TRJ Vol. 6 Issue 6 November-December 2020 ISSN: 2454-7301 (Print) | ISSN: 2454-4930 (Online)

ANFIS-MPPT Control Algorithm for a PEMFC System used in Electric Vehicle Applications

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Abstract− Fuel cells are power sources that have a relatively high energy density and use a renewable fuel as its primary energy source, that is, the hydrogen. Therefore, they are often considered as an ideal candidate for a zero emission vehicular applications due to their low operating temperature which makes them well suited for personal vehicle applications. The output power of a fuel cell is immensely dependent on cell temperature and membrane water content. A maximum power point tracking controller is essentially required to extract the optimum power from the fuel cell stack.

In this paper, a control scheme is planned to effectively absorb power from fuel cell stack. The power system also needs to be designed to suit the operation inside the module of Electric vehicle. Here, adaptive Neuro-fuzzy inference system (ANFIS) based maximum power point tracking controller is testified for a proton exchange membrane fuel cell (PEMFC) system can be used in electric vehicle applications. In order to extract the optimum power, a high step-up boost converter is connected between the fuel cell and the BLDC motor.. The performance of the proposed controller is tested under normal operating conditions and also for sudden variations in the cell temperatures of the fuel cell in MATLAB Simulink environment.

Keywords: Fuel cells, MPPT techniques, ANFIS, BLDC motor etc.

I. INTRODUCTION

The performance of all-electric vehicles is still not sufficient to satisfy today's drivers who are used to the high energy density of fossil fuels as energy carrier. Batteries are the main energy storage system of today's electric vehicles. To minimize the number of charge/discharge cycles of the battery, a flywheel can be integrated in the driveline [1]. Especially in urban traffic this could decrease the number of charge/discharge cycles, and thereby increase battery life.

In this light, it becomes important to investigate into technologies that will help in making fuel cell based vehicles more competitive on energy efficiency scale, and performances that different design choices, in terms of design of fuel cell, type of electrolyte configuration, design of the drive system, and then to assess the final impact of energy efficiency and performance. Moreover, due to the limited space for components in vehicles, the choice of peak torque versus thermal capability for a certain electric machine size also becomes highly important.

Fuel cell electric vehicles (FCEVs) are powered by proton exchange membrane fuel cells (PEMFCs), which are low-temperature (typically less than 100 °C), electrochemical devices that convert hydrogen and oxygen directly into electric power. There is no combustion of petroleum-based fuels. The "stack" consists of PEMFCs combined in series and parallel to provide the desired electrical performance.

II. LITERATURE REVIEW

In recent years, fuel cells have gained more attention from researchers and automakers due to their high energy density, high efficiency and low noise. [1]

Fuel cells are categorized into different types depending on the type of electrolyte substance notably proton exchange membrane fuel cell (PEMFC), alkaline fuel cell (AFC), solid oxide fuel cell (SOFC), molten carbonate fuel cell (MCFC), direct methanol fuel cell (DMFC), phosphoric acid fuel cell (PAFC)and photonic ceramic fuel cell (PCFC). All these designs are based on the type of electrolyte used and the efficiency of chemical reaction leading to electrical output, along with amount of heat produced.[2]

Among all the types of fuel cell technologies, PEMFC is dominantly getting used in electric vehicles due to its small size, quick startup, low operating temperature and high power density. The output voltage of the PEMFC system depends on the oxygen partial pressure, membrane water content and cell temperature. The voltage-current (V-I) characteristics of the PEMFC system are non-linear. Hence, only a single operating point is available for PEMFC system with maximum output voltage and power. Therefore, a maximum power point tracking (MPPT) controller is required for PEMFC system to extract the maximum power. [4, 5]

Fuel Cell Electric Vehicles (FCEVs) can replace conventional vehicles. The PEMFC is used as the main energy system (MES), and a super-capacitor or a battery is used as rechargeable energy storage system. MES provides extended driving range, and RESS provides good acceleration and regenerative braking. [6]

