, variable load, Power supply, tacho generator and torque meter. The system can be shown in Fig. (6). the DC motor data and parameter values are listed in table (1) and (2) respectively. It is assumed that an analog tacho-generator is used here. It is coupled to the motor shaft and its output voltage varies linearly with its speed. A voltage signal obtained from a Tacho-generator is fed back to the comparator input where signal is subtracted from the set-point speed to produce an error signal.

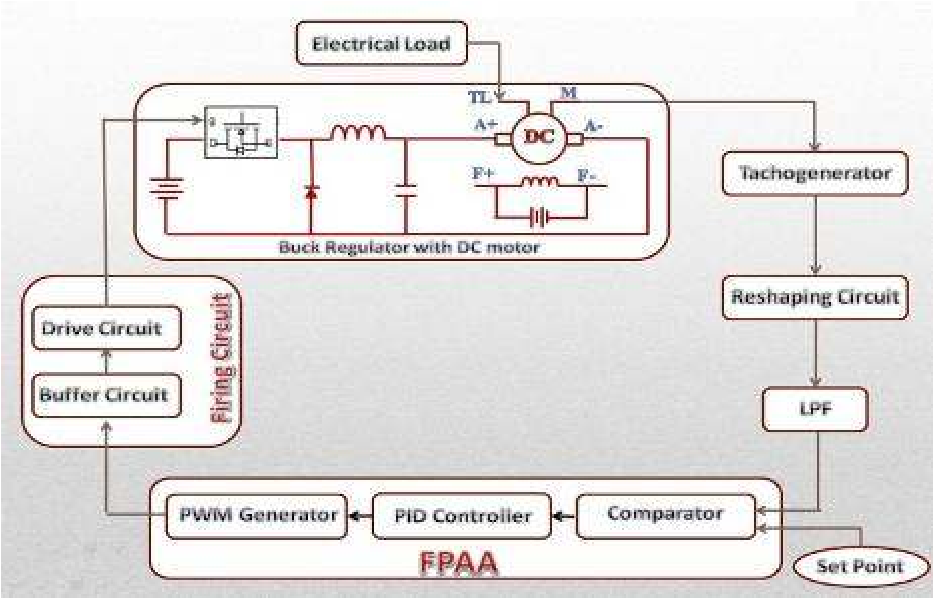

Figure. (5) Over all system model.

Figure. (6) The real parts of the experimented set.

Table (1) DC Motor data

Rated speed	1400 r/min
Rated armature voltage	220 V
Rated field current	0.6 A
Rated load torque	13 N.m
Motor power	2 KW

Table (2) DC motor parameters

Parameters	symbol	value	unit
Armature resistance	R_a	5.97	Ω
Armature inductance	L_a	60.81	mH
Field resistance	R_f	246.7	Ω
Field inductance	L_f	52	H
Mutual inductance	L_{af}	1.6	H
Total inertia	J	0.012	$Kg.m^2$
Viscous fraction coefficient	B	0.0204	N.m.s

This error signal is then fed to a PID controller and PWM circuit which are implemented using FPAA Technology, gives a very fast response to sudden changes in motor speed. For example, if the error speed is negative, this means the motor is running slow so that the controller output should be increased and vice-versa. Normally a filter may be necessary in the feedback circuit for speed. It's also necessary to protect the FPAA device from high current draw and provide the appropriate voltage required to switch the MOSFET. So we designed the circuit shown in Fig. (7).

