Journal of Renewable
Energy and Environment

Research Article

Journal Homepage: www.jree.ir

A New Maximum Power Point Tracking Method for PEM Fuel Cells Based On Water Cycle Algorithm

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PAPER INFO

Paper history:
Received 24 June 2015
Accepted in revised form 09 January 2016

Keywords:
Proton Exchange Membrane Fuel Cell
Maximum Power Point Tracking (MPPT)
Water Cycle Algorithm
Perturb and Observe
Voltage based MPPT
Current based MPPT

ABSTRACT

Maximum Power Point (MPP) tracker has an important role in the performance of fuel cell (FC) systems improvement. Tow parameters which have effect on the Fuel cell output power are temperature and membrane water. So contents make the MPP change by with variations in each parameter. In this paper, a new maximum power point tracking (MPPT) method for Proton Exchange Membrane (PEM) fuel cell is proposed. This method is based on water cycle algorithm (WCA). In order to show the performance and the accuracy of the proposed method, a system consisting of one Proton Exchange Membrane (PEM) fuel cell, one boost converter, one WCA based MPP tracker and one load is considered. WCA determines voltage corresponding to the maximum power of FC then one PID controller tunes the duty cycle of the boost converter. The performance of the proposed method is compared with three other MPPT methods (Perturb and Observe, Voltage-based MPPT and current-based MPPT). The results show that the proposed MPPT method has a high accuracy and a fast response, they also indicate that the proposed method has the better performance in comparison with the other studied methods.

1. INTRODUCTION

Fuel Cells (FCs) are static electric power sources that convert chemical energy of fuel directly into electrical energy. FCs offer advantages such as high efficiency, zero or low emission (of pollutant gases), and flexible modular structure [1, 2]. FCs are divided into several types, namely, Solid Oxide Fuel Cell (SOFC), Molten Carbonate Fuel Cell (MCFC), Phosphoric Acid Fuel Cell (PAFC), Alkali Fuel Cell (AFC) and the Proton Exchange Membrane Fuel Cell (PEMFC). PEMFC is one of the most important types of fuel cells for having low operating temperature, high power density, fast startup and high efficiency [3]. The ability of PEMFC systems for producing power is limited [3]. It is therefore necessary to force the system to operate in a condition that matches up with the FC's maximum power point (MPP). At the maximum power point, FC can produce its maximum power output. A maximum power point tracking (MPPT) controller traces the MPP of FC using a MPPT algorithm. A DC-DC converter is controlled by the MPPT controller. There are several methods to search and track the maximum power of FC, such as Perturb and Observe [4-10], voltage and current based MPPT [11], fuzzy control [12], adaptive extreme seeking control [13]. A good study on MPPT method has been brought in [14]. MPPT methods have a common target to achieve MPP but they vary in price, hardware, popularity, speed and measured parameters [14].

Water cycle algorithm (WCA) is a new optimization method that is inspired by natural water cycle [15] and it is used to find MPP of the fuel cell in this paper. It is consist of several steps, the first step is initial population in form of raindrops. The second one is calculation of cost or value of each raindrop. Then similar to natural water cycle, streams and rivers flow into the sea at last. Therefore, if the value of river (or stream) becomes more than the value of sea (or river) then river became sea and stream became river [15]. One advantage of this algorithm is in raining stage which is lost in the probability of trapping in local maximum or minimum points. Raining occurs in this algorithm and new position for streams is given in this stage. WCA uses FC input parameters such as cell temperature, membrane water content, hydrogen and oxygen partial pressure

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values, and output current of FC to determine the voltage, V_{ref}, corresponding to the MPP of FC.

The main contribution of this paper is the presentation of a new robust and reliable tracking method of MPP under fast variation of operating conditions. Though this paper proposes a fast and new MPPT control scheme based on water cycle algorithm (WCA) for PEMFC system, this method can use for each FC that have mathematical dynamic model.

The proposed method is compared with perturb and observe maximum power point tracking (P&O), voltage based maximum power point tracking (VMPPT) and current based maximum power point tracking (CMPPT) methods in different situation.

2. FUEL CELL CHARACTERISTICS

Fuel cell voltage can be represented by a polarization curve as a function of load current density in a steady state, which is affected by FC input parameters such as cell temperature, oxygen partial pressure, hydrogen partial pressure and membrane water content. The cell voltage (V_{Cell}) decreases from its equilibrium thermodynamic potential E_{Nernst} (open circuit voltage) when the current is drawn from the fuel cell. The fuel cell voltage drop contains activation loss (ξ_{act}), ohmic loss (ξ_{ohmic}) and concentration loss (ξ_{con}). The basic expression for the cell voltage is defined as follows [2, 3, 11 and 16]:

$$V_{Cell} = E_{Nernst} + \xi_{act} + \xi_{ohmic} + \xi_{con} \quad (1)$$

Where the thermodynamic potential (E_{Nernst}) is described by the Nernst equation.

$$E_{-Nernst} = 1.229 - 8.5\times10^{-4}(T - 298.15) + 4.308 \times10^{-5} T\,(lnP_{H2} + 0.5\times lnP_{O2})$$

(2)

Where P_{H2} and P_{O2} are hydrogen and oxygen partial pressures, respectively, and T is the fuel cell temperature. Activation loss (ξ_{act}) is described by the Tafel equation as following:

$$\xi_{act} = \xi_1 + \xi_2 T + \xi_3 T lnC_{O2} + \xi_4 T lnI \quad (3)$$

Where ξ (i= 1:4) are parametric coefficients for each cell model. C_{O2} is the concentration of dissolved oxygen at