Comparative study of maximum power point tracking techniques for fuel cell powered electric vehicle

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Abstract. Proton Exchange Membrane Fuel Cell System (FCS) based power generation is considered for powering electric vehicle in this paper. PEMFCS delivers a fresh and best substitute to the conservative vestige fuel-based methods which is the green future. Maximum Power Point Tracking (MPPT) method is essential to elicit utmost accessible power from FCS. Perturb and Observe (P&O) and Incremental Conductance (INC) method is implemented as MPPT technique. In this work, Brush Less DC (BLDC) motor is connected to load, fed by a Fuel Cell System (FCS) through Boost Converter (BC). The efficient MPPT technique is observed using MATLAB/Simulink.

1. Introduction

In the recent applications and rapid growth on using green technologies, Electric Vehicle (EV) has become the next future of the world. Main problems rely on the environmental influences of conservative fossil fuels, and currently growing demand for these energy sources and their deficiency. Many researchers, currently show their interest in this domain towards developing technologies through renewable energy integration[1]. One of our National Electric Mobility Mission Plan (NEMMP) 2020 is to deploy 5 to 7 million electric vehicles in the country. Fuel cell promises to be one of the best sustainable and renewable power sources due to its high-low carbon emission and power density. For various applications such as Electric Vehicles, FCS can be utilize as a brand new power primary source [2]. Although the initial cost is high the fuel cell has the advantage that it has zero running cost. The break even period will be around ten to fifteen year period based on the energy usage policy[3]. Since the FC system is dependent on the temperature control and the pressure regulation, the direct connection to load is impossible. To avoid consumption of excessive fuel and to improve efficiency MPPT techniques are used to tackle the present energy crisis and to develop an efficient system to extract maximum power from fuel cell. MPPT algorithm controls the power converters to continuously detect the instantaneous maximum power from FCS.

Several MPPT techniques include Incremental INC method, P&O method, Neural Networks, Fuzzy Logic (FL) Techniques, Particle Swarm Optimization (PSO), and Genetic Algorithms etc. The MPPT tracks the MPP of FCS using the techniques [4-5]. The techniques changee the boost converter duty cycle of to obtain the current and voltage corresponding to MPP. In this method, Fuel cell voltage is

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boosted and fed to BLDC motor. BLDC motor is more suitable for EVs because it has many advantages compared to the conventional electrical motors; such as high power densities, better speed and torque characteristics, and different speed of operation, highest efficiency and long life of operation [6]. In comparison with induction motors, BLDC motor is simpler. The BLDC motor should be driven at its nominal power, to ensure the operation at highest efficiency and within safe operating point [7]. The paper aims to model, design and analyse the BLDC motor and boost converter, also to study the effect of P&O and INC techniques on FCS. The paper provides a comparative to find the most suited techniques to drive the motor between P&O and INC techniques. Section 1 introduces the importance and need of fuel cell towards electric vehicle applications. Section 2 describes the modeling of fuel cell, MPPT Techniques adopted and BLDC motor drive system. In Section 3 simulation results and discussion are carried out followed by conclusion in section 4.

2. Modelling of fuel cell integration to electric vehicle

2.1. Fuel Cell Modelling

A fuel cell through an electrochemical reaction it convert chemical energy to electrical energy. The reaction of hydrogen (H2) anode, oxygen (O2) cathode. The total outputs from a cell are described using equation (1) equation (2) and equation (3) respectively;

\[ H_2 \rightarrow 2H^+ + 2e^- \]  
\[ \frac{O_2}{2} + 2H^+ + 2e^- \rightarrow H_2O \]  
\[ H_2 + \frac{O_2}{2} \rightarrow H_2O \]

The output voltage of H2-O2 FC is found to be \( E_0 = 1.229V \) [8].

\[ V = V_{FCS} = V_{at} - V_{con} - V_{\Omega} \]

(5)

Where \( V_{FCS} = \) FCS output voltage, \( V_{at} = \) voltage at open circuit, where \( V_{con} \) and \( V_{\Omega} \) are the initiation, the attention, and the ohmic FCS above voltage correspondingly. The nonlinear characteristic of FCS voltage is described by the formula given by equation (6) [2].

\[ V_{FCS} = V_{cell} - \frac{RT}{2aF} \ln \left( \frac{I_{FSC}}{i_L} \right) - \frac{RT}{2F} \ln \left( \frac{I_{FSC}}{i_0} \right) - I_{FSC}R_m \]

(6)

Where \( I_{FSC} = \) FC output current, \( i_L = \) limiting current, \( i_0 = \) current density, \( a = \) transfer co-efficient of charge
\( R_{\text{int}} \) = internal resistance[14]. The FC stack is designed by predetermined model of 1.26kWp PEMFCS in MATLAB/ Simulink, stack device has following parameters shown in table 1.

