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Research paper

Design a fuel cell based drive dc motor for an electric vehicle applications

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Abstract

The Applications of a Fuel cell (FC) in the field of the electric vehicle has realized wide popularity since the past few years because of the problem of relative increases in fossil fuel prices in addition to depletion of this fuel. The objective of this study is to design DC drivers based on DC-DC buck converter for separately excited DC motor as a traction motor used for an electric vehicle. This motor is fed by Polymer Electrolyte Membrane (PEM) FC as a renewable energy source. Many control strategies are implemented to produce the suitable gating signal for the buck converter and get the best motor operation response which where Proportional Integral (PI) controller, Fuzzy Logic (FL) controller, and FL based self-tuning PI controller. The proposed FC power system is modeled and simulated using Matlab-Simulink and Fuzzy toolbox. The performance and accuracy of the proposed algorithm have been investigated in different situations. The simulation results showed that the speed response of the DC motor controlled by the FL based self-tuning PI controller had improved the performance (overshoot, rising time, settling time and steady-state error) when compared to the typical PI controller, and FL controller.

Keywords: *Fuel Cell; Polymer Electrolyte Membrane; Self-Tuning; Fuzzy Logic; Electric Vehicles.*

1. Introduction

Nowadays, the electric vehicle is progressive technology in automobile engineering. In the advanced country, the government taking seriously in developing a green vehicle based on renewable energy that will protect the environment and reduces the air pollution, and overcome the problem of increasing the fuel price [1], [2]. FC consider as one of the effectively renewable power sources compared with other renewable energy sources, such as solar and wind generation technologies, FCs has the benefit that which can be set at any location in the electrical system, without any geographic restrictions as it doesn't be influenced by the climate factors [3]. The basic function of the FC is converting the chemical energy into electrical current. The main fuel that is used in the FC is the hydrogen, because of this gas is available in large quantities in nature and it has minimum pollution effect. Many other advantages can be gained using FC, such as: (a) its high energy conversion and its stability, (b) FC has no noise effect and has no or limited rotational elements, and consequently, electrical power is generated relatively mutely, (c) FCs are modular; thus it can gather many FC to achieve the required output power, (d) finally FC is clean device, there are no emissions, only the production of pure water [4 - 7]. Regardless of their advantages, FCs has some disadvantages; the first as they depend on chemical reactions, thus they have normal delays that caused for lower in output power density, the second one is it produces an inconstant voltage output when current changes rapidly [8]. These drawbacks can be overcome by designing a suitable system controller for the FC fuel and output voltage.

Many applications are possible to be used by FCs: basically in transportation application (electrical vehicles), in addition to it used as a backup power supply in fixed locations (houses, clinics, domestic utility, etc.) and mobile applications (laptop, mobile) [9], [10]. DC motor is the main part of an electric vehicle, which supplied by an electrical source. These motors play a vital role in the electric vehicle. It is an efficient motor that is easier to control the speed. The enhanced performance of power electronics and performance oriented motor drives are considering the most important factors behind the revolution of electric vehicle technique [1], [4]. Several control techniques have been proposed to ensure stability as well as the fast transient response of DC motors namely; Artificial Neural Network, FL controller, and Proportional Integral Derivative (PID) controller have been proposed in [6], [11], [12]. In this paper, speed regulation of DC motor and fuel amount control for the FC is achieved using three control strategies: PI controller, FL controller, and FL based self-tuning PI.

2. Proposed FC power system

Block diagram of the suggested FC power system is shown in Fig. 1; it involves a PEM FC stack, a DC-DC converter, DC motor as an electric motor vehicle, and controller. In this work, the FC performance is used as a power supply. Concerning DC-DC converter topologies, the buck converter is designed for adjusting the load voltage because of its simplicity, low cost and high efficiency. DC motors play a vital role in industrial areas. It is an efficient motor that can control the speed. Armature controller method is employed in this work for speed control of the separately excited DC motor. The terminal voltage of FC is controlled by varying the duty cycle of buck converter as well as the magnitude of fuel hydrogen compassion ratio. Three control strategies are designed to

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achieve the best performance of the system will be discussed in the next subsections.

