

Fuel Cell Emulator with MPPT Technique and Boost Converter

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ABSTRACT

One of the advanced power applications using energy storage is the integration of energy storage technologies with VSC-based FACTS controllers. With the support of energy storage device, FACTS controllers will have the ability to exchange active power or energy with the ac network in steady state. This paper discusses the impact of Static Synchronous Compensator incorporating energy storage device (STATCOM-ES) on subsynchronous resonance (SSR). It also proposes the design of an auxiliary SSR damping controller (SSDC) for STATCOM-ES to damp the subsynchronous oscillations which the system is undergoing because of a series capacitor in the transmission system. The system under consideration is IEEE FBM which is modified to incorporate STATCOM-ES at the electrical midpoint. The investigation of SSR characteristics when a STATCOM - ES operating in bus voltage regulation mode is carried out by eigenvalue and damping torque analysis. Transient analysis based on the nonlinear model is also performed to validate the results obtained by conventional methods.

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1. INTRODUCTION

The transportation system or automation is dependent on the uses of fossil fuels. With the decreasing supplies of fossil fuels, alternative fuels are needed to support as the demands increasing. Renewable energy mostly chose for its green and efficiency to the environment. Among the green energy that often considered for its cleanliness is fuel cell technology. The fuel cell is a power source that have a relatively high energy density and use the primary energy source of hydrogen gas. It often considered as the ideal candidate for zero emission vehicular applications due to low operating temperature and silent operations [1], [2]. Fuel cells technology converts the hydrogen energy to electric source through chemical reactions. There are variety types of fuel cell available that are classified per their electrolytes. Polymer electrolyte membrane (PEM) fuel cells or alternatively called proton exchange membrane fuel cells (PEMFC) has gained more attention compared to other types of fuel cell for its advantages; high efficiency, low working temperature and compact structure. Figure 1 shows the chemical reaction in the fuel cell.

Anode Reaction:



Cathode Reaction:



Overall Cell Reaction:

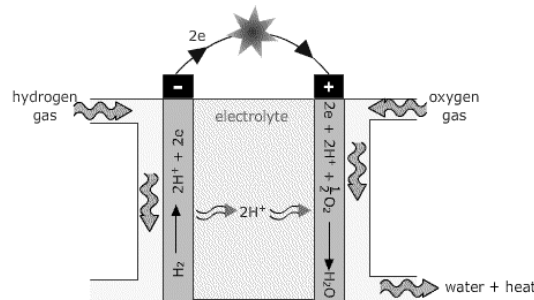


Figure 1. Fuel Cell Reactions

Fuel cells call for the excessive cost of construction if needed for high power application as its only produce low output voltage. To reduce or minimize the cost, the ability to extract the maximum power from the fuel cell is important so that fuel cells can produce power at its optimum condition. A large number of internal parameters can affect the fuel cell output voltage [1], [3-5], but the I-V curve only represents a unique point which represent the maximum power point (MPP).

At this point, the fuel cell produces its maximum power. It is necessary to force the fuel cell to operate at MPP, owing to its ability to produce power from the available fuel flow. This can avoid excessive fuel flow and low operation performances. The MPP of fuel cell can be determined using the maximum power point tracking (MPPT) algorithm. The MPPT algorithm can be used to find the duty cycle of the converter by comparing the value of current, power or voltage of the fuel cell. There are several methods for MPPT that can be applied based on the system requirement. MPPT method varies in complexity, implementation in hardware and sensed parameters. There are many study of different MPPT for fuel cell such as hill-climbing/ perturb and observe (P&O), adaptive MPPT control [6], adaptive fuzzy logic controller [7], resistance matching [8], voltage and current based MPPT [9], constant voltage [10] and adaptive extremum seeking control [11]. P&O is the most commonly used because of its simple structure to be used in fuel cell MPPT. Other than P&O, constant voltage also usually used as it can be used as single algorithm or combined with other algorithm depends on the system needs.

A conventional dc-dc boost converter is reaching its limitation in favour of fulfil the fuel cell system requirement. Interleaved boost converter (IBC) is a suitable topology owing to its ability to has high efficiency, reduced in ripple produced and small passive components size. It also commonly used for raise the fuel cell voltage high enough for load and prevent the stack for overloading [12]. Many studies have been done on IBCs and available in the literature. In furtherance to get the suitable parameters values such as input inductors and output capacitor, a study carried out in [13]. Interleaved switching of power converters leads in reducing the fuel cell ripple current and increase power output [14-18].