**Table 1. Fuel cell parameters**

| FUEL CELL SYSTEM | Stack power | Fuel flow nominal | Fuel flow maximum |
|------------------|-------------|------------------|------------------|
| Voltage of one cell | 1.115V | 12.22 lpm | 23.46 lpm |
| System Temperature | 328 K | Air supply pressure | 1.0 bar |
| Fuel supply pressure | 1.5 bar | Air flow nominal | 2400 lpm |

2.2. Adopted maximum power point technique

The main use of MPPT algorithm in FCS is to operate the structure with peak proficiency. The converter using MPPT algorithms controls the power converter there by making it to work at its MPP[7]. In this work, a P&O and INC technique is adopted.

2.2.1. Perturb and observe method

Now this method, perturb duty cycle of the power converter indicates changing the voltage among the FCS and the power converter. Here FCS voltage is taken as the perturb parameter. The fuel cell working voltage is perturbed by a slight volume, and the variation in power is restrained. If the modify power is optimistic, then the operating voltage move the fuel cell functioning point closer to the MPP as explained in figure 1. The voltage perturb in the same direction should move the working point toward the MPP and vice versa. Then the algebraic sign of the perturbation should be upturned to move back towards the MPPT.

![P&O algorithm flowchart](image1)

**Figure 1. P&O algorithm flowchart**

![INC method flowchart](image2)

**Figure 2. INC method flowchart**
The methodology for MPPT using P&O method shown in the flowchart by way of shown in figure 2. The duty cycle thus can be labelled by the power and voltage relationship as given in equation (7);

\[
\frac{dp}{dv}(t) = \frac{p(t) - p(t-1)}{v(t) - v(t-1)}
\]  

(7)

The advantages of using this method include easiness and comfort of achievement. Still, this method has limits such as reduced efficiency, oscillations near peak power etc.

2.2.2. Incremental conductance (INC) technique

The incremental conductance method is based on the principle that the incline of the power versus current (voltage) of the module is nil at the MPP, negative (confident) on the left of it and positive (undesirable) on the right. The condition for MPP is given in equation (8) as found in [4],

\[
\frac{\Delta I}{\Delta V} = -\frac{I}{V_{ref}}
\]  

(8)

Where,
\(\Delta V\) - change in fuel cell voltage
\(V_{ref}\) - reference voltage

In both schemes under consideration, time taken for attaining extreme power be determined by on the rate of the increment of the reference voltage. This paper propose modifications in INC methodd which enhances the tracking capability at slopes. The algorithm for determining voltage is shown in figure 2.

The change in MPP is considered by comparing the increment of the power versus voltage (current) between two consecutives samples.

2.3. Converter modelling

The function of converter is the output \(V_0\) voltage is larger than the input \(V_{in}\) voltage. A basic boost DC – DC converter topology is shown is figure 3.

![Figure 3. Boost converter circuit.](image)

The figure 3.switch is closed the current movements through the inductor and inductor gets charged. When this switch is opened the diode becomes onward biased and the stockpiled energy is free from inductor and current flow thorough the inductor and capacitor. This operation recurrences and results in higher output voltage which is then transferred to the load. The duty cycle of converter can be attained from the following ratio is described in equation (9)[10].

\[
V_0 = \frac{V_{in}}{1 - D}
\]  

(9)

Where:
\(V_0\) = Voltage (output)
Vin = Voltage (input)
D = duty cycle for converter

Table 2. Converter parameters

| Sl.No | Parameters         | Value  |
|-------|--------------------|--------|
| 1     | Voltage for input  | 24.0 V |
| 2     | Frequency          | 10.0 KHz |
| 3     | Inductance         | 500μH |
| 4     | Capacitance        | 10mF |
| 5     | Ripple Voltage     | 5.0 % |
| 6     | Ripple Current     | 5.0 % |

2.4. Modelling of brushless DC motor

The order of switching sequence for six switches of the VSI provided by the electronic commutation of the brushless DC motor. The 3 ph. star coupled brushless DC motor can be labelled by the following equation (10) equation (11) equation (12) and equation (13) [11].

\[ V_{mp} = R(i_p - i_q) + L \frac{d}{dt}(i_p - i_q) + v_p - v_q \]  
(10)

\[ V_{pq} = R(i_q - i_p) + L \frac{d}{dt}(i_q - i_p) + v_q - v_p \]  
(11)

\[ V_{qr} = R(i_p - i_q) + L \frac{d}{dt}(i_p - i_q) + v_q - v_p \]  
(12)

\[ T_e = K_{em} + J \frac{d\omega_m}{dt} + T_L - v_p \]  
(13)