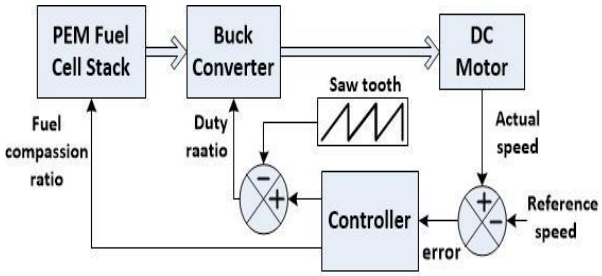


Fig. 1: Block Diagram of the Proposed FC Power System.

2.1. FC stack model

A FC is a static energy conversion device that mechanism as a battery; it converts the chemical power of a fuel (hydrogen gas) and an oxidizer (oxygen or air) immediately into electrical power with some heat and produces water as it's by- product. The FC is made of an electrolyte between a pair of electrodes (anode & cathode) as shown in Fig. 2 [6], [9], and [13].

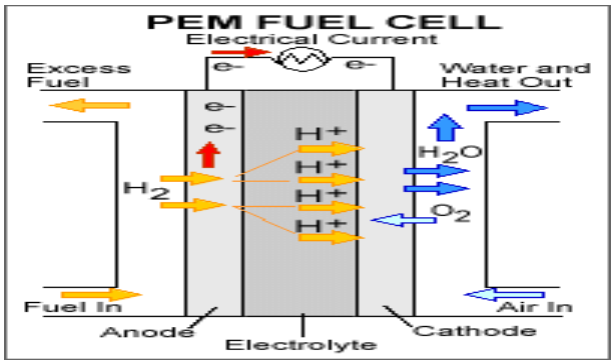


Fig. 2: FC Operation Diagram.

Hydrogen gas passes over one electrode (anode), and with the help of electrolyte catalyst layer (existed between anode and electrolyte), separates into hydrogen protons (H^+) and charged electrons (e^-); The electrolyte permits the protons to pass through whereas preventing the electrons; thus protons passed to cathode through electrolyte whereas an electrons transferred to the cathode through an external electrical power circuit (load), generating an electrical current.

At the cathode hydrogen protons and electrons merge with oxygen (O_2) by usage of another catalyst layer (existed between electrolyte and cathode), to produce water (H_2O) which flows out of FC and high temperature. Defined reactions can be stated by the following equations [5], [10]:

$$H_2 \rightarrow 2H^+ + 2e^- \quad \text{(Anode reaction)} \tag{1}$$

$$\frac{1}{2}O_2 + H^+ + 2e^- \rightarrow H_2O \quad \text{(Cathode reaction)} \tag{2}$$

$$H_2 + \frac{1}{2}O_2 \rightarrow H_2O + heat + Electrecity \quad \text{(Overall)} \tag{3}$$

There are several kinds of FCs depending on the type of the electrolyte. Most mobile applications and mainly automobiles are governed by PEM FCs; as it: (1) lower process temperature (fast switched on & off), (2) smaller action pressure thus it superior safety, (3) can be easily set into mode system, and (4) have minor release ratio and greater conversion ratio, so it can generate power immediately once it start-up [2], [3]. In order to validate the proposed FC power system, a case study of 3.2 KW PEM FC which has the parameter as listed in Table 1.

