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Self-tuning PID Controller using Genetic Algorithm

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تصميم مسيطر تناسبي-تكاملي-تفاضلي ذاتي التوليف باستخدام الخوارزمية الجينية

ABSTRACT

This work presents design, modeling, simulation and hardware implementation of a separately excited DC motor speed control using Field Programmable Analog Array (FPAA) Technology. The framework presents a low power self-tuning analog Proportional-Integral-Derivative (PID) controller using a model-free tuning method, this overcomes the problems associated with reconfigurable analog arrays. In comparison with a self-tuning digital PID controller, the analog self-tuning PID controller combines the advantages of low power, no quantization noise, high bandwidth and high speed. The prototype hardware uses a commercially available field programmable analog array and Genetic Algorithm as tuning method. The practical results show that a self-tuned controller can outperform a hand tuned solution and demonstrate adaptability to plant drift, also it shows enhancement in the reduction of overshoot, settling time and the steady-state transient response of the controlled plant.

الملخص

يهدف البحث الى تصميم، نمذجة، محاكاة، والتطبيق العملي للسيطرة على سرعة محرك منفصل الاثارة باستخدام بطاقة المصفوفات التناظرية المبرمجة حقليا (FPAA). يقدم هذا العمل منظومة سيطرة توليف ذاتي مباشر من نوع (PID) تتميز باستهلاكها المنخفض للقدرة. منظومة سيطرة التوليف الذاتي التناظرية من نوع (PID) تجمع مزايا الاستهلاك المنخفض للقدرة، معدل

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ضجيج منخفض، حزمة ترددية عالية فضلا عن السرعة العالية بالمقارنة مع منظومة سيطرة توليف ذاتي رقمية من نوع (PID). يقدم الجزء العملي للمنظومة المقترحة استخدام بطاقة (FPAA) مع الخوارزمية الجينية (GA) لغرض القيام بعملية التوليف. اظهرت النتائج العملية تفوق منظومة السيطرة ذاتية التوليف على المنظومة يدوية التوليف فضلا عن الى قابليتها على التكيف مع التغيير الحاصل في المنظومة. اظهرت نتائج الاختبار حالة تحسن في نسبة ال overshoot، زمن الاستقرار وخطا الحالة المستقرة.

Keywords: GA, Self-tuning PID Controller, FPAA, Speed control, DC Motor.

1. Introduction

In recent years Field Programmable Gate Arrays (FPGA) have revolutionized digital design, at first they were only used for rapid prototype development, but now FPGAs are used as a preferred way to optimize system design and use of system synthesis software. In addition the use of an FPGA solution is increasingly finding FPAA technology is in the process of causing a similar revolution in Analog design (Waters, 2003).

Proportional-Integral-Derivative (PID) controller has been widely used for processes and motion control system in industry. Now more than 90% of control systems are still with PID controllers. The most critical step in the application of PID controller is parameters tuning. Today self-tuning PID controller provides much convenience in engineering. The parameter settings of a PID controller for optimal control of a plant depend on the plant's behavior. The tuning method includes online model-free method. This method tunes the PID controller in loop with the given plant using an optimization algorithm such as steepest descent or Newton's method to minimize some cost function .Yet the above method cannot guarantee to find the global optimum and its calculation is also expensive (Xu-zhou, 2007).

Control design tasks have to respect several requirements imposed on the static and dynamic behavior of the controlled system. Controllers often include many searched parameters and their different constraints. The search/optimization process may be complicated, discontinuous or non-convex, and analytical methods often may not be able to yield satisfactory results. Opposite to this, evolution-based search approaches are able to construct new control laws and non-intuitive solutions. As well, one of the most frequently used evolutionary techniques is the Genetic Algorithm (GA) (Sekaj, 2005).

With the abilities for global optimization and good robustness, and without knowing anything about the underlying mathematics, GAs are expected to overcome the weakness of traditional PID tuning techniques and to be more acceptable for industrial practice (Ali,2009).

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 (Ma, 2010). The objective of a control system design is to make a physical system behaves 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. 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 (Chander, 2010).

2. The Overall System Model

The overall system model consists of two FPAA kits, one is used to design a PID controller and the other is used for Pulse Width Modulation (PWM), firing circuit, Buck converter, DC motor, tachogenerator, reshaping circuit (AC to DC converter with low-pass filter), operational amplifier as buffer for isolating, Analog to Digital Converter (ADC) circuit and Personal Computer (PC). As shown in fig. (1) below.

