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MODELLING AND SIMULATION OF EXTREMUM SEEKING CONTROL FOR PEMFC

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Abstract- The Proton Exchange Membrane Fuel Cell (PEMFC) has a limited ability to produce electrical power and for using this electrical power more efficiency, there should be a DC-DC converter that gives desired output DC voltage and a suitable controller to work the PEMFC at maximum power point. In this study, the output voltage of PEMFC stack is boosted by means of cascade DC-DC boost converter that controlled with extremum seeking control (ESC) method. Moreover, the characteristic of The PEMFC and the proposed converter are analyzed. The simulations are done in Matlab/SIMULINK environment.

Keywords: PEMFC, ESC, Cascade DC-DC Boost Converter.

I. INTRODUCTION

Demand for fossil fuels has increased with the increase in energy demand as well as industrialization and population growth. As a result, serious problems such as air pollution, climate change and global warming have emerged. However, the limited and rapid depletion of fossil fuel reserves has led to the search for alternative energy sources. The PEMFC is the best alternative hydrogen energy that can replace fossil fuels [1].

However, the ability of PEMFC for producing electrical energy is limited [2]. Therefore, it is important to work at maximum power point (MPP). There are various algorithms for maximum power point tracking (MPPT) that have been advised by Zhong, et al. [3]. Bizon [4] proposed to MPPT technique for the PEMFC stacks rely on a modified ESC. Jiao [5] suggested extremum seeking sliding mode control method for the PEMFC power system that controlled by MPPT controller under different temperature and water content conditions. Bizon [6] in another analyzed a FC hybrid power source topology that can operate at MPP of fuel cell stack.

It is generally preferred because the P&O algorithm in photovoltaic power applications is simple. However, P&O is not a suitable method for MPP tracking of the fuel cell that shows instability in changing environmental conditions. The advantage of extreme seeking control is that the fuel cell does not require information in advance for MPPT [2]. The ESC of PEM fuel cell connected to the cascade DC-DC boost converter is analyzed in this study.

II. DESCRIPTION OF SYSTEM

A. The PEMFC

The PEMFC is an electrochemical device that works efficiently at low temperature and diffuses gases and pure water for producing DC nonlinear voltage [7, 8]. It has no moving parts so it does not make much noise while working. A solid polymer electrolyte that transmits the protons but no the electrons to change the ions between electrodes as given in Figure 1.

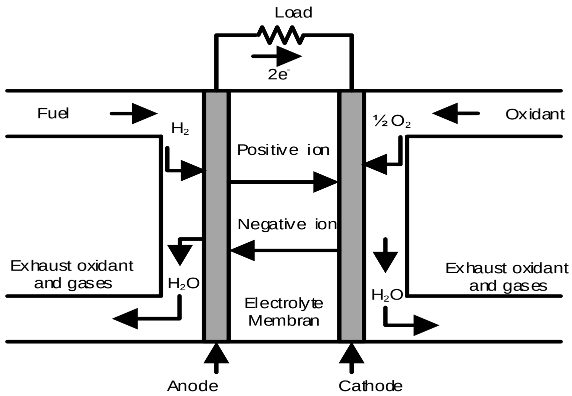

Figure 1. PEMFC operating diagram

The electrolyte membrane of PEMFC is in touch with electrodes on either side. At the anode side the fuel (hydrogen) is decomposed into positive (protons) and negative (electrons) ions. The electrolyte membrane allows only the positive ions to go from anode side to cathode side and does not transmit the negative ions. The free negative ions shift from anode to cathode by using an external way on load. By this way the PEMFC produces DC nonlinear voltage. At the cathode side, water or exhaust oxidant occur by recombination negative and positive ions with oxidant. The chemical reactions are given in Equation (1) [9].

$$\begin{aligned} &H_2 \Rightarrow 2H^+ + 2e^- \\ &1/2O_2 + 2H^+ + 2e^- \Rightarrow H_2O \\ &H_2 + 1/2O_2 \Rightarrow H_2O \end{aligned} \quad (1)$$

The expression of the PEM fuel cell voltage is given in Equation (2).

$$V_{Cell} = E_{Nernst} + \eta_{Akt.} + \eta_{Omic} + \eta_{Const.} \quad (2)$$

where, E_{Nernst} is thermodynamic potential, $\eta_{Akt.}$ is losses at the anode and cathode, η_{Omic} is the losses caused by the current flowing through the cell internal resistance, and $\eta_{Const.}$ is the concentration losses. Lost voltage statements are negative.