Table 1: Parameters of the FC

Parameters	Values
Rated power of stack	10.6 KW
Open circuit voltage	220 V
Nominal voltage	80 V
Nominal current	133.3 A
No. of cells	65
Nominal stack efficiency	55 %
Operating temperature	65 C°
Nominal air flow rate	300 Ipm

2.2. DC-DC Buck converter model

DC - DC converter plays a weighty role resulting in extensive applications in cellular phones, laptop charger, LED drivers, maximizing energy harvest for PV solar systems and wind turbine-generators, hydro-power plants, electric vehicles, and many more [12]. A buck converter stepping down the amplitude of input DC voltage (V_s) to a lower value of output DC voltage (V_o) with minimum ripple according to the following equation:

$$V_o = k * V_s \tag{4}$$

K is duty ratio. It represents the fraction of the commutation Ts during which the switch (Sw) is on. The ranges K is between 0 (Sw is off) and 1 (Sw is on). Fig. 3 shows the electrical circuit schematic of this converter; It comprises of a power switch (Sw), diode (D), inductor (L), filtering capacitor (C), and load [11].

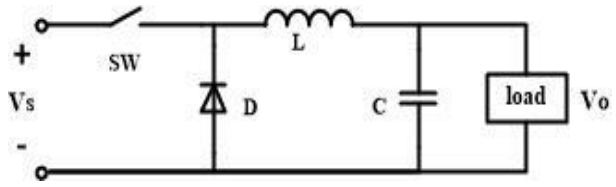


Fig. 3: The DC-DC Buck Converter Circuit.

The value of the inductance (L) and the switching frequency (f_{sw}) determine the mode of operation (continuous or discontinuous current conduction mode) in addition to the input current ripple (inductor current ripple). Moreover, the capacitor (C) determines the output voltage ripple. So, proper selection of these components keeps the converter out of discontinuous mode, besides the ripple of the input current and output voltage within the allowable range [11], [14], and [15]. The above conditions lead to,

$$L = \frac{K(V_s - V_o)}{f_{sw} * \Delta I} \tag{5}$$

$$C = \frac{(1-K)V_o}{8Lf_{sw}^2 \Delta V_C} \tag{6}$$

Table 2 enlists the main components values for the converter.

Table 2: Buck Converter Parameters

Parameters	Current ripple	Voltage ripple	Switching frequency (f_{sw})	Inductor (L)	Capacitor (C)
Values	A	V	KHz	50-mH	50 µF

2.3. Control strategies

2.3.1. PI controller

PI controller is the mainly treat method used for speed control of electrical motors, as it provides a fine control in addition to it can be designed merely [16]. It operates to improve the performance response of the controlled system such as to decrease the peak overshoot and steady-state error. There are many tuning methods for the PI controller such as trial and error method, or Ziegler-Nichols method [17]. In the present work, the Ziegler-Nichols

method based on time domain response is used to obtain the PI controller parameter gains. Ziegler-Nichols laws are depended on the time constant (T) and delay time (D) of the system step response. Then PI controller parameter gains are adjusted by using trial and error for tuning the system response to obtain the best system performance.

2.3.2. FL controller

When the numerical model of the system is compound and non-linear, PI controllers cannot give a precise solution. Contradictory, FL controller can offer high performance for complex non-linear systems and can overcome nonlinearities as well as uncertainties [16], [18]. FL controller has been studied and design whereas two input variables: The first is the error signal E (t) that equal to the difference between desired value and actual value. The second is the change of error DE (t). Two output signals are present from the proposed FL controller, the first one is compared with a saw-tooth signal to generate a control signal which drives the main power switch (MOSFET) of the buck converter, and the second one is the output that will control the value of the hydrogen fuel composition of the FC. The set of input and output variables are firstly fuzzification to be fit with the input ranges of FL controller and transformed in terms of its linguistic variable by using five fuzzy subsets. (Neg., Neg. S, Z, Pos., and Pos. S) denote these subsets whereas: Neg. is Negative, Neg. S is Negative Small, Z is Zero, Pos. is Positive, and Pos. S is Positive Small. The membership functions types of the FL controller are triangular memberships that used. The fuzzy inference of the FL controller is based on the Mamdani's method. The fuzzy system rules bases are created as shown in Table 3.