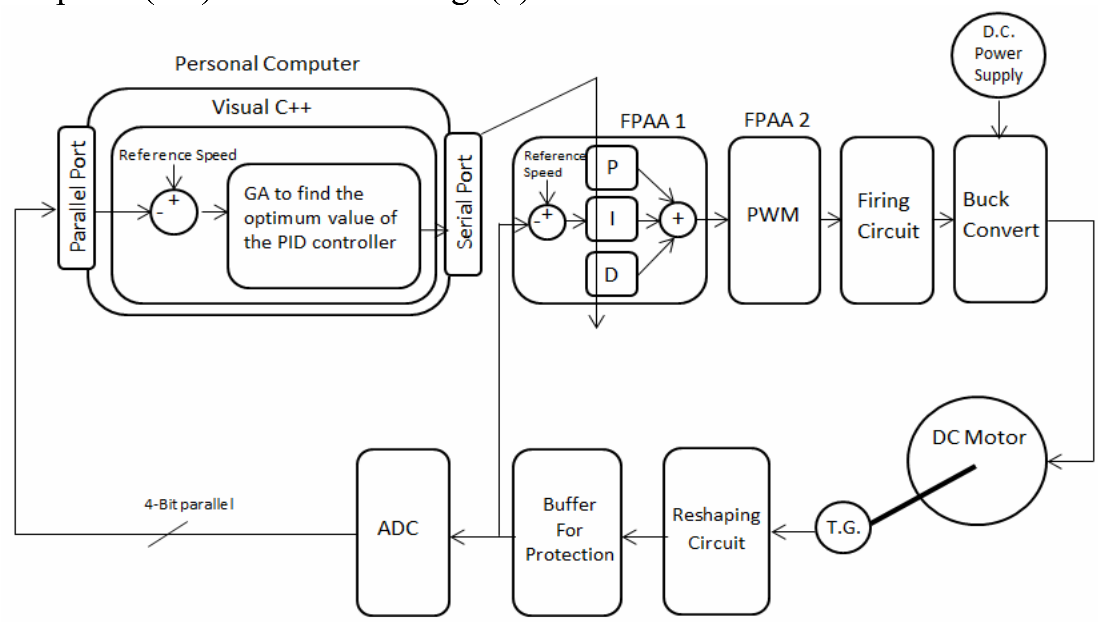


Fig. (1): Overall system model.

2.1. PID Controller

PID control is a traditional linear control method used commonly in industrial applications. PID letter stands for the calculation (algorithm) that involves three separate parameters, the proportional, the integral and derivatives. A PID and PI controllers are designed for buck dc-dc converter for operation during a startup transient and steady state, respectively (Yusoff, 2010).

In the parallel form of the PID controller, three simple gains K_P, K_I and K_D are used in the decoupled branches of the PID controller. The parallel PID control architecture can be given the following equivalent time-domain and Laplace S-domain mathematical representations:
Time-domain PID controller formula

$$u_c(t) = k_P e(t) + k_I \int_0^t e(t)d(t) + K_D \frac{de}{dt} \qquad (1)$$

Transfer function PID controller formula

$$U_c(s) = \left[k_P + \frac{k_I}{s} + k_D s\right] E(s) \qquad (2)$$

In the PID formulae, K_P is the proportional gain, K_I is the integral gain, K_D is the derivative gain, and the controller operates on the measured reference error time signal *e(t)*.

PID control remains an important control tool for three reasons: past record of success, wide availability and simplicity in use. These reasons reinforce one another, thereby ensuring that the more general framework of digital control with higher order controllers has not really been able to displace PID control. It is really only when the process situation demands a more sophisticated controller or a more involved controller solution to control a complex process that the control engineer uses more advanced techniques. Even in the case where the complexity of the process demands a multi-loop or multivariable control solution, a network based on PID control building blocks is often used (Johnson, 2005).
PID controller structure is shown in fig. (2) (Yang, 2011).