The current density-voltage-power and current density-efficiency-power graphs of PEMFC are given in the Figures 2 and 3, respectively.

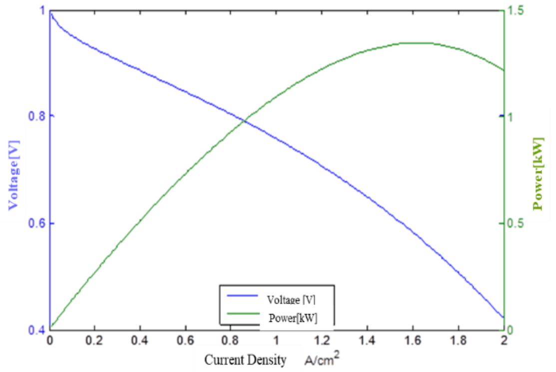

Figure 2. PEMFC operating graph (current density-voltage-power)

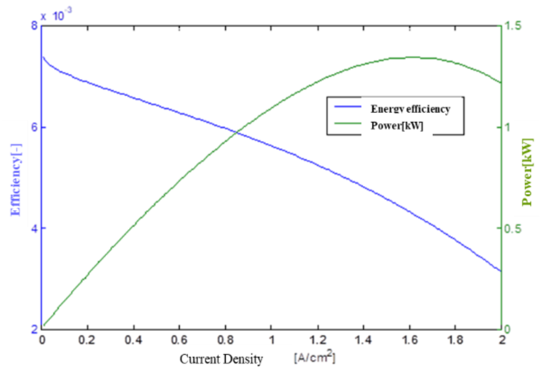

Figure 3. PEMFC operating graph (current density-efficiency-power)

B. The Cascade DC-DC Boost Converter

The cascade DC-DC boost converter is used to get required high output voltage (V_O) by increasing the input voltage (V_{in}). Despite the cascade DC-DC boost converter circuit boost rate is high its duty cycle and voltage stress on circuit elements is low and it has high efficiency so it is more favorable than the conventional DC-DC boost converter. The cascade DC-DC boost converter consists of two boost inductors (L_1 and L_2); one switch (M); and capacitors (C_1 and C_2) three diodes (D_0, D_1 and D_2) [10].

The voltage transfer gain of cascade DC-DC boost converter is shown in Equation (3).

$$\frac{V_O}{V_{in}} = \frac{1}{(1-d)^2} \quad (3)$$

State-space-average model is a technique for creating a time-invariant model [11]. It is important to perform the state space average model and small signal analysis to find the transfer function of the system.

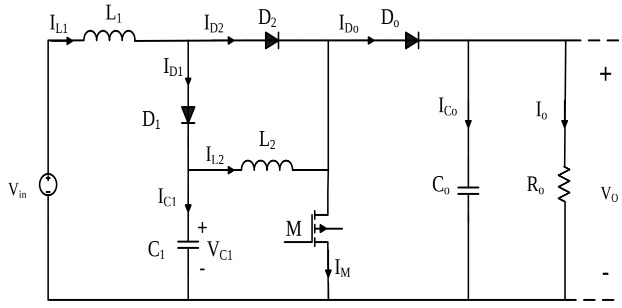

Figure 4. The cascade DC-DC boost converter

State space average model is found with the help of Equation (4).

$$\dot{x} = \bar{A}x + \bar{B} \Rightarrow \begin{cases} \bar{A} = dA_1 + (1-d)A_2 \\ \bar{B} = dB_1 + (1-d)B_2 \end{cases} \quad (4)$$