Ranges that are used to generating the proper membership function is (-85 and 85) for the error signal, and (-45 and 45) for the change of error signal. The error is depending on the maximum value of the error between any two sampling of time. The range of change in error is depends on the maximum difference value between the value of error and a previous value of error for the sampling time. The output of FL controller is the duty cycle ratio range between (0 and 1) and used as a gating signal for the converter and fuel compassion hydrogen ratio.

Table 3: Fuzzy Rules for the Controller

Δe e	Pos.	Pos. S	Z	Neg. S	Neg.
Z	Neg. S	Neg.	Neg.	Neg.	Neg.
Pos. S	Z	Neg. S	Neg.	Neg.	Neg. S
Pos.	Pos. S	Z	Neg. S	Neg.	Z
Pos.	Pos.	Pos. S	Z	Neg. S	Pos. S
Pos.	Pos.	Pos.	Pos. S	Z	Pos.

2.3.3. FL based self-tuning PI controller

This method is combined the two previous controller methods (PI & FL); whereas the FL is used for the tuning of the PI controller of the controlled system [12, 19]. In this method the FL controller has two input variables: The first is the error signal E(t) that equal to the difference between the reference value and actual value. The second is the change of error DE(t) as in previous FL controller method, the output of this controller is used for updating the integral controller gain (ΔKi) of the PI controller to produce the best gain value of integral controller that gives the best performance of the controlled system.

2.4. DC motor

Separately excited DC motor is used as motor traction of an electric vehicle because of their simplicity, high starting torque, ease of application, high reliabilities, flexibilities and favorable cost [12], [20]. Armature control method is employed in this work; Table 4 lists the parameter of this motor.

Table 4: Parameters of DC Motor

Parameter	Value
Rated power	3.2 KW
Armature Voltage	220V
Armature resistance	2.8 Ω
Armature inductance	20.4 mH
Rated Speed	1500 r.p.m
Motor torque constant	10 N.m

3. Simulation of FC power system

The proposed FC power system is simulated in MATLAB/Simulink environment as shown in Fig. 4.

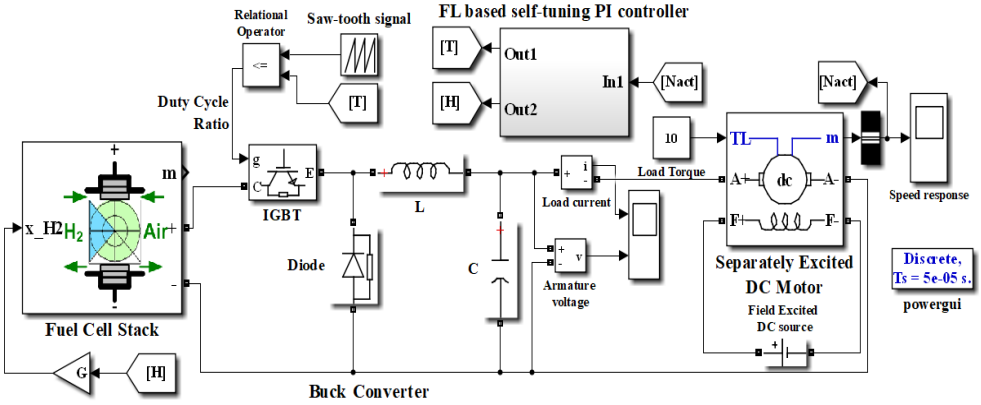


Fig. 4: Simulink Block Diagram of the Proposed FC System.

A subsystem as in Fig. 5, Fig. 6, and Fig. 7.

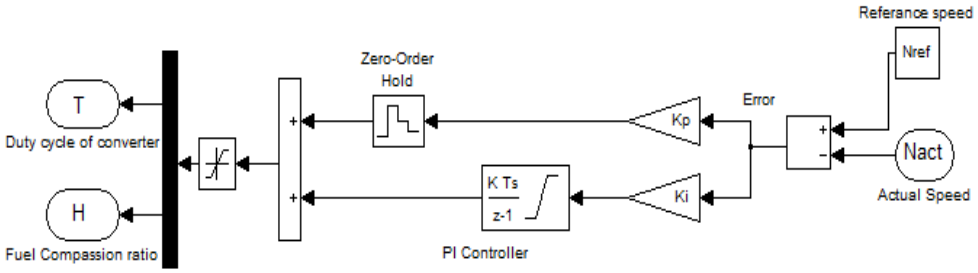


Fig. 5: Subsystem of PI- Controller.