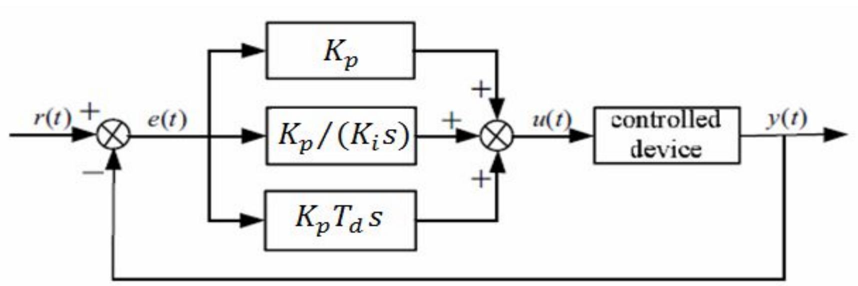


Fig. (2): PID Controlled system

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 disadvantage that it is not continuous and the microcontroller resources are mostly used for PID algorithm than for other activities. Also, there are some difficulties for fast time response applications (Lita, 2009). In the industry control, PID is the most commonly used method. Because of their intuitiveness, simple structure robust performance are good features. PID parameters tuning, however, was a complex work tradition. PID parameters tuning method was artificial Trial, but it could not achieve the optimal controller (Fei, 2011).

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 technology.

2.2. Configurable Analog Circuits

2.2.1. Field Programmable Analog Array

An FPAA is an IC that can be programmed and reprogrammed to perform an open-ended set of analog circuit functions (http://servenger.com)

FPAA circuit can be used effectively in applications where the low electric power, the lower development and component cost, the effective electronic of Computer Aided Design (Anadigm designer2) possibility are important because it is the main software that comes with the Field Programmable Analog Array (FPAA) and deals with it. The advantage of FPAAs in the field of faster and more economical circuit planning is significant (Gy¨or¨ok, 2010).

The general architecture of FPAA circuit made by Anadigm is presented in Fig.(3), 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 analog section to the design requirements (Cioe, 2009).

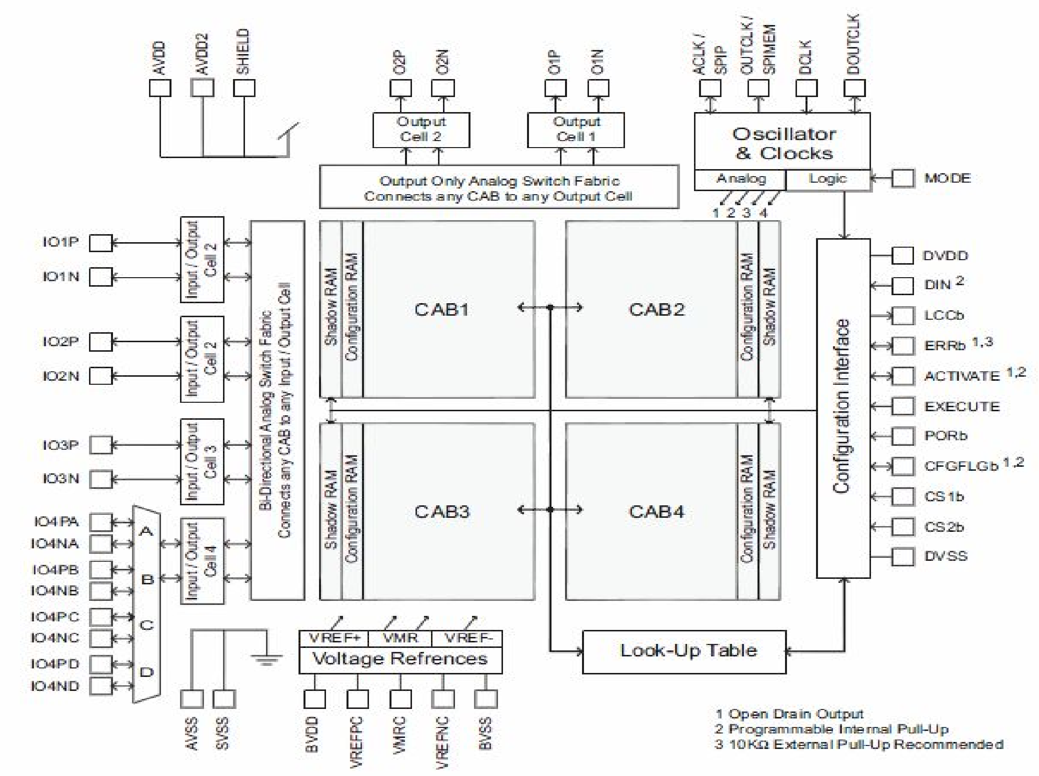


Fig. (3): Block diagram of AN221E04 FPAA.