The aim of this paper is to develop the low cost of IBC controller which perform a MPPT technique for a fuel cell system. The operation of the converter is presented. This paper organized as follows: A dynamic model of fuel cell, the MPPT technique and converter details is presented in Section 2. In Section 3, the simulations are shown and discussed. The conclusions are presented in Section 4.

2. SYSTEM CONFIGURATION

Block diagram of the fuel cell MPPT system is shown in Figure 2. This system includes the fuel cell model, a dc-dc converter, MPPT controller and load. A boost converter is chosen for its simplicity and high efficiency as well as step up the load voltage. The fuel cell act as the dc source for the converter, as well as the input for MPPT. The MPPT functioning to control the duty cycle of the converter, so that the maximum output power from fuel cell can be obtain.

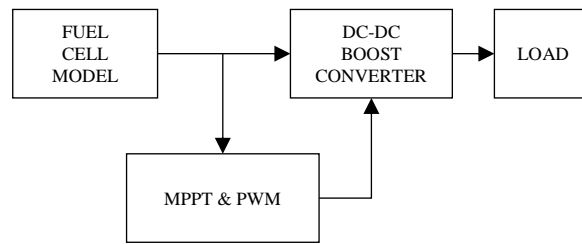


Figure 2. Block diagram of FC-MPPT system for PEMFC

2.1. Fuel Cell Model

2.1.1. Mathematical Modelling

The static and dynamic model of the PEMFC is developed for power generation application. The mathematical model is based on the electro-chemical equations of the parameters in PEMFC. The model is simulated in MATLAB/Simulink and used to analysed the V-I and P-I curves of fuel cell. Table 1 shows the specification for the H-500 of Horizon fuel cell model.

Table 1. Horizon H-500 specifications

Symbol	Parameters	Values
P_{mpp}	Maximum power	450.4 W
V_{mpp}	Maximum power voltage	18 V
I_{mpp}	Maximum power current	22.25 A
V_{oc}	Open circuit voltage	44 V

The polarization curve as shown in Figure 3 are represented by the voltage versus current density in a steady state. It influenced by the temperature, oxygen partial pressure, hydrogen partial pressure and water membrane content [19]. When current is drawn from a fuel cell, the cell voltage V_{cell} decreases from its equilibrium thermodynamic potential, E_{nerst} . This voltage losses consist of activation loss n_{act} , ohmic loss n_{ohmic} , and concentration loss n_{con} .

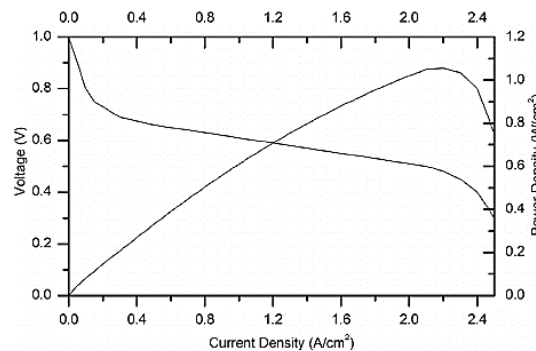


Figure 3. Typical fuel cell polarization and power curve

The produced voltage of a single cell is depicted by the Nernst equation.

$$E_{cell} = E_0 + \frac{RT}{2F} \ln \frac{P_{H_2} P_{O_2}^{1/2}}{P_{H_2O}} \quad (4)$$

E_0 is the standard potential of the hydrogen or oxygen reaction which is about 1.23V, R is the universal gas constant, F is the Faraday's constant, T is the temperature, and P_{H_2} is partial pressure of hydrogen at anode, P_{H_2O} and P_{O_2} are partial pressure of water and oxygen at the cathode. E_{cell} is the open

circuit voltage of the cell and it is higher than the cell output voltage of the cell effect by losses which are activation losses, ohmic losses, and concentration losses.