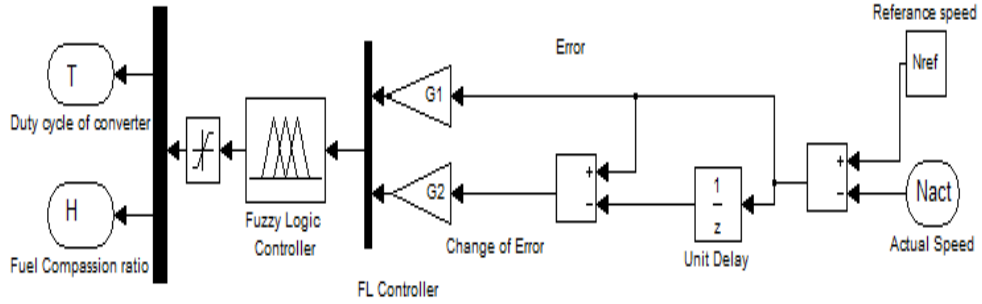


Fig. 6: Subsystem of FL- Controller.

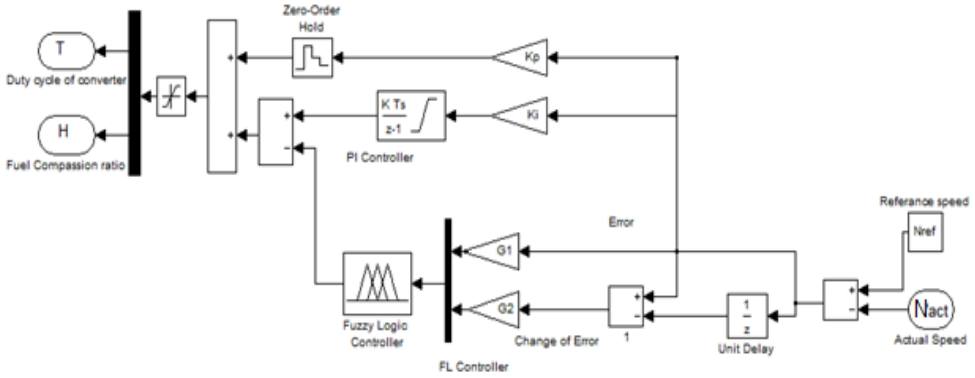


Fig. 7: Subsystem of FL Based Self-Tuning PI Controller.

From Fig.7, it is cleared that the fuzzy system refrains the gains of the PI controller rendering to values of the error and change of error of the speed to meet the best system response specifications of the motor speed.

4. Simulation results

Fig. 8, Fig. 9, Fig. 10, and Fig. 11 represents the speed response of DC motor with variable load torque and variable hydrogen fuel composition ratio: Initially motor runs at load torque equal to 10 N.m, after 1.5 sec. load torque increased to 15 N.m, and at sec. 3, load torque becomes 5 Nm. Then the load torque becomes 10 N.m at 4.5 sec. At sec. 7, the hydrogen fuel composition ratio is decreased from 100% to 50% and finally it becomes 20% at sec. 8.