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 (Cioe, 2009).

2.2.2. PID controller implemented with FPAA

Anadigm has created a graphical design environment that runs in Microsoft® Windows® where the designer selects from a large library of pre-tested analog functions and then places and connects them to create the desired circuit (http://servenger.com)

In Anadigm Designer2, a specialized tool can be used for synthesis of PID regulator. It permits the circuit layout configuration depending on the requirements specified by the user.

The resulted layout for the implementation of the PID controller in the FPAA within the Electronic Design Automation (EDA) tools is presented in Fig. (4) (Lita, 2009).

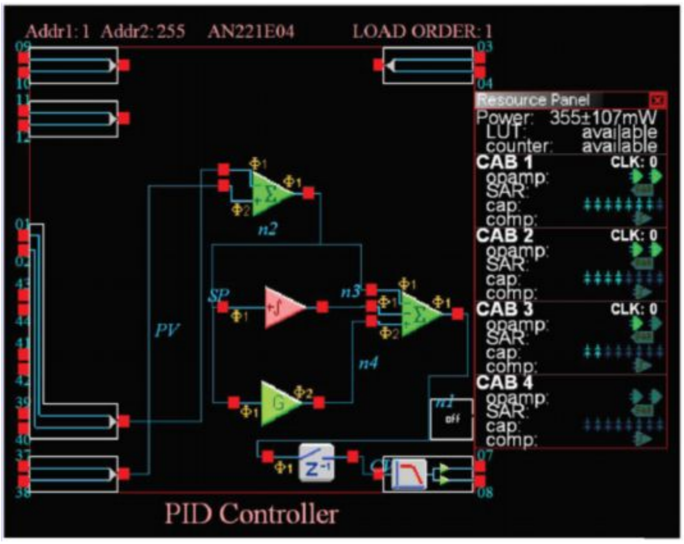


Fig.(4): Implementation of the PID Controller in FPAA.

2.2.3. Pulse Width Modulation (PWM) using FPAA

The output signal of PID controller is fed to PWM circuit which are also implemented using FPAA Technology, gives a very fast and accurate response to sudden changes in PID output. The PWM circuit is shown in fig.(5). It consists of an arbitrary signal generator that generates a triangular wave. The output of PID controller will be crossed with the triangle wave to generate pulses with variable duty cycle. The output of PWM circuit can be directly connected to the firing circuit to drive the buck converter circuit that will drive the motor.

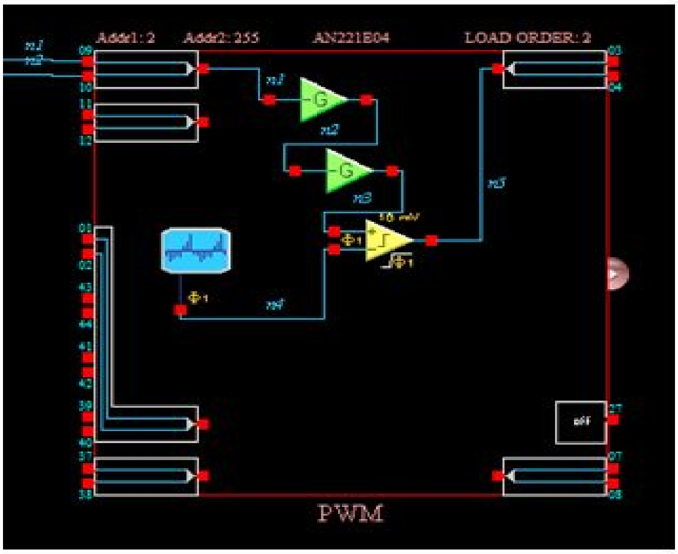


Fig. (5): PWM using FPAA technology.

2.3. Self-tuning of PID controller

The Anadigm Designer 2 software provides a set of C functions to be used for reconfiguring the chip on the fly if parameters design is required to be dynamically changed. This makes possible realization of a self-tuning

PID controller, which has better performances than manually tuned controller. This facility is very useful in critical applications like nuclear domain or other, where a fast and precise response is desired. A possible architecture for the Self-tuning or adaptive PID controller is proposed in Fig. (6), where the tuning algorithm runs on a microcontroller that configures the FPAA dynamically (Lita, 2009).