The output voltage of fuel cell stack can be calculated by [14-25]:

$$V_{FC} = N_{cell} E_{cell} = E - V_{act} - V_{ohmic} - V_{conc} \tag{5}$$

Where:

- E = Open Circuit Voltage
- V_{act} = Activation Losses Voltage
- V_{ohmic} = Ohmic Losses Voltage
- V_{conc} = Concentration Losses Voltage
- N_{cell} = Number of Cell

Relationship between voltage and current can obtain [22], [23] as:

$$V_{FC} = E - AT \ln \left(\frac{I_{FC}}{I_o} \right) - BT \ln \left(\frac{I_L - I_{FC}}{I_L} \right) - I_{FC} R_{int} \tag{6}$$

Whereas V_{FC} is the output voltage of the fuel cell, I_{FC} output current of the fuel cell, I_o is the exchange current, I_L is the limiting current, R_{int} is the internal resistance, A is the activation coefficient and B is the concentration coefficient.

When two materials are in reaction, it will produce a charge or the charge is moved from one to another. For example, the electron from fuel cell will flow from anode and gather at the cathode surface and at the same time the positive ions of hydrogen will be attracted at the same time. So that, the charge double layer (CDL) labelled as V_c occurred. CDL can be calculated by:

2.1.2. Electrical Equivalent Model

Testing this fuel cell (FCs) in laboratory can be dangerous and very expensive. Indeed, the emulator is, portable device and a low cost designed to evaluate power systems and control strategies for fuel cell systems, which is easy to use and can behave electrically like the real FCs [20]. Figure 4 shows the typical fuel cell polarization curve. Figure 5 shows the equivalent electrical circuit of PEM fuel cell that consists of R_{act} , R_{conc} , and R_{ohmic} which equivalent to activation, concentration and ohmic overvoltage respectively.

In this paper, the fuel cell emulator is developed by using their electric circuit model as shown in Figure 5. The simulation is done in MATLAB/Simulink software. The value for open circuit voltage, E is generated using the DC supply. Values for every resistor is shown in the following Table 2.

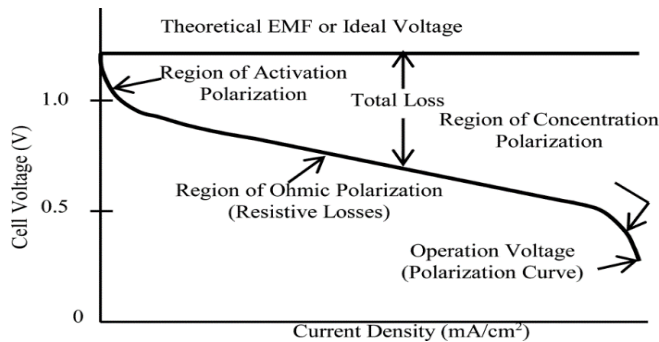


Figure 4. Typical fuel cell polarization curve

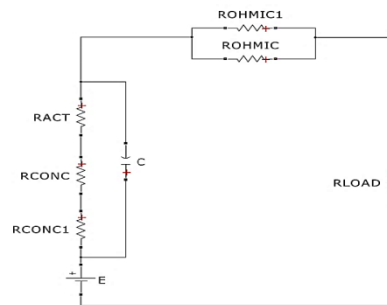


Figure 5. Electrical equivalent circuit for fuel cell emulator

Table 2 Comparison between Mathematical and Electrical Model

Parameters	Mathematical	Electrical
E	$1.229 - 8.5 \times 10^{-4}(T_{cell} - 298.15) + 4.308 \times 10^{-5}(\ln P_{H_2} + \frac{1}{2} \ln P_{O_2})$	$V_{cell} + V_{act} + V_{conc} + V_{ohmic}$
R _{act}	$-0.9514 + 3.12 \times 10^{-3}T_{cell} - 1.87 \times 10^{-4}T_{cell} \ln i + 7.4 \times 10^{-5}T_{cell} \ln C_{O_2}$	$-\frac{V_{act}}{i}$
R _{conc}	$B \ln(1 - \frac{i}{i_{lim}})$	$-\frac{V_{conc}}{i}$
R _{ohmic}	$-i \times R_{int}$	$-\frac{V_{ohmic}}{i}$

2.2. Implementation of MPPT Technique in The Fuel Cell System

PEMFC cannot be used directly as an energy supply. The FC has DC output that mostly dependent to the current which imposes a high output voltage variation. The voltage range sometimes is not acceptable for most of DC electrical device. That is why, an alternative solution of using MPPT to provide a better performance of fuel cell system.