Due to the need for regenerative power and the high variation of power demands in vehicles, fuel cells are generally used in conjunction with a reversible power sources. These sources consist of storage devices such as batteries or ultra-capacitors. A PEMFC and battery hybrid system for tramway applications has also been studied. The used management strategy was based on supplying the power requirements of the tramway forcing the fuel cell to work around its maximum efficiency. [13,14]

A hybrid system combining a PEMFC stack and a lead acid battery pack was developed for a lightweight cruising vehicle and the design of a vehicle powered by a PEM fuel cell to charge a lead acid battery pack has been studied. The results of these studies show that such a hybrid system is a good solution for the dynamic power supply requested by road vehicles. However, such systems are mode adapted for drive cycles with a low number of starts and stops like those encountered in highway driving modes.

To extract the best from the output of Fuel cell, MPPT controllers for the PEMFC system are designed and implemented. The MPPT controllers for PEMFC system can be broadly classified as perturb and observe (P&O) method, incremental conductance (INC) method and artificial intelligence (AI) based controllers. P&O method is commonly used MPPT technique in PEMFC systems. [17]

The P&O algorithm perturbs the operating point by decreasing or increasing the control variable by a small amount and computes the PEMFC stack output power before and after perturbation.. Even though, P&O algorithm is simple and easy to implement, its accuracy instead-state is low due to the perturbing process causes the operating point of the PEMFC system oscillate around MPP, which eventually leads to the energy loss.[18,19]

Incremental Conductance or INC controller is designed to increase the dynamic performance and tracking efficiency of the PEMFC system. This method is based on the slope of power versus current curve. This method will give fast and accurate tracking of MPP point than the P&O method. However, it generates the oscillations at the optimum operating point which will reduce the efficiency of the PEMFC system. [20,21]

PEMFC system has non-linear V-I characteristics. Many research activities have focused their study on faster tracking controllers based on artificial intelligence (AI) schemes. The AI based techniques provides better solution for non-linear systems. The AI methods are mainly classified as fuzzy logic controller (FLC) and artificial neural networks (ANN). [22]

The extraction and controlling of MPP using different configurations of FLC are studied and results shows quite an effective control to achieve good output. An adaptive fuzzy controller for PEMFC system is also designed which involves summation of advantages of fuzzy systems and other simple control schemes like PID. FLC has the advantages: of fast response, flexible operation and also the exact mathematical model of the system is not required. FLC uses an expert knowledge to formulate the fuzzy inference rules. The efficiency of the FLC depends on the skills of the user or control engineer [23, 24]. One major drawback of fuzzy based control schemes or adaptive control schemes based controller is that it requires more memory which increases the cost of controller. [25]

Artificial Neural network or ANN algorithms based control schemes for MPPT detection and approximation have the capability to find complex non-linear relationships between independent and dependent variables without the need of an accurate mathematical model of the system. ANN based MPPT controllers for PEMFC have been designed. ANN uses a radial basis function network (RBFN) structure or feed forward multi-layer perception (MLP) model to track the MPP [26]. ANN controller has been used to approximate the voltages and currents corresponding to the MPP of PEMFC system for different cell temperatures. The major drawback of this controller is that it requires large numbers of training data and also more calculations are involved which increases the size of the controller [27].

III. PEMFC MODELLING

PEMFCs are a promising technology for vehicle applications thanks to their higher efficiency, low emissions and direct production of electricity. A PEMFC is a device converting the chemical energy into electrical energy. Its input is the load current flowing in the PEMFC stack and the output is the voltage provided by the PEMFC.