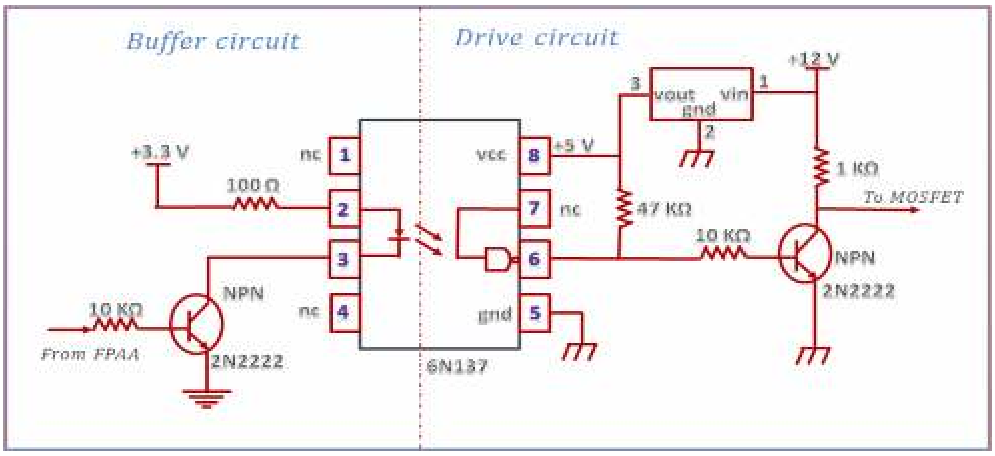

Figure. (7) Firing circuit.

The output port of PWM circuit can be directly connected to the firing circuit for driving the motor. The real time implementation details of the real time PID and PWM circuit are shown in Fig. (8).

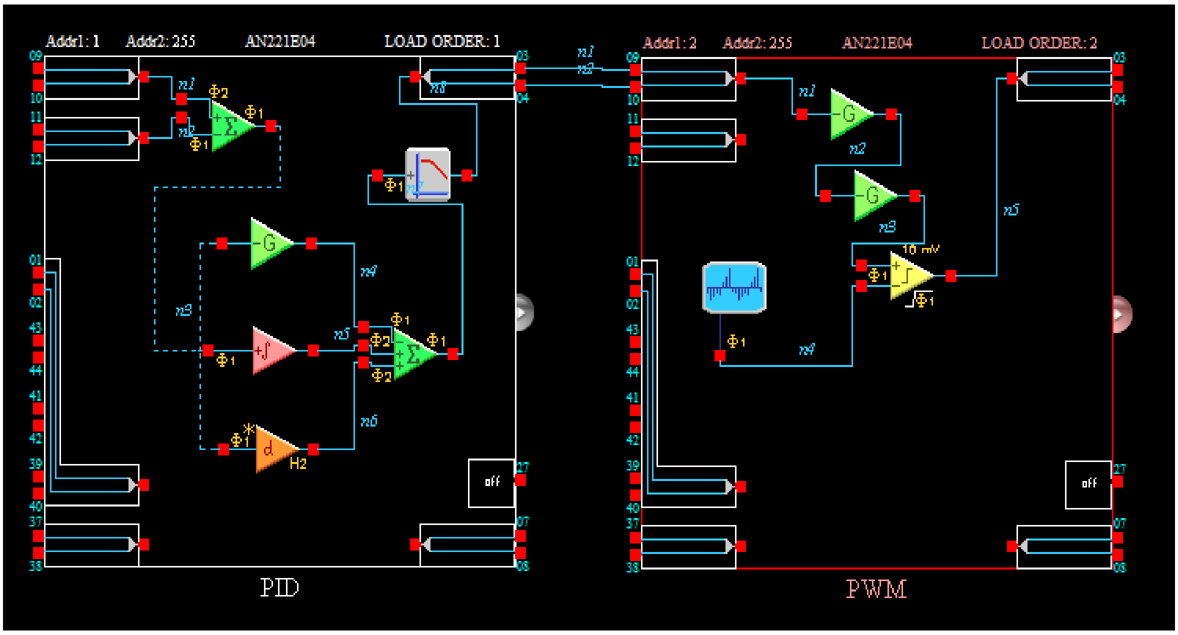

Figure. (8) PID and PWM Controller using FPAA technology.

The DC motor is fed by the DC source through a buck converter that consists of the MOSFET Transistor, the free-wheeling diode along with a low-pass LC filter. The DC motor drives a mechanical load that is characterized by the load torque which can be a function of the motor speed. MOSFET transistor is triggered by a pulse width modulated (PWM) signal generator shown in Fig. (8) To control the average motor voltage. The obtained response of the DC motor drive to successive changes in speed reference and load torque is shown in Fig. (9).