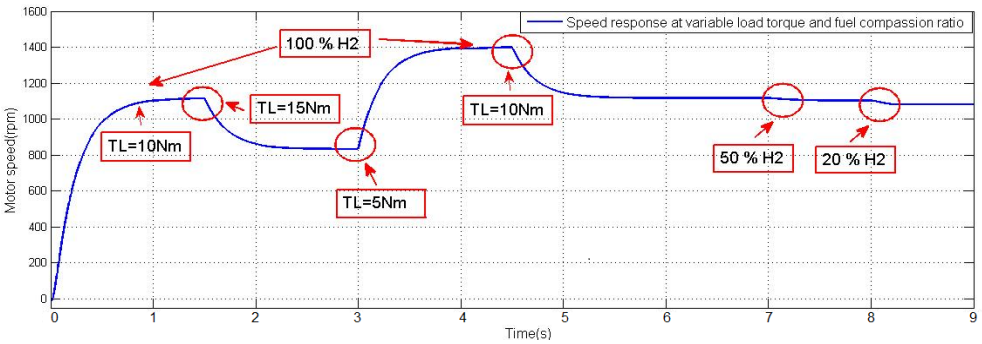


Fig. 8: Speed Response of DC Motor at Open Loop (K = 0.55).

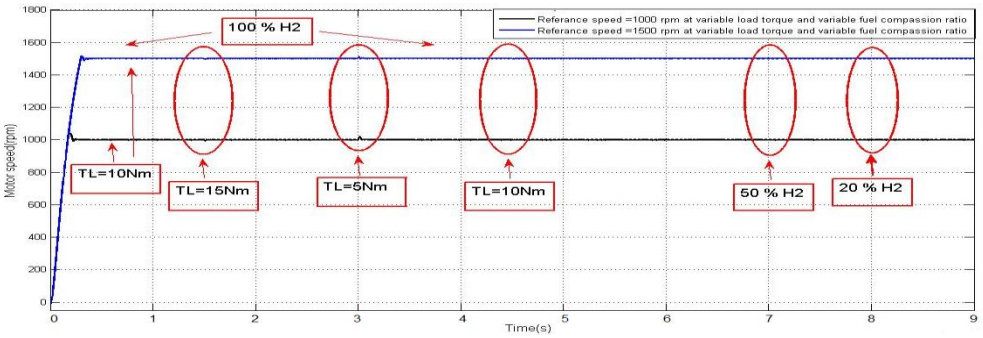


Fig. 9: Speed Response of DC Motor with PI Controller.

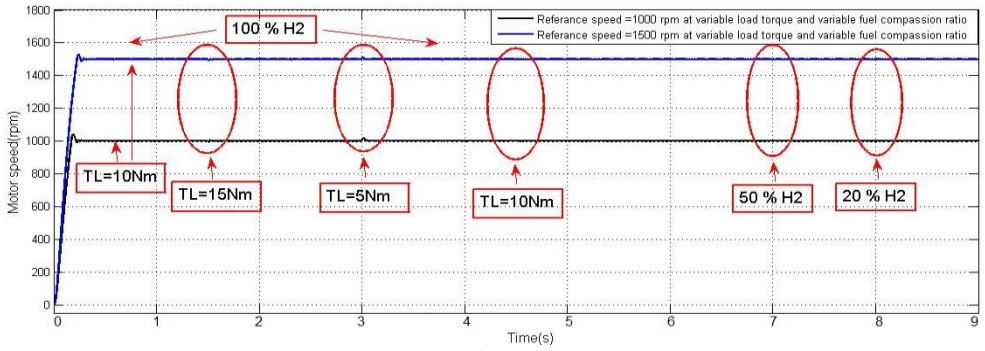


Fig. 10: Speed Response of DC Motor with FL Controller.

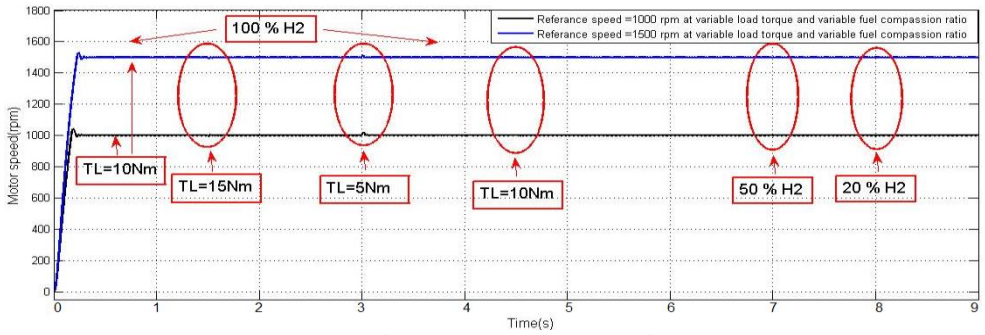


Fig. 11: Speed Response of DC Motor with FL Based Self-Tuning PI Controller.