The output voltage of a single cell can be defined as follows:

$$v_{fc} = n_{fc}\, v_{cell} = nfc\, (E_{Nernst} - E_{act} - E_{con} - E_{Ohm})$$

Where, ENernst (Nernst voltage) is the thermodynamic potential of the cell representing its reversible voltage. The Nernst voltage is calculated starting from a modified version of Nernst equation with an extra term to take into account changes in temperature with respect to a new standard temperature; Eact is the activation voltage drop which is the amount of voltage lost in driving the reaction. This voltage drop is described by the general form of Tafel's equation; Econ is the concentration voltage drop, which is the voltage lost when the concentration of the reactant at the electrode is diminished according to Fick's first law and Faraday's law; Eohm is the ohmic voltage drop, which is the amount of voltage lost due to the resistance to electron flow in the electrodes and the resistance to ion flow in the polymer membrane. It represents the conducting resistance between the membrane and electrodes and the resistance of electrodes. Each term of equation above can be calculated by the following equations:

$$E_{Nerst} = 1.229 - 8.5\, e^{-4}\, (T_{fc} - 298.15) + 4.308\, e^{-5}\, [\ln(p_{H2}) + 0.5 \ln (p_{02})]$$

$$E_{act} = (RT / \alpha zF) \ln (i_{fc} / I_0) = T_{fc}\, [a + b \ln (i_{fc})]$$

$$Econ = - 0.016 \ln (1 - (i_{fc} / 25))$$

$$E_{ohm} = i_{fc}\, R_{ohm}$$

Where R_{ohm} is the internal electrical resistance, it is a function of the membrane conductivity and cell temperature is defined as:

$$R_{ohm} = t_m / \sigma_m$$

Where t_m and s_m are the thickness of the membrane and the membrane conductivity respectively, the membrane conductivity is defined as:

$$\sigma_m = (0.005139\lambda m - 0.00326)\, e^{(1.155 - (350/Tfc))}$$

Where, λ_m is the membrane water content. The value of λ_m varies between 0 and 14, which is equivalent to the humidity of 0% and 100%. Under supersaturated conditions, however, the maximum possible value of lm can be as high as 23. In addition, lm can also be influenced by the membrane preparation procedure, the relative humidity of the feed gas, the oxygen and hydrogen excess ratios, and the age of the membrane.

The dynamic gas transport model describes the variation of the partial pressure of the reactants during the FC operation. The following balance equation describes the amount of hydrogen and oxygen in the input and the output and that reacted in the FC:

$$\frac{dp_{ca}}{dt} = \frac{RT_{fc}}{V_{ca}}\,(W_{ca,in} - W_{ca,out} - W_{ca,rec})$$

Where, the oxygen consumption rate $W_{ca,rec}$, the inlet cathode mass flow rate $W_{ca,in}$ and the outlet cathode mass flow rate $W_{ca,out}$ are given respectively by:

$$W_{ca,rec} = M_{O_2}\frac{n_{fc}i_{fc}}{4F}$$

$$W_{ca,in} = \frac{1}{1+\omega_{atm}}W_{in}$$

With,

$$\omega_{atm} = \frac{M_v}{M_a}\,\frac{\varphi_{atm}p_{sat}T_{atm}}{p_{atm} - \varphi_{atm}p_{sat}T_{atm}}$$

$$W_{in} = k_{ca,in}(p_{sm} - p_{ca})$$

$$W_{ca,out} = k_{ca,out}(p_{ca} - p_{rm})$$

Where, Mv and Ma are the molar mass of vapor and air respectively, fatm is the relative humidity at ambient conditions, ω_{atm}, $k_{ca,in}$ and $k_{ca,out}$ are the humidity ratio, the cathode inlet orifice constant and the cathode outlet orifice constant respectively. The angular speed ω_{cp} verifies the following differential equation:

$$\frac{d\omega_{cp}}{dt} = \frac{1}{J_{cp}}(\tau_{cm} - \tau_{cp})$$

Where, J_{cp} is the compressor motor inertia. τcm and τcp denote the compressor motor torque and the load torque required to drive the compressor respectively.