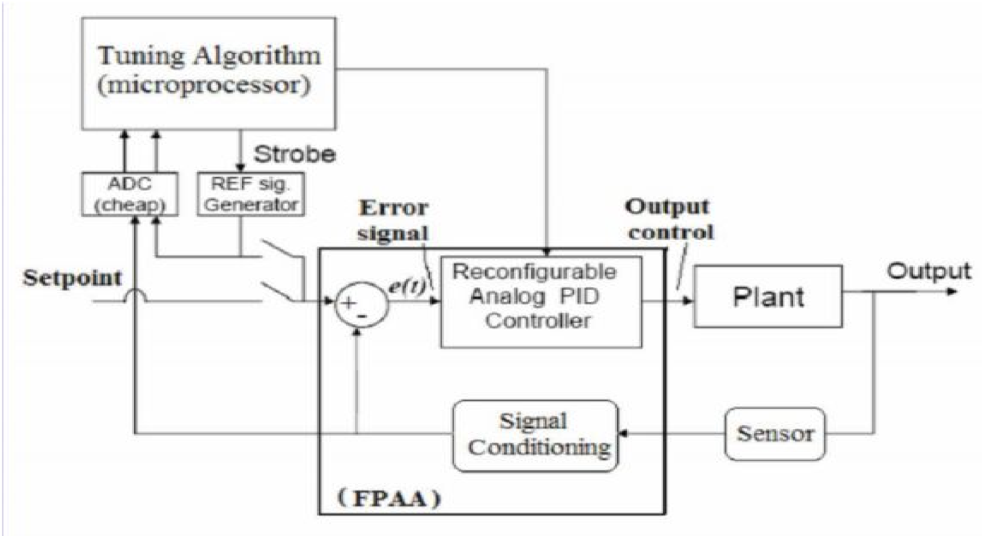


Fig. (6): Self-tuning PID controller architecture

2.5. DC-DC Converter (Buck Converter)

The DC motor is fed by the DC source through a buck converter that consists of the MOSFET Transistor, the free-wheeling fast recovery diode, inductance and capacitor.

Buck converter is a typical voltage reduction DC/DC topology, which has been widely used 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. (7). (Yigeng, 2010).

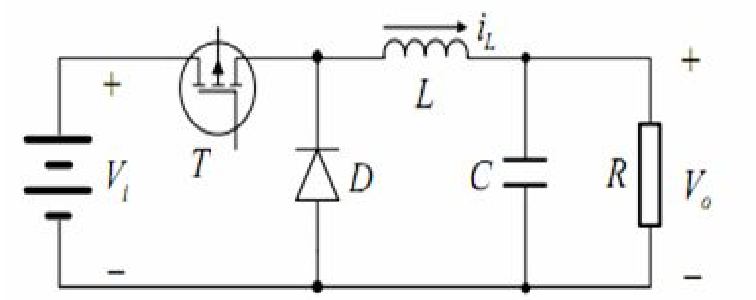


Fig. (7): Buck converter topology.

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 inductance current (i_L) (Agarwal, 2010).

However, continuous current condition is considered for this paper. The circuit operation is divided into two modes. First mode (mode 1) begins when the controlled switch (T) is switch on, the input current rises, through filter inductor (L). 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 switch off, and the freewheeling diode (D) conducts due to energy stored in the inductor (L) and the inductor current continues to flow through inductor (L) capacitor (C), load (R), and diode (D). During this interval, $V_L = -V_O$ for time duration (1-d)t until the switch is turned on again.

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

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

Where S is Laplace operator and d is duty cycle. Assuming constant DC input voltage, equation (7) can be further transformed as:

$$\frac{V_O\,(s)}{d} = \frac{\frac{V_i\,(s)}{L.C}}{S^2 + \frac{S}{R.C} + \frac{1}{L.C}} \qquad (4)$$

As a result, one can dynamically control the duty cycle d to achieve the desired output voltage, a PID controller is normally selected to reduce transient overshoot and eliminate steady state error (Yu, 2011).