The signs V, I and e denotes phase voltage, phase current and back EMF correspondingly, in 3 ph. a, b and c the inductance and resistance are per phase values and \(T_E\) and \(T_L\) stand for electrical and load torques correspondingly. \(J_R\) is the inertia of the rotor, \(K_f\) is the friction constant and \(\omega_m\) is the rotor speediness back EMF and \(T_E\) can be conveyed in equation (14) equation (15) equation (16) and equation (17)

\[ v_p = \frac{k}{2} \omega_F(\theta_m) \]  
(14)

\[ v_q = \frac{k}{2} \omega_F(\theta_m + \frac{2\pi}{3}) \]  
(15)

\[ v_r = \frac{k}{2} \omega_F(\theta_m + \frac{4\pi}{3}) \]  
(16)

\[ T_e = \frac{k}{2} \left( F(\theta_m)v_p + F\left(\theta_m - \frac{2\pi}{3}\right)i_q + F\left(\theta_m - \frac{4\pi}{3}\right)i_r \right) \]  
(17)

The voltage of motor equation is a direct mixture of the further two voltages equation only two voltages are needed. By tossing away one equation and removing one variable consuming the current association the equation is expressed as shown in equation (18) [11].

\[ i_p + i_q + i_r = 0 \]  
(18)
The voltage equation (19) and equation (20) become

\[ E_{pq} = R(i_p - i_q) + L \frac{d}{dt}(i_p - i_q) + v_p - v_q \quad (19) \]

\[ E_{pr} = R(i_q - i_r) + L \frac{d}{dt}(i_q - i_r) + v_r - v_q \quad (20) \]

Fuel Cell output maximum power tracking is carried out by P&O and IC method and fed to boost converter controlling the BLDC motor which remains used in electric vehicles. The used FC’s can deliver power of 1.26KW under the voltage of 24 V and 50 A. Table 1 gives the details of parameters of the FCS, by adjusting the fuel flow pressure and air flow pressure the voltage output of the cell is varied as per the desired value.

![Proposed system block diagram](image)

**Figure 4. Proposed system block diagram**

The parameters of brushless motor are given in the table 3.

| Brushless DC Motor parameters |
|------------------------------|
| **Brushless DC Motor**       |
| Poles                        | 4            |
| DC Voltage                   | 300V         |
| Resistance                   | 0.40 Ω       |
| Inductance                   | 13.0 mH      |
| Rated Speed                  | 1500 rpm     |
| Torque                       | 0.40 V (rad/sec) |

The 3 ph. brushless DC motor is worked in a 2 ph. technique, whereas the third ph. is off. The 2 ph. to be energized are determined by position of the rotor. The position sensors vary the signals every 60° (electrical degrees).

**Table 4. Inverter switching sequence**
Based on table 4., the switches are getting trigger corresponding to their coil get energies or de-energies are shown in figure 5.

| Voltage Switching Interval | Seq. No. | Position Sensor | Switch Closed | Phase Current |
|---------------------------|---------|-----------------|---------------|---------------|
| 0° -60°                   | 0       | H1 1 H2 0 H3 0  | Q1 Q4         | + - off       |
| 60° -120°                 | 1       | H1 1 H2 1 H3 0 | Q1 Q6         | + off -       |
| 120° -180°                | 2       | H1 0 H2 1 H3 1 | Q3 Q6         | off + -       |
| 180° -240°                | 3       | H1 0 H2 1 H3 1 | Q3 Q2         | - + off       |
| 240° -300°                | 4       | H1 0 H2 1 H3 1 | Q5 Q2         | - off +       |
| 300° -360°                | 5       | H1 1 H2 1 H3 1 | Q5 Q4         | off - +       |

Figure 5. Simplified BLDC motor drive schemes

2. Simulation results and discussions

The Fuel cell connected to BLDC motor as displayed in figure 4, is developed spending MATLAB/Simulink model with boost converter and MPPT tracking controller, figure 6, shows the converter input voltage, P&0 and INC methods output voltage. The converter input voltage for both P&0 and INC methods is constant.

Figure 6. Output voltage of using and IC MPPT technique
Figure 6. shows the relationship between P&O and INC techniques as MPPT tracker connected to Fuel cell with the boost converter shows 270V constant output voltage without any voltage spikes when compared to IC method which produced 250V output voltage with spikes between 0.3sec and 0.7 sec been produced to drive the BLDC motor. Figure 7. depicts the switching pulses generator to BLDC motor.

Figure 7. Switching pulse to the six switches of the BLDC motor

Figure 8. Brushless DC motor analysis.
From figure 8., it states that brushless DC motor, stator current of three phases, three phase’s stator back emf, rotor speediness and brushless DC motor torque remains observed. The performance of the brushless DC motor using P&O method MPPT tracking facilitates to achieve rotor rated torque and rated speed to 1500rpm. The advantage of P&O algorithm is reduced fluctuation everywhere the MPP. The P&O technique is most suited to variations of external factors’ as it took less time and comparatively extra steady than the INC technique.

4. Conclusion
In this work, comprehensive modelling, plan and detailed investigation of BLDC motor, boost converter with MPPT of FCS by using P & O and INC techniques were achieved and analyzed. Also, the MPPT tracking methods namely P&O and IC controller are compared wherein which with P&O controller supported in producing constant higher voltage to drive the Electric Vehicle motor at rated speed. The result confirms the P&O controller proposed for fuel cell system driving the electric vehicle is an efficient methodology.

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