The total net FC power, P_{net}, can be defined as:

$$P_{net} = P_{fc} - P_{cm}$$

Here,

$$p_{fc} = v_{fc} \times i_{fc}$$

$$P_{cm} = (k_t / R_{cm})\, (v_{cm} - k_v\omega_{cp})$$

Where P_{fc}, is the FC power, which is the product of FC voltage, v_{fc}, and FC current, i_{fc}, and P_{cm} is the power consumed by the compressor. One of the problems in the PEMFC generation systems is that the amount of electric power by the PEMFC is always changing with water membrane content. An MPPT control strategy, which has fast response characteristics and is able to make good use of the electric power generated in any water membrane content, is needed to solve the aforementioned problems. Furthermore, the PEMFC proper operation is achieved by controlling those auxiliaries, in particular the air supply system. The air consumption system is about 20% of the power supplied by the fuel cell, which reduces the effective capacity of the

PEMFC. This is why; the air system control is an important challenge for the development of the fuel cell electric vehicles. Indeed, maintaining an adequate level of the oxygen partial pressure in the cathode during rapid variations of fuel cell current in MPPT operation mode is important to avoid a degradation of the membrane and a decrease in the system efficiency.

IV. ANFIS BASED MPPT SCHEME

A fuel cell operates like a battery by converting the chemical energy from reactants into electricity. It differs from the battery in that as long as a fuel such as the hydrogen and an oxidant such as the oxygen are supplied, it will produce DC electricity, water and heat continuously. The control system that we are trying to implement will be dedicatedly used for Electric vehicles. The most common traction system used here is BLD motor, and is becoming more popular as a variable speed drives over induction and synchronous motors due to its high power factor, high torque to current ratio, high power density, compact structure and silent operation.

The output power of the FC system depends on many operating parameters like cell temperature, anode and cathode pressures, relative humidity, stoichiometry and anode and/or cathode gas mole fraction. However, for fixed operating conditions, there is only one unique point on Power-Current curve, which represents the Maximum Power Point (MPP) at which a FC system produces its maximum power. PEMFC system has non-linear V-I characteristics. The AI based techniques provides better solution for non-linear systems. The AI methods are mainly classified as fuzzy logic controller (FLC) and artificial neural networks (ANN). The extraction and controlling of MPP using different configurations of FLC are also implemented.. FLC has the advantages: fast response, flexible operation and also the exact mathematical model of the system is not required. FLC uses an expert knowledge to formulate the fuzzy inference rules. So that the efficiency of the FLC depends on the skills of the user or control engineer. Another major drawback of this controller is that it requires more memory which increases the cost of controller. On the other hand, ANN algorithms have the capability to find complex non-linear relationships between independent and dependent variables without the need of an accurate mathematical model of the system. ANN uses a radial basis function network (RBFN) structure or feed forward multi-layer perception (MLP) model to track the MPP. ANN controller has been used to approximate the voltages and currents corresponding to the MPP of PEMFC system for different cell temperatures. The major drawback of this controller is that it requires large numbers of training data and also more calculations are involved which increases the size of the controller.

Due to these issues surrounding FLC and ANN, in this study, I am trying to merge the two techniques that may result in selecting the advantages of each scheme, by over-ruling the problems associated in different schemes. This is taken as a scope for the development of new controller which can track the power more effectively compared to the existing controllers. In this study, an Adaptive Neuro-fuzzy inference system (ANFIS) based MPPT controller for the PEMFC system used in electric vehicle applications. ANFIS is basically a fuzzy inference system optimized by neural networks. Hence the controller has the advantages of both neural network and fuzzy logic controllers. The input variables to the controller are PEMFC voltage (VFC) and current (IFC) and the output is duty cycle (D).