As stated before, the power generated is varies in the fuel cell system and MPPT is one of the control strategy which has fast response in overcoming the problems. However, the maximum power point (MPP) also varies with temperature and membrane water content condition. The MPPT at all operating conditions is a challenging problem. The various operating condition could affect the stack current and fuel flow, thus lead to changes in fuel consumption and the extraction of maximal power of the fuel cell. There are many MPPT methods available in the literature, but the constant voltage (CV) algorithm is the simplest MPPT control method.

The CV method does not require any input. However, the measurement of the voltage V_{FC} is necessary to set up the duty cycle of the DC-DC converter later. Figure 5 shows the flowchart of the constant voltage algorithm in finding the duty cycle for the converter. The MPPT controller uses the FC voltage to find MPP and then generates control instructions for the converter. The converter forces the fuel cell to work at current which defies by MPPT controller. The constant voltage can be expressed in a linear relation below;

$$V_{ref} = K_v \cdot V_{oc} \tag{10}$$

Where K_v is the constant voltage factor. V_{oc} is fuel cell voltage when I_{fc} is zero. In Figure 6, K_v has been brought using different temperature to find out which factor is suitable to use. Based on the graph shown below, the suitable K_v by referring to the variation temperature on the fuel cell system, value chose is 0.9. Figure 7 shows the flowchart of the CV algorithm.

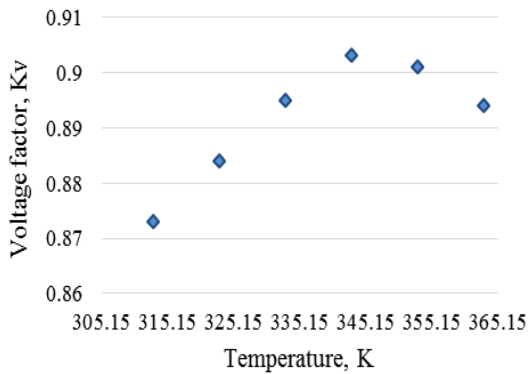


Figure 6. Voltage factor versus various temperature

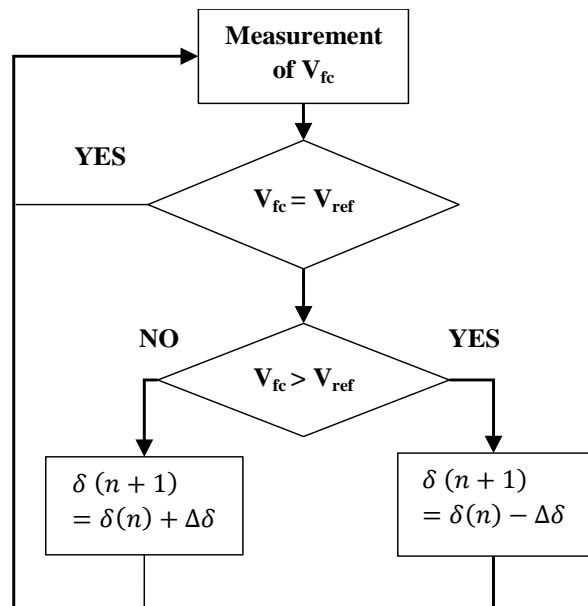


Figure 7. Flowchart of the CV algorithm

2.3. Interleaved Boost Converter

The circuit diagram of the interleaved boost converter (IBC) is shown in Figure 8. The circuit is made up of two conventional boost converters which are connected in parallel. For this project, the diodes D1 and D2 are change to IGBT which are S3 and S4 but has a same function as a diode. The main components in the converter are switches S1 and S2, couple of inductors L1 and L2, diodes D1 and D2, capacitor C, and resistor R as a load. The interleaved converter has 4 conditions of operations. Table 3 shows the parameters used in the topology of interleaved boost converter.