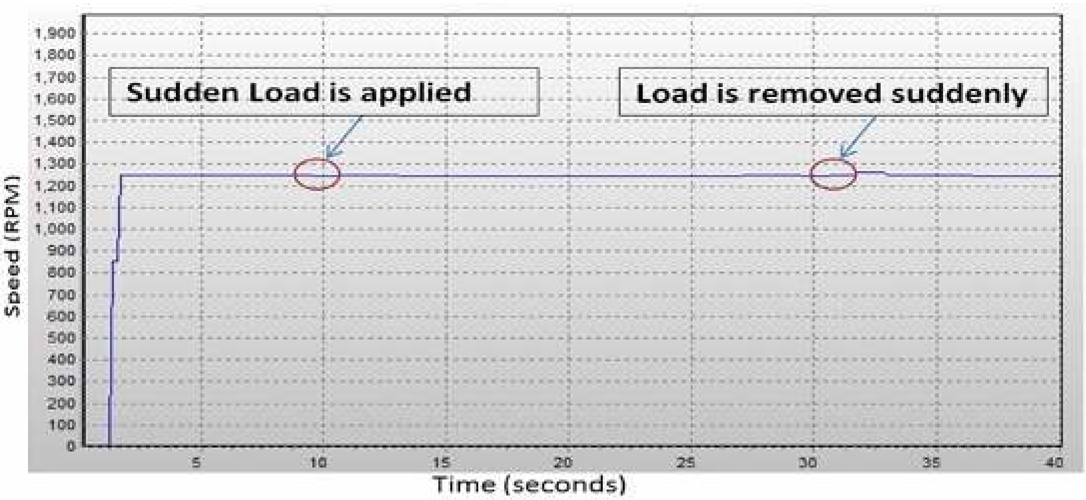

Figure. (9) Response of the DC motor drive to successive changes in speed reference and load torque.

Matlab Simulation Results and Analysis:

The control objective is to make the motor speed follow the reference input speed change by designing an appropriate controller. The PID controller is used to reduce or eliminate the steady-state error between the measured motor speed and the reference speed to be tracked. At first, a model of PID Controller with a 220V separately exited DC motor was done using

Matlab/Simulink. The transfer function model of the motor is then used to design the PID controller to generate a set of coefficients associated with the desired controller characteristics. Fig. (10) Shows the Matlab/Simulink Systems model. The model consists of a separately excited dc motor fed by a DC source through a chopper circuit, designed feedback controller, PWM models, in addition to the variable load and voltage source. The PWM generates the pulse signal corresponding to duty command presented by the PID controller. The speed command intelligent PID controller for speed control of D.C. motor is compared to the speed signal to produce a speed error signal. This signal is processed through a PID Controller to determine the torque command.