2.6. Interfacing ADC to a PC through Parallel Port

Nibble mode is the preferred way of reading 8 bits of data without placing the port in reverse mode and using the data lines. Nibble mode uses a Quad 2 line to 1 line multiplexer to read a nibble of data at a time. Then it “switches” to the other nibble and reads its. Software can then be used to construct the two nibbles into a byte. The ADC circuit is shown in fig. (8).

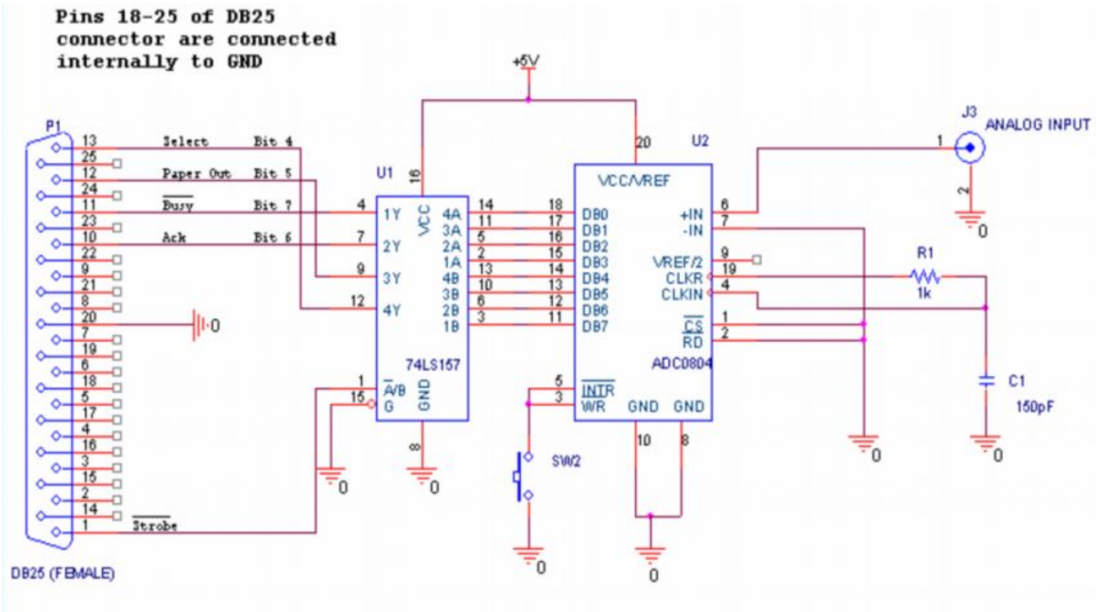


Fig. (8): Hardware circuit connecting ADC0804 to a PC through parallel port.

3. Genetic Algorithm

3.1. Overview of Genetic Algorithm

GA is a stochastic global adaptive search optimization technique based on the mechanisms of natural selection. Recently, GA has been recognized as an effective and efficient technique to solve optimization problems. Compared with other optimization techniques, GA starts with an initial population containing a number of chromosomes where each one represents a solution of the problem which performance is evaluated by a fitness function. Basically, GA consists of three main stages: Selection, Crossover and Mutation. The application of these three basic operations allows the creation of new individuals which may be better than their parents. This algorithm is repeated for many generations and finally stops when reaching individuals that represent the optimum solution to the problem. The GA architecture is shown in Fig. (9) (Thomas, 2009).