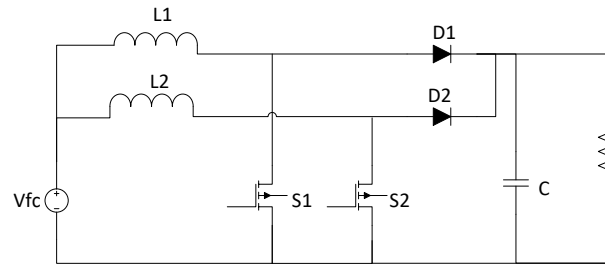


Figure 3 Interleaved boost converter topology

Table 3 Converter parameters

Parameters	Value
Switching frequency	20k Hz
Input voltage	Vfc
Inductance	1mH
Capacitance	220uF

a. Mode 1: Switch S1 closed, switch S2 opened

D₁ is in a reverse biased state and D₂ is in a forward biased state. The voltage input supplies the energy to the L₁ producing in increasing current of the L₁. Meanwhile, inductor current 2 decreases because of L₂ supply energy to the load.

b. Mode 2: Switch S1 closed, switch S2 closed

Both D₁ and D₂ are reverse biased. This condition makes both inductor charges the energy from voltage input resulted in increased current.

c. Mode 3: Switch S1 opened, switch S2 closed

D₂ is in reverse biased condition while D₁ is in forward biased condition. Inductor 1 discharges and supply energy to the load producing the decreasing of inductor current 1. The increasing of current 2 happen because voltage input supplies energy to the inductor 2.

d. Mode 4: Switch S1 opened, switch S2 opened

Both D₁ and D₂ are forward biased. This condition makes both inductor 1 and 2 discharges and the energy was supply to the load makes the decreasing of current 1 and 2.

3. RESULTS AND DISCUSSION

The fuel cell mathematical model is built in MATLAB/Simulink environment. Table 4 shows the parameters used to model the fuel cell stack. The V-I characteristic is obtained by simulation based on voltage versus current density, whereas the power curve from the power versus current density. The polarization curve is shown in Figure 9.

Table 4 Parameters of fuel cell based on Horizon H-500

Items	Values
Type of fuel cell	PEM
Number of cells	36
Rated Power	500W
Performance	21.6V @ 24A
Reactants	Hydrogen and Air
External temperature	5 to 30°C
Max stack temperature	65°C

Figure 10 and 11 shows the schematic diagram of converter combined with fuel cell along without MPPT or with MPPT respectively, simulated in MATLAB environment. The results show the input current, output current and output voltage of the converter. The input current in the simulation without MPPT shows higher ripple compare to the input current of the same converter run with MPPT method. The input current of the converter shows reduction of ripple that could help in protect the fuel cell stack from damage. The input current of the converter is 3.1A and the current ripple is around 0.12A, compare with the simulation run combined converter and fuel cell with the absent of MPPT technique which has higher input current ripple.

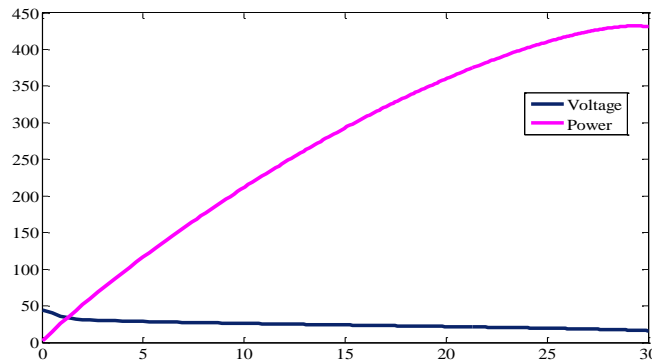


Figure 4 Power and voltage versus current density curve

The output current of the converter also shows consistency when simulated with MPPT. This also lead to higher power conversion efficiency. The output current of the converter with MPPT method is higher than without MPPT. Along with a steady voltage output, the performance is getting better. MPPT shows significant changes in terms of input or output current as well as the ripple reduction.