Fig. 12 and Fig. 13 show the DC motor speed step response with PI, FL, and FL based self-tuning PI controller at many references speed and constant load torque that equal to 10 N.m. Initially, the reference speed is 1000 rpm, after 1 sec. It increased to 1200 rpm, and finally after 2 sec. The reference speed becomes 1500 rpm. In Fig. 12 the hydrogen fuel compassion ratio is constant (100%), whereas in Fig. 13 it controlled depending on the required speed reference of DC motor with variable the hydrogen fuel compassion ratio. The best system performance with FL based self-tuning PI controller. The armature voltage, armature current , electrical torque and gate signal of the buck converter shown in Fig 14 with the references speed and constant load torque that equal to 10 N.m. when the reference speed is 1000 rpm, after 1 sec, It increased to 1200 rpm, then finally after 2 sec the reference speed becomes 1500 rpm.

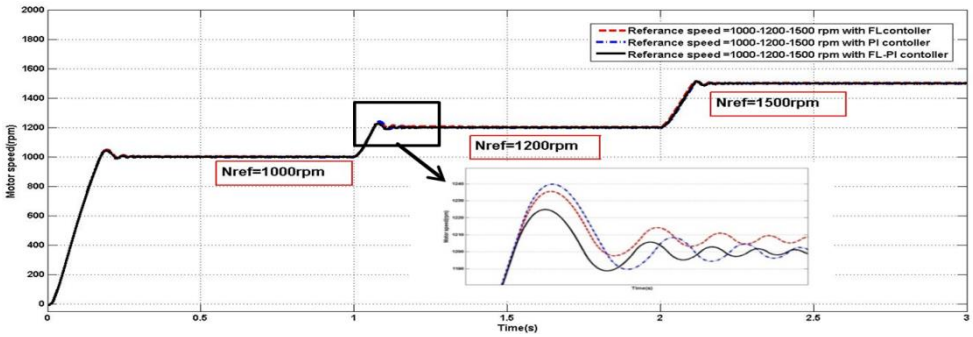


Fig. 12: Speed Response of DC Motor Using Three Types of Controllers at Constant Fuel Compassion Ratio.

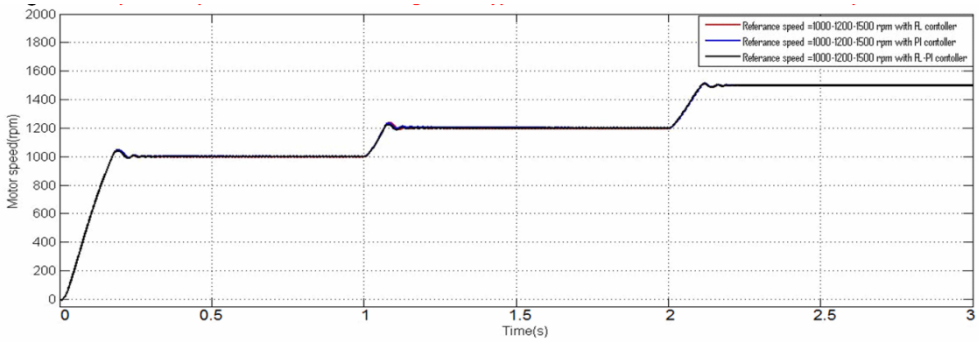


Fig. 13: Speed Response of DC Motor Using Three Types of Controllers at Controlled Fuel Compassion Ratio.