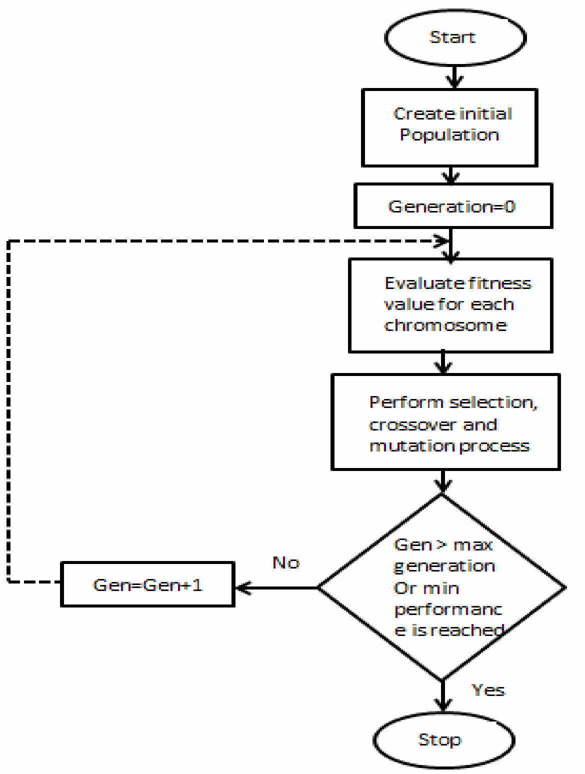


Fig. (9): Genetic Algorithm Architecture

3.2. GA implementation in Visual C++

The Anadigm Visual C++ Prototyping tool is a utility that helps to quickly create PC-based software that utilizes the AnadigmDesigner2 generated C Code. This enables one to create demonstration software, do initial embedded development prior to hardware availability, and to simply verify the functionality of the C Code. The tool creates an MFC (Microsoft Foundation Classes) based Windows application that contains all necessary code to communicate with the Anadigm development board, through both parallel and serial ports. The tool generates standard Anadigm C Code files, as well as C++ class wrappers that provide an easy interface to the C Code, as well as demonstrating how the C Code API's may be used (AnadigmDesigner2 software help topics).

After completing the PID controller circuit schematic in AnadigmDesigner2 as shown in fig (4), choose

Dynamic Config. -> Visual C++ Prototype… from the main AnadigmDesigner2 menu. This will bring up the Project Settings Tab.

The project settings tab contains all the settings related to the Visual C++ project that will be generated.

By pressing the Generate button the Visual C++ program will open a C Code where we can write the genetic algorithm.

The GA parameters used in this work are listed in table (1) below.

Table (1) Parameters of GA

GA property	Value/Method
Population Size	20
Maximum Number of Generations	50
Performance index/fitness function	Mean square error
Selection Method	Tournament Selection
Crossover Method	Arithmetic Crossover
Crossover Probability	75%
Mutation Method	Add-Sub Mutation
Mutation Probability	0.1%

Because the system implementation works in real time, that means the speed of the genetic algorithm is important, so we use the tournament selection because it is considered one of the fastest types of selection.

Also we use the crossover and mutation method as shown in the table above because the GA deals with real value numbers (the values of the three genes in chromosome P, I and D)

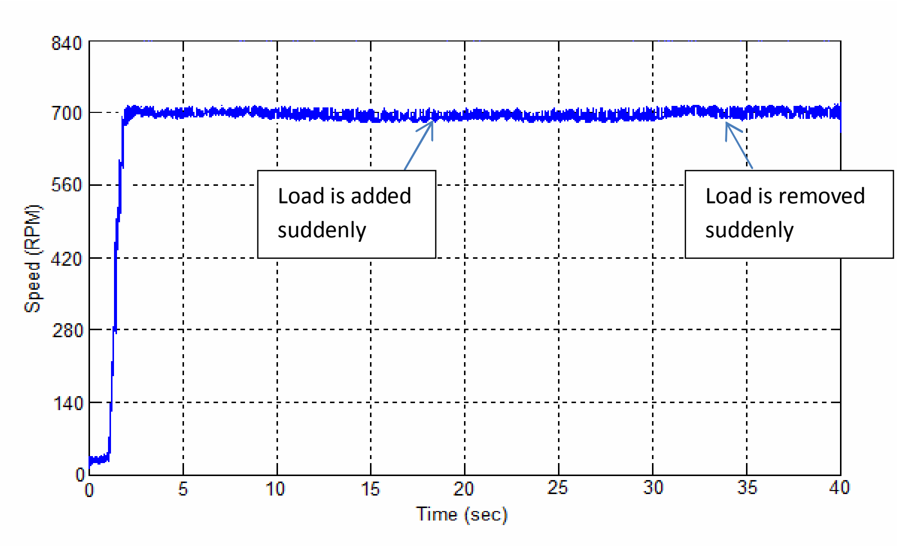
The GA will work until finding the best values of the PID controller or finishing the last generation without finding the optimum values of the PID controller. From the practical experiments and from some papers that deal with similar projects we take the number of generations.