V. METHODOLOGY

ANFIS is the combination of both neural networks and fuzzy inference system. Thus, it offers the benefits of inference mechanism of fuzzy system and learning ability of neural networks. Many inputs are applied to the neural network depending upon the inputs the neural network has some standard output, so depending upon the input and the output the neural network is trained, after training the neural network the output is applied to the fuzzy logic which generates the IF THEN rules and membership functions. This ANFIS controller is widely used for controlling the non-linear system. As this is the best controller as compared to conventional PID controller, and other controller. This controller is used in planes to controller them now a day's research is going on for Intelligent systems which learn by themselves and do operations of significance in many applications.

Figure above shows the typical ANFIS structure of the Sugeno fuzzy system. It has two inputs (X and Y) and single output (F) with 5 layers. The fuzzy if-then rules of the Sugeno fuzzy system are given as follows:

Rule 1: If X is A1 and Y is B1, then $F_1 = p_1X + q_1Y + \text{þ}\ r_1$

Rule 2: If X is A2 and Y is B2, then $F_1 = p_2X + q_2Y + r_2$

Here, square specifies an adaptive node, whereas a circle specifies a fixed node. The purpose of the each layer in the ANFIS is given as follows:

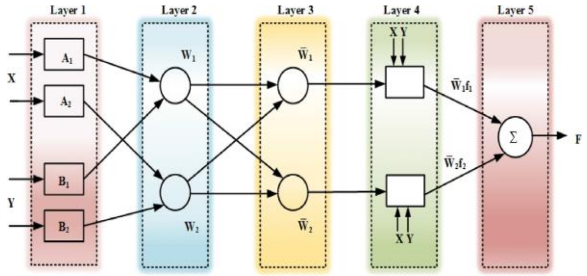

Fig.1– ANFIS Architecture

Layer 1: In this layer the input values are converted to fuzzy values. Each node in fuzzification layer is an adaptive node with a node function given as:

$Q1,i = \mu_{Ai} (X)$ for i = 1,2

$Q1,i = \mu_{B_{i-1}} (X)$ for i = 3, 4

where $O_{1,i}$ is membership value for the inputs X and Y, m is membership function. The subscripted i and 1 indicates the node and layer numbers respectively.

Layer 2: This layer is called as product layer. Each node in this layer is fixed node. The output of this layer is product of the every incoming signals.

$O_{2;i} = w_i = \mu_{Ai} (X) \mu_{Bi} (Y) \quad i = 1, 2$

The output of the each node indicates the firing strength of each rule.

Layer 3: The third layer in Sugeno fuzzy system is normalization layer. Each node in this layer is a fixed node. This layer normalizes the firing strength by dividing rule's firing strength with sum of firing strengths of all the rules. If $\overline{w_i}$ is normalized firing strength, then

$$O_{3,i} = \overline{w_i} = \frac{w_i}{w_1 + w_2}$$

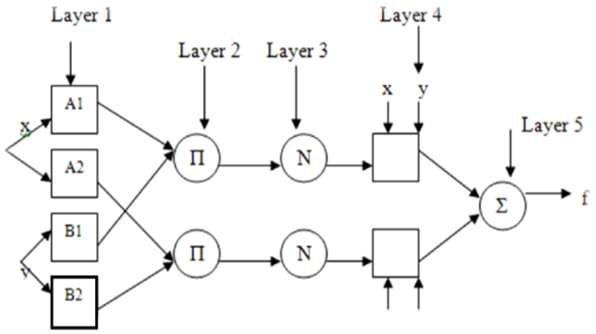

Fig.2-ANFIS structure for 2 –input variables for TSK Model

Layer 4: It is defuzzification layer. Each node in this layer is an adaptive node with node function given as:

$$O_{4,i} = \overline{w_i} (p_i X + q_i Y + r_i)$$

Where, pi, qi, ri are consequent parameters.

Layer 5: It is output layer and has only a fixed node. It calculates the overall output value by summing all the incoming signals.

$$O_s = \sum_i \overline{w_i} F_i = \frac{\sum_i \overline{w_i} F_i}{\sum_i \overline{w_i}}$$

Input variables to the ANFIS controller are PEMFC voltage (VFC) and current (IFC) and the output is duty cycle (K).