In Equations (5) and (6), the matrix form of the state equations is given for switch on and off states, respectively [12]:

$$\begin{bmatrix} \frac{di_{L1}}{dt} \\ \frac{di_{L2}}{dt} \\ \frac{dv_{C1}}{dt} \\ \frac{dv_0}{dt} \end{bmatrix} = \begin{bmatrix} 0 & 0 & 0 & 0 \\ 0 & 0 & \frac{1}{L_2} & 0 \\ 0 & -\frac{1}{C_1} & 0 & 0 \\ 0 & 0 & 0 & -\frac{1}{C_0R_0} \end{bmatrix} . \begin{bmatrix} i_{L1} \\ i_{L2} \\ v_{C1} \\ v_0 \end{bmatrix} + \begin{bmatrix} \frac{1}{L_1} \\ 0 \\ 0 \\ 0 \end{bmatrix} . [v_{in}] \quad (5)$$

$$\begin{bmatrix} \frac{di_{L1}}{dt} \\ \frac{di_{L2}}{dt} \\ \frac{dv_{C1}}{dt} \\ \frac{dv_0}{dt} \end{bmatrix} = \begin{bmatrix} 0 & 0 & -\frac{1}{L_1} & 0 \\ 0 & 0 & \frac{1}{L_2} & -\frac{1}{L_2} \\ -\frac{1}{C_1} & -\frac{1}{C_1} & 0 & 0 \\ 0 & \frac{1}{C_0} & 0 & -\frac{1}{C_0R_0} \end{bmatrix} . \begin{bmatrix} i_{L1} \\ i_{L2} \\ v_{C1} \\ v_0 \end{bmatrix} + \begin{bmatrix} \frac{1}{L_1} \\ 0 \\ 0 \\ 0 \end{bmatrix} . [v_{in}] \quad (6)$$

The state-space average model of cascade DC-DC boost converter is given in Equation (7) via Equations (4), (5) and (6).

$$\begin{bmatrix} \frac{di_{L_1}}{dt} \\ \frac{di_{L_2}}{dt} \\ \frac{dV_0}{dt} \\ \frac{dV_{C1}}{dt} \end{bmatrix} = \begin{bmatrix} 0 & 0 & 0 & -\frac{(1-d)}{L_1} \\ 0 & 0 & -\frac{(1-d)}{L_2} & \frac{1}{L_2} \\ 0 & \frac{(1-d)}{C_0} & -\frac{1}{C_0R_0} & 0 \\ \frac{(1-d)}{C_1} & -\frac{1}{C_1} & 0 & 0 \end{bmatrix} . \begin{bmatrix} i_{L_1} \\ i_{L_2} \\ V_0 \\ V_{C1} \end{bmatrix} + \begin{bmatrix} \frac{1}{L_1} \\ 0 \\ 0 \\ 0 \end{bmatrix} . [V_{in}] \quad (7)$$

where,

d : Duty cycle

v_{in} : Input voltage

v_0 : DC output voltage

v_{C1} : Voltage of C_1 capacitor

i_{L1} : Current of L_1 inductance

R : Load resistance

i_{L2} : Current of L_2 inductance

C. P&O MPPT Control Method

The working point of the FC is usually determined by the controller [3]. It is generally recommended in photovoltaic power applications. Among these, perturbation and observation (P&O) have become the most used method in terms of simplicity. The working principle of this algorithm is based on past current and power tracking. Figure 5 shows the basic algorithm of P&O.

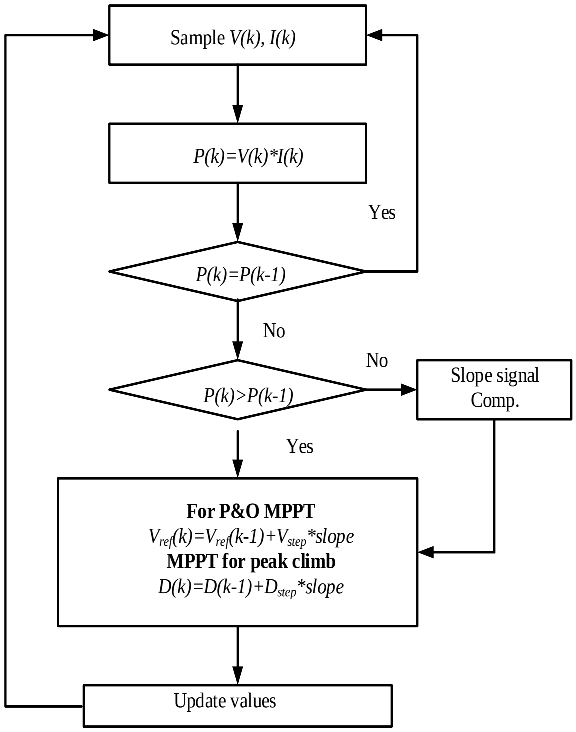

Figure 5. P&O algorithm

If P is positive, it is assumed that the working point is closer to the MPP, and if it is negative, it goes back and moves away. The variable step size of the variable power slope perturbation of this algorithm is as follows [13].