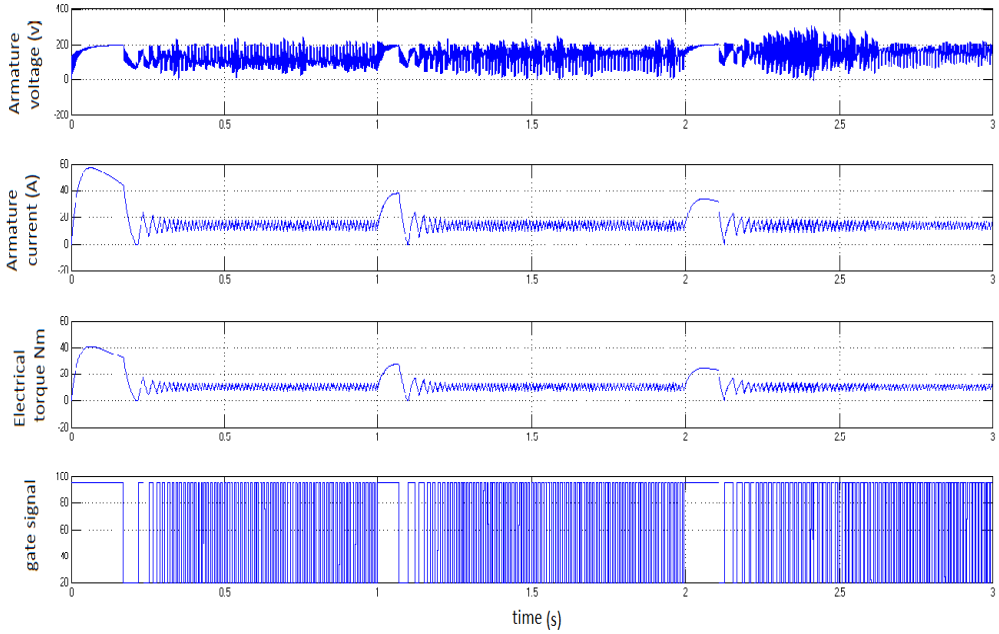


Fig. 14: DC Motor Parameters Response-Using FL Based Self-Tuning PI Controller at Controlled Fuel Compassion Ratio.

Table 5 lists the terminal voltage and output power of FC system at different condition and percentage ratio of hydrogen fuel composition. whereas Table 6 lists the comparison among the three proposed controllers in term of steady state error, peak over shoot, settling time, rising time, and delay time at reference speed equal to 1500 rpm, rated load torque equal to 10 N.m, and constant fuel composition ratio 100%.

Table 5: Output Voltage and Power of FC Power System at Nref=1500rpm

Compassion ratio of fuel hydrogen%	Vo	FL based PI	FL	PI	Open loop
100	2185W	2187W	2189W	2952W	206.6
50	2254W	2259W	2261W	2919W	204.5
20	2260W	2264W	2266W	2885W	202.3

Table 6: Comparison Among the Output Responses of Controller

Design controller	Steady state error	Peak over shoot	Settling time	Rising time	Delay time
Open loop	Large and variable	0%	1.15s	0.95s	0.175s
PI	0.93%	0.92%	0.37s	0.310s	0.114s
FL	-0.67%	0.95%	0.38s	0.312s	0.115s
FL based self-tuning PI	-0.52%	0.89%	0.37s	0.307s	0.114s

5. Conclusion

The modeling of the FC circuit with DC-DC buck converter and DC motor are studied and designed in the open loop system. Then three different techniques have been used to design a closed loop system controller for the motor speed and fuel compassion ratio: PI, FL, and FL based self-tuning PI control techniques. The simulation results demonstrate that the performance of the controllers is satisfactory under different load torque condition in term of rising time, delay time, settling time, peak overshoot and steady state error. It is observed, the proposed technique is given the best output performance speed response of the motor compared to the other controllers.

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