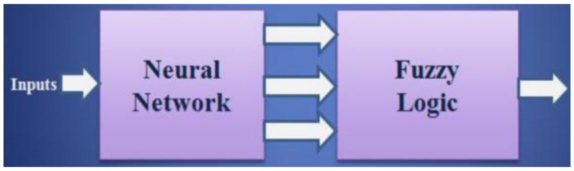

Fig.3-Block diagram of ANFIS Controller

A. *Training of ANFIS*

Using the MATLAB/Simulink model of the PEMFC system, the PEMFC system temperature is varied from 300 K to 340 K in a step of 20 K, to obtain training data sets for ANFIS. The PEMFC voltage and current for each pair of training data is recorded.

During training process, 529 training data sets and 200 epochs are used. By using this predefined input/output data set, the ANFIS generates a fuzzy inference system (FIS) whose MF parameters are tuned by using the hybrid optimization method combining back propagation algorithm and least square algorithm. The training error is approximately reduced to 6% and the training waveform is shown in figure 4.

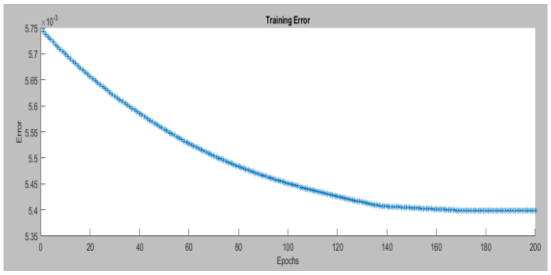

Fig.4-Training error versus epochs for ANFIS

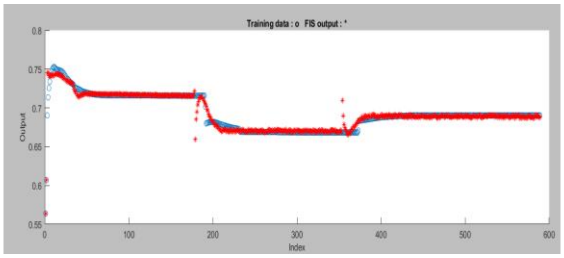

Fig.5-Training data and ANFIS output

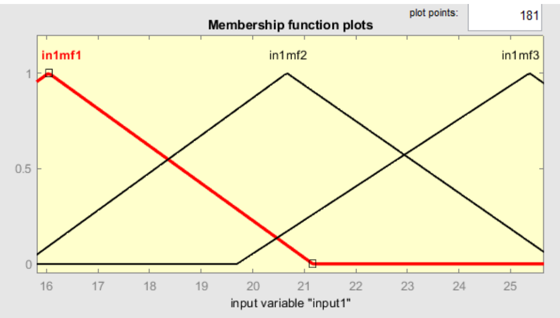

Fig.6-Input voltage membership function

Figure above shows the ANFIS output and training data. It illustrates that even at 6% of training error, the output of the ANFIS is closely matches with the actual output of the system.

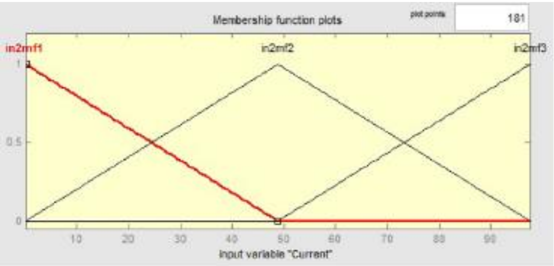

Fig.7-Input current membership function

The MF's of each input are shown in Figs.6 and 7. Nine fuzzy set rules are generated by using the six input MF's. Fig. 8 shows the output of fuzzy rules for corresponding PEMFC voltage and current. The surface view of the rules generated by ANFIS is shown in Fig. 9. It is a three-dimensional plot between voltage, current and duty cycle.