$$I[k+1]=I[k]+M\frac{\Delta P[k]}{\Delta I[k]} \quad (8)$$

where, M is the step size corrector. $\Delta P[k]/\Delta I[k]$ determines the momentary power gradient in kth sampling period. If the sign of the power derivative $\Delta P[k]$ and the voltage derivative $\Delta I[k]$ are the same, the reference current must be raised or vice versa.

The most important issue of conventional digital based MPP control techniques is that they do not have firm theoretical backing. Finally, it is difficult to analyze the stability and robustness and it can be deteriorated in some negative environments. For example, the P&O method works well under static conditions, but displays irregular behavior under quickly changing conditions such as fuel cells. For example, a sudden change in the water content of the membrane causes a sudden change in power. This causes it to be like $\Delta P[k]/\Delta I[k]\rightarrow\infty$. The P&O method has some drawbacks for MPPT control of PEMFC as explained above and given in example.

D. ESC

ESC is an adaptive nonlinear control method. According to the adaptive control law, MPP can be successful when control is converged. ESC scheme is shown in Figure 6. The P&O method is especially used for MPPT control of PV system, but the ESC method is preferred for fuel cells.

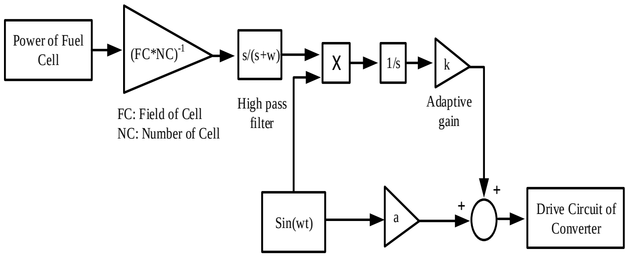

Figure 6. ESC schema

The process may be characterized by an unknown non-linear input-output characteristic having a mobile MPP with traceable operational or environmental conditions using one of ESC schemes. Selection of control system parameters has an effect on system performance. Therefore, the periodic sinusoidal perturbation signal frequency (w) and the high pass filter cut-off frequency (w_h) are selected as Equation (9).

$$w >> w_h >> \text{Dynamic speed of fuel cell with controller} \quad (9)$$

E. Overall System

PEMFC stack is an input source for DC-DC cascade boost converter and the ESC is controller of the all system as given in Figure 7.

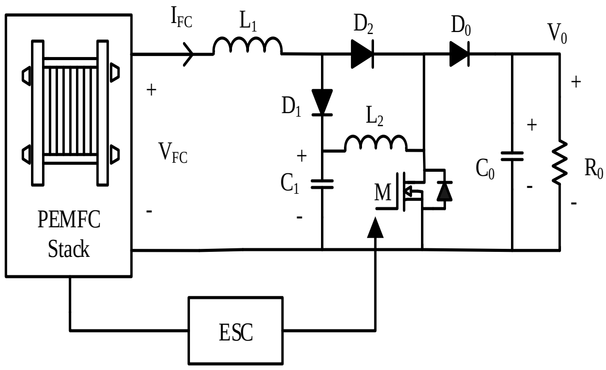

Figure 7. Block schema of overall system

III. SIMULATION RESULTS

In this section, an ES controller is designed for the fuel cell combined cascade DC-DC boost converter to get maximum power. ESC algorithm is successful as given in Figures 8 and 9 that show current-voltage and current-power graphs, respectively.

The parts indicated with green color on the figures show the transition state of the system and the parts indicated with red color show the places where the system is actually working via ES controller.