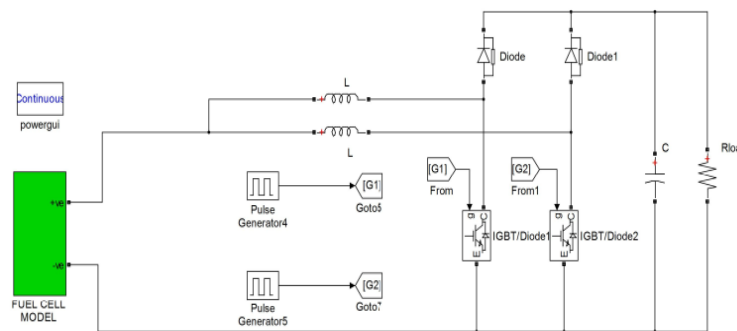


Figure 5 Schematic diagram IBC with fuel cell model

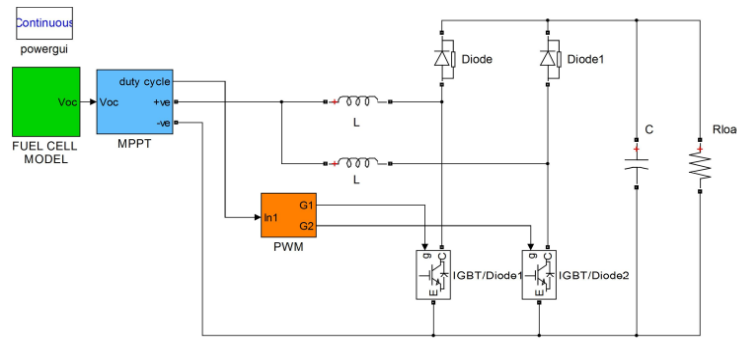


Figure 6 Schematic diagram IBC combined with MPPT and fuel cell model

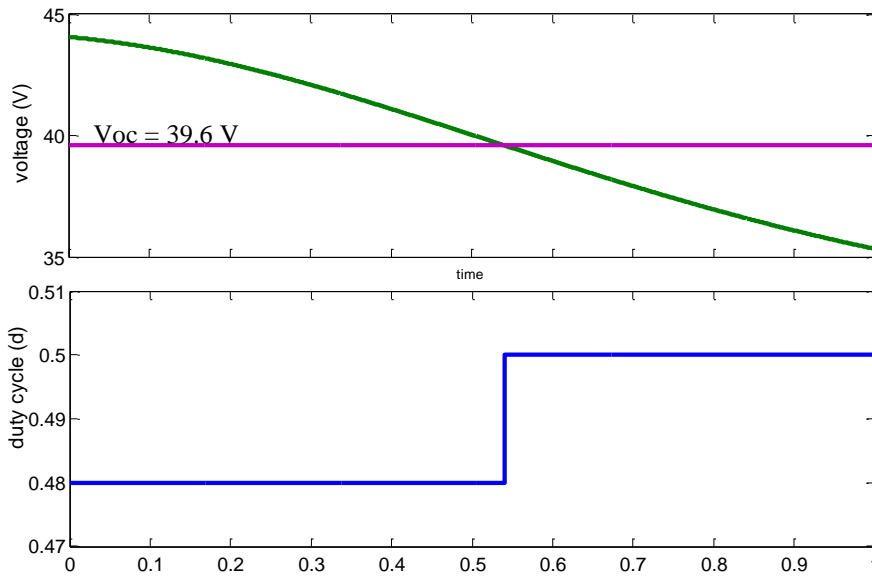


Figure 7 Duty cycle different for MPPT

The complete fuel cell control system with MPPT technique is shown in Figure 12. The overall MPPT system is built in MATLAB environment. We design the MPPT controller base on basic parameter of fuel cell which is voltage produce instead of current and power as the voltage produce is nonlinear. Figure 13 Output from interleaved boost converter without MPPT and with MPPT. Figure 14 shows the schematic of the interleaved boost converter simulated with fuel cell emulator. Fuel cell emulator gives lower voltage produces as the specification for the emulator is limited as the low-cost constructions and smaller ratio compare with real time fuel cell. Table 4 presents the output results from the converter without MPPT and with MPPT respectively.

Table 4 Analysis performance of the fuel cell model with the IBC

Items	Input current ripple (A)	Output voltage (V)	Output current (A)
Without MPPT	0.8	32-84	0.3-0.9
With MPPT	0.12	82.2	1.445