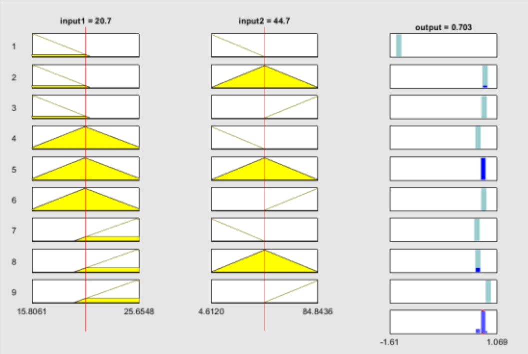

Fig.8-Generated fuzzy rules

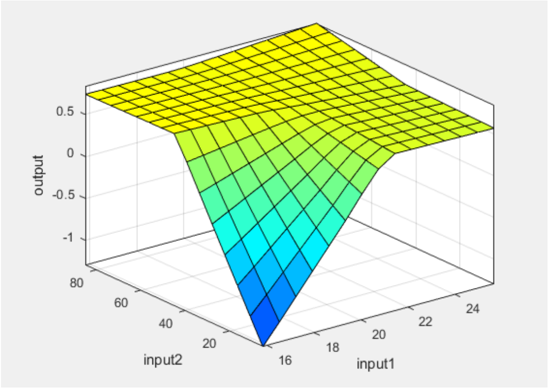

Fig. 9-ANFIS generated rules- Surface View.

In this paper, authors have proposed an adaptive neuro-fuzzy inference system (ANFIS) based MPPT controller for the PEMFC system used in electric vehicle applications. ANFIS is basically a fuzzy inference system optimized by neural networks. Hence the proposed controller has the advantages of both neural network and fuzzy logic controllers. The input variables to the proposed controller are PEMFC voltage (VFC) and current (IFC) and the output is duty cycle (D).

VI. SIMULATION RESULTS

The accuracy and performance of the proposed MPPT controller is investigated by performing simulations in Simulink platform for normal operating conditions of the PEMFC and also for the sudden variations in the cell temperatures of the PEMFC system. The specifications of the PEMFC system are listed in Table 1.

Table 1- PEMFC Specifications

Parameters	Value
Maximum power (W)	**1260**
Maximum voltage (V)	**24.23**
Maximum current (A)	**52**
Number of cells	**42**
Nominal fuel flow rate (lpm)	**417.3**
Nominal air flow rate (lpm)	**2400**
Hydrogen partial pressure (bar)	**1.5**
Oxygen partial pressure (bar)	**1**

The performance of the proposed MPPT controller is analyzed by comparing the results with fuzzy logic controller.

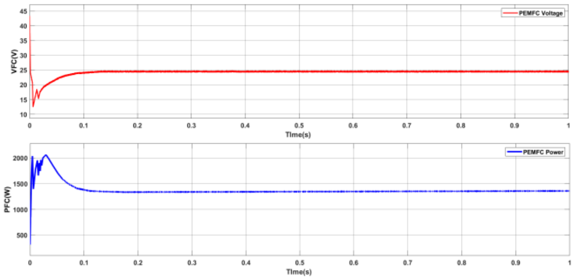

Fig. 10- PEMFC output voltage and power

Case Study: During normal operating conditions

In this case, the operating voltage of the PEMFC is considered as 340 K constant. The simulation results for this case are shown from Figs. 10