4. The Results

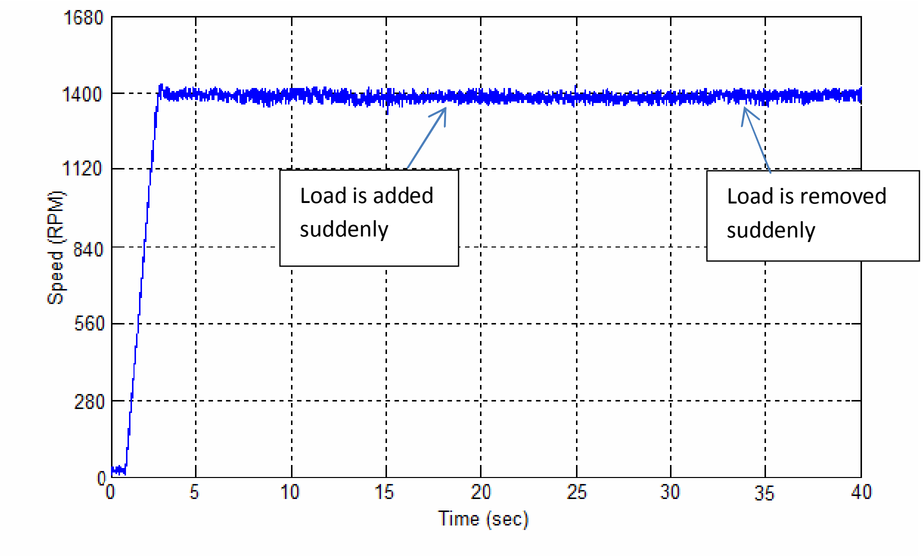
The DC motor set is an experiment set from TERCO Instruments Limited. It contains of variable load, Power supply, speed meter, torque meter and DC motor. The real system can be shown in Fig. (10). An AC tachogenerator is used. It is coupled to the motor shaft and its output voltage varies linearly with the motor speed. A voltage signal obtained from a Tachogenerator is fed back to the reshaping circuit (convert it from AC to DC voltage) then to buffer to provide protection for FPAA and ADC circuit, this signal is fed to the FPAA that will be subtracted from the set-point to produce the error signal, the error signal represents the input of the PID. Also, it is fed to ADC circuit to produce a parallel 4-bit signal, this signal is entered to the PC (Visual C++ running the GA software) through the parallel port as shown in fig. (1).

Fig. (10). the real parts of the experiment set.

After connecting the system as shown in fig. (10),the obtained response of the DC motor drive to successive changes in load torque is shown in Fig. (11).



(a)



(b)

Fig. (11): (a) Practical response of the DC motor drive to successive changes in load torque that's equal to 6 N.m at 700 RPM
(b) Practical response of the DC motor drive to successive changes in load torque that's equal to 6 N.m at 1400 RPM

From the above responses we can find the following:

1- For fig (11)(a)
   Delay time (t_d) = 1.6 sec
   Rising time (t_r) = 2 sec
   Peck time (t_p) = 2.2 sec
   Settling time (t_s) = 2.8 sec

2- For fig (11)(b)
   Delay time (t_d) = 1.95 sec
   Rising time (t_r) = 2.71 sec
   Peck time (t_p) = 3.04 sec
   Settling time (t_s) = 3.69 sec

The overshoot reduction cannot be calculated accurately because it's a small value.

5. Conclusions

1- Simulation of the closed loop DC motor using PID controller is very useful to find the initial values for PID controller
2- The usage of a PC as a microcontroller enables us to use any intelligent algorithm to tune the PID controller
3- The system provides flexibility and easy interface to any of the DC motor

4- The designed system provides easy method to change the speed just by moving a slide bar in the program
5- The designed buck converter circuit provides a pure DC source to the DC motor that is given a stable desired speed
6- The usage of the GA provides easy and flexible way to find the three gains of the PID controller in comparison with other method
7- The self-tuning PID controller using GA made a reduction in overshoot, settling time and steady-state transient response with values shown above compared with traditional PID controller.

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Biographies

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Dr. Thair Ali Salih received the MSc. degree in Communication engineering from the Technology University, in 1986. He received the Ph.D. degree in Communication from Aleppo University in 2010. Currently, he is a Lecturer at Technical Collage/Mosul. His research interests include Spread spectrum systems and robotic System.

Mohammed Y. Hazim received the B.Sc. degree in computer engineering from the technical college in 2009. He is currently an M.Sc. student in Computer engineering dept. at Technical College, Mosul. He is interested in subjects of power optimization techniques, artificial intelligence in power system area.