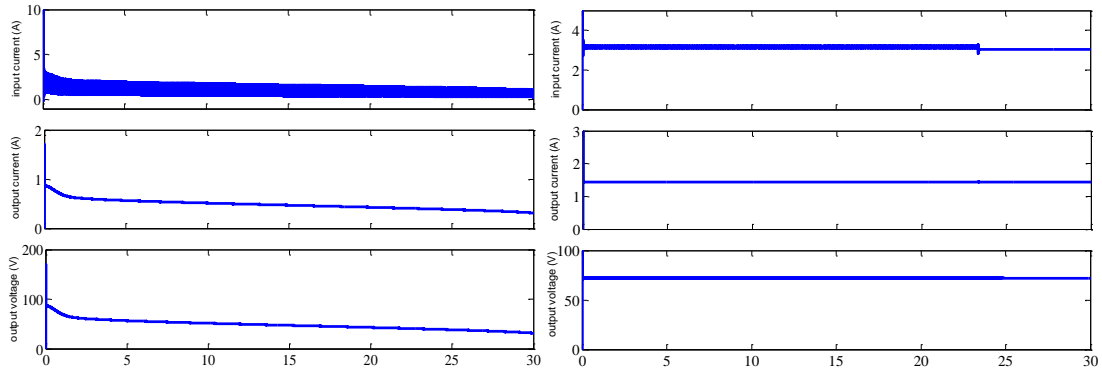


Figure 13. Output from interleaved boost converter without MPPT and with MPPT

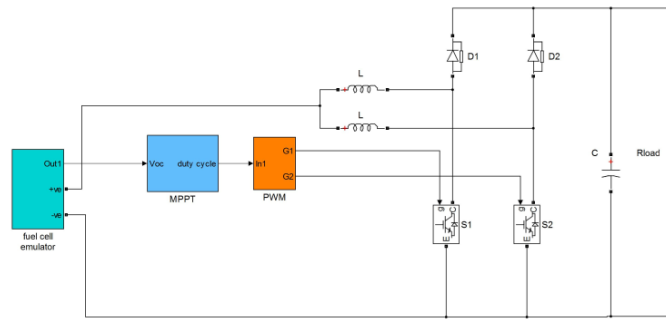


Figure 8 Schematic diagram of converter combined with fuel cell emulator along MPPT

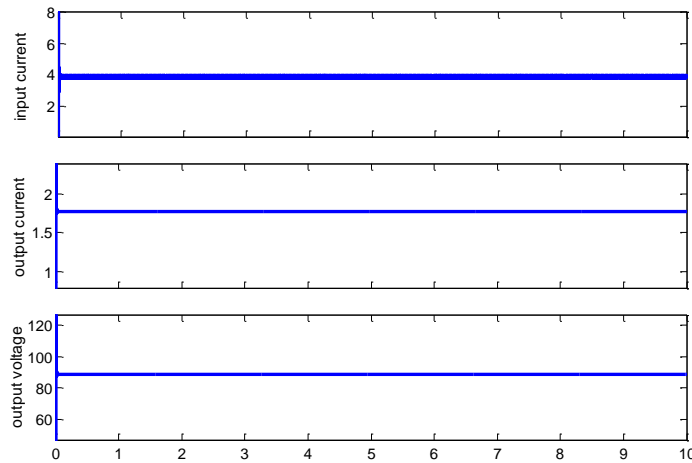


Figure 9 Output from converter combined with fuel cell emulator

Figure 15 shows the output from the converter combined with fuel cell emulator which built based on the electrical equivalent circuit. Table 5 shows the results comparison of fuel cell conditions combined with MPPT. Based on the results, the converter boosts the voltage up to twice its initial input voltage.

Table 5. Results comparison of fuel cell emulator combined with IBC

Topology	Input voltage (V)	Output voltage (V)	Output voltage ripple (V)	Input current (A)	Input current ripple (A)	Output current (A)
FC Math Model	44	82.2	0.05	3.4	0.12	1.545
FC Electrical Model	44	87.6	0.07	3.9	0.06	1.75

4. CONCLUSIONS

A modelling, control and implementation of the fuel cell MPPT control system with dc converter reported in this paper. Firstly, a steady power curve characteristic of the fuel cell is made. Fuel cell has its own MPP point, at which its produce maximum power. Due to the complexity of electrochemical reaction process, it is difficult to decide whether the fuel cell is working at the MPP by the modelling approach. Therefore, an MPPT algorithm is used to automatically keep the fuel cell working at the MPP for all the time. The MPPT technique used is constant voltage method which is easier and simpler to simulate through the MATLAB/Simulink environment. The control scheme of this MPPT results in solved the fuel cell optimization problems but also maximised the efficiency of the overall system that combined with the converter for more applications.

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