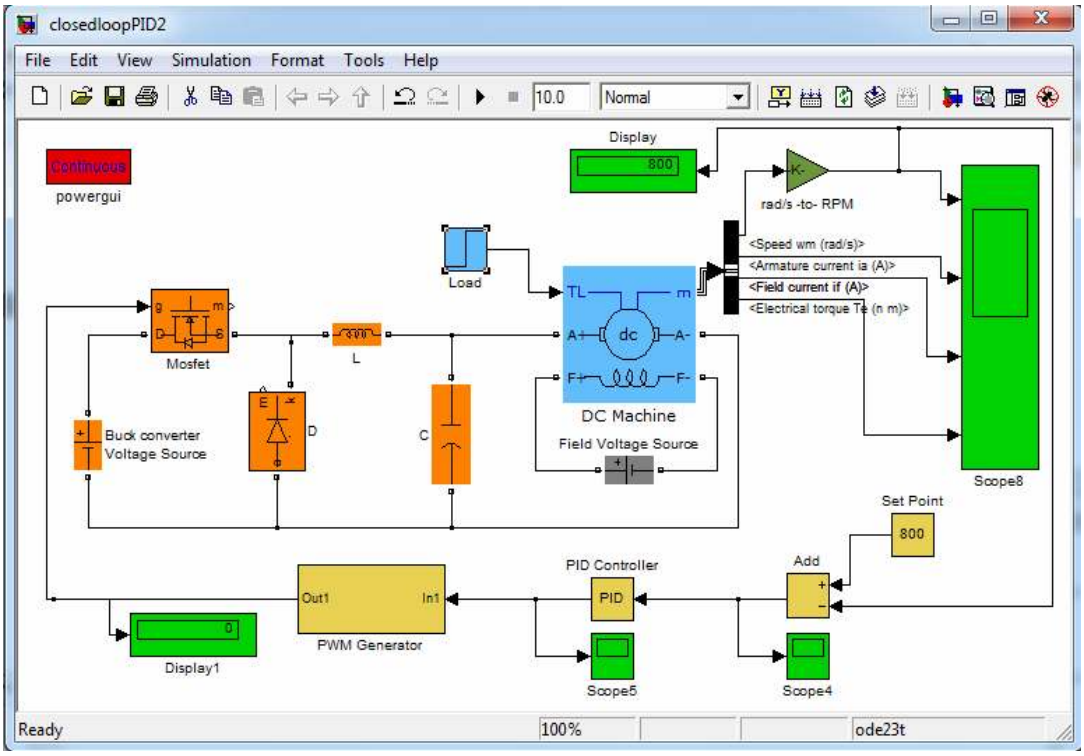

Figure. (10) Matlab/Simulink System model.

The simulation of PID controller based on the trial and error method is presented and applied to the DC motor. These methods are feasible due to the unique and simplified structure of this motor. The PID controller designed has been simulated and observed to have good performance, the values of PID controller were found as follows:

P=21.2, I= 4.78, D= 0.127

Where the results show that the overshoot before adding the PID control was 10.12%. The rising time and the settling times were equal to 30 ms and 78 ms respectively as shown in Fig. (11), but after adding PID control the maximum overshoot was approximately zero which is a good result. So a speed controller has been designed successfully for closed loop operation of the DC motor and the motor runs very closed to the reference speed, also the settling time is reduced to 58 ms shown in Fig. (12).

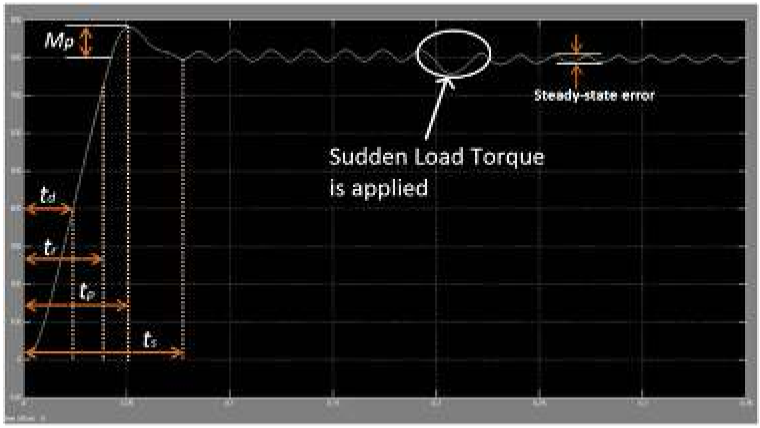

Figure. (11) Transient response without PID controller.

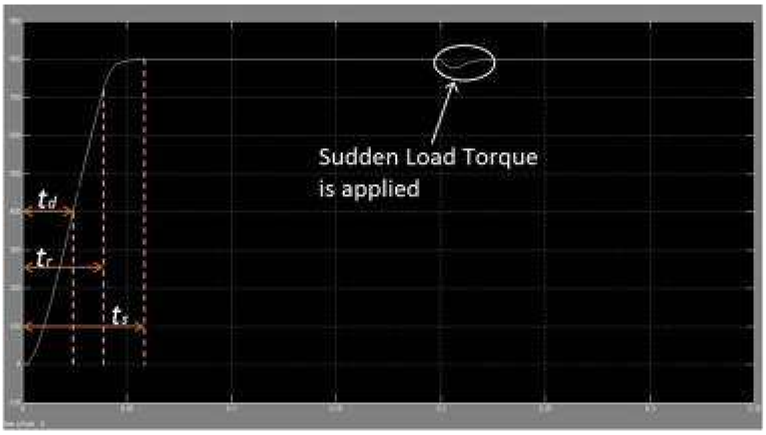

Figure. (12) Transient response with PID controller.

<u>Conclusion:</u>

In this paper, a high efficiency, low cost DC motor controller were designed and built. The controller takes user input to control the speed and drives the motor at that speed regardless of load. The speed control is accomplished in FPAA technology configured for proportional integral and derivative control. This provides quick, smooth motor response to the user input speed and keeps the speed regulated as the motor sees an increased load. The new speed controller produced less voltage deviation from variation of voltage reference. Small overshoot, more damping and sensitive to load variation makes FPAA PID controller works in better dynamic performance.

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