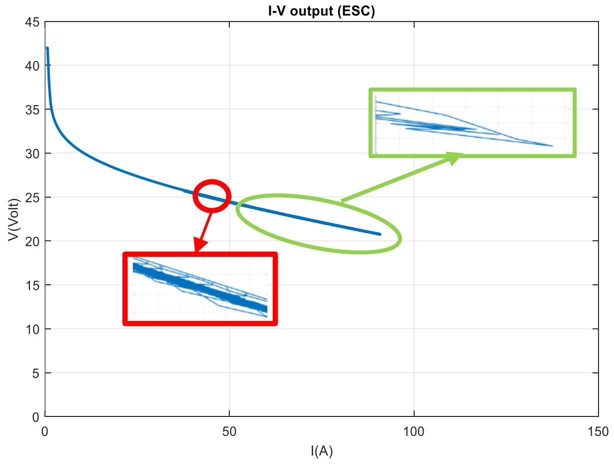

Figure 8. The current-voltage graph for PEMFC stack

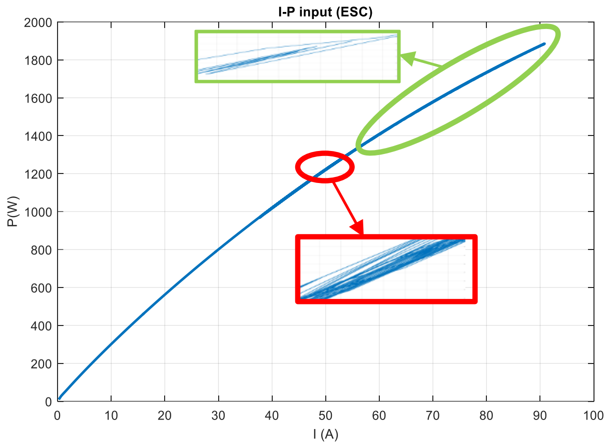

Figure 9. The current-power graph for PEMFC stack

MPP current is around 50 A in as shown Figure 8, while the voltage declined to 24 V. The maximum power around 1250 W as given in Figure 9.

The output power of PEMFC stack is given in Figure 10 and the output power of overall system output is given in Figure 11.

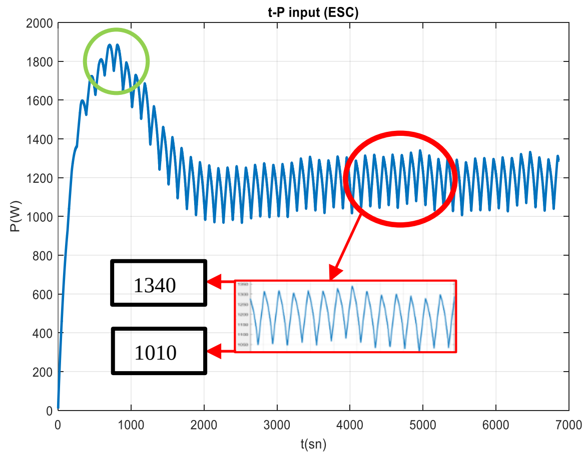

Figure 10. The output power of PEMFC stack

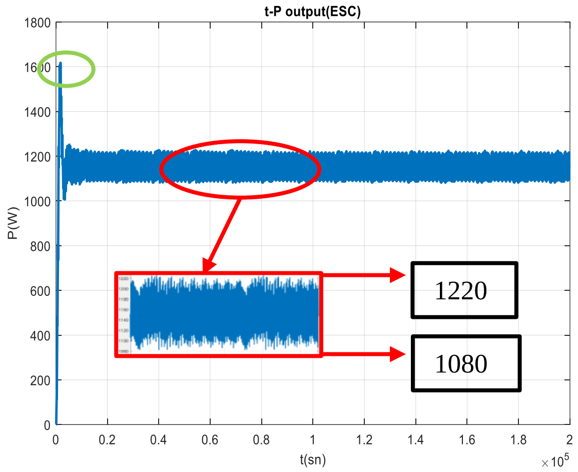

Figure 11. The output power of overall system output

IV. CONCLUSIONS

The ESC method is used instead of P&O method for MPPT control of PEMFC, because The P&O method has some drawback when it works under suddenly changing circumstances. For static conditions, the P&O method is preferred.

The ESC method has been analyzed and applied the system that consists of PEMFC stack and cascade DC-DC boost converter to get maximum power. The average output power of PEMFC stack is 1175 W and the average output power of overall system is 1150 W. The total efficiency of the system is around 97%. As given in results, the ESC method is suitable for PEMFC stack. This controller seems to control the output indirectly through the help of switching. Thus, the electricity generated by the fuel cell is used more efficiently in this study.

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BIOGRAPHIES

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