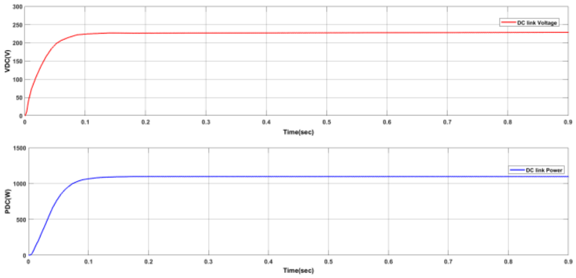

Fig.11- DC link output voltage and power

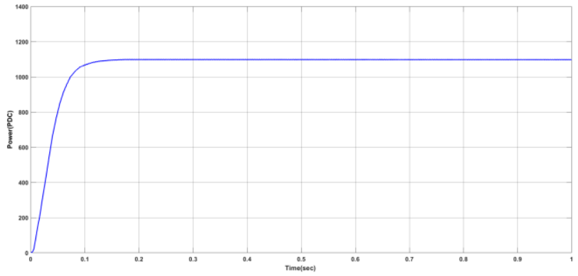

Fig.12- DC link power with proposed ANFIS controllers

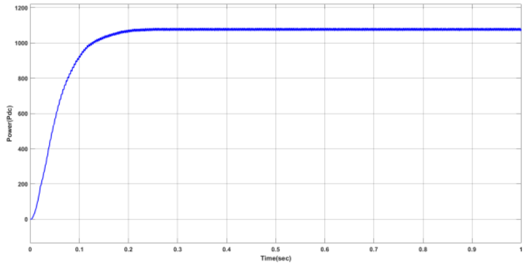

Fig.13- DC link power with fuzzy logic controllers

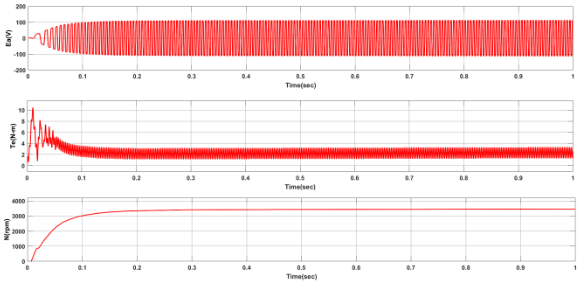

Fig.14-BLDC motor characteristics

Fig. 10 shows the PEMFC output voltage and power for the considered temperature. The PEMFC system generates a voltage of 23.4 V and a power of 1140 W. This PEMFC voltage is given to the HSBC in order to meet the required DC link voltage. The DC link voltage and power of the proposed FCEV system by using ANFIS MPPT controller are shown in Fig. 11. The PEMFC output voltage 23.4 V is boosted upto 235V at the DC link by using ANFIS.

To verify the effectiveness of the ANFIS controller, the DC link power is compared with the power extracted using the FLC controller. From Fig. 12-13 it is observed that the proposed ANFIS controller has tracked the maximum power faster than the FLC. The time taken to reach the MPP by using ANFIS is around 0.13sec, whereas with FLC it is around 0.22sec.

The characteristics of the BLDC motor such as back EMF (E), electromagnetic torque (Te) and speed (N) are shown in Fig. 14. The electromagnetic torque and speed of the motor reaches steady state at 0.21 sec. At the constant temperature of the PEMFC system, the BLDC motor operates at a speed of 3200 rpm and with a torque of 2.4N-m.

CONCLUSION

The proton exchange membrane fuel cells (PEMFC) present attractive proprieties for vehicle applications for the following reasons like lower operation temperature, thus they can be rapidly turned on and off; lower operation pressure, hence greater safety; they can be easily set into mode system; and they have lower emission ratio and higher conversion ratio. In this paper, an adaptive neuro-fuzzy inference system based MPPT controller is introduced and also a high step-up boost converter is designed for 1.26 kW PEMFC system used in electric vehicles. The proposed controller is designed for both constant and dynamic temperature conditions of the PEMFC system. The results of the ANFIS controller are compared with fuzzy logic MPPT controller. The simulation results infers that the ANFIS has the quick and accurate response than the FLC. The proposed ANFIS controller increases the average DC link power by 1.95% when compared to the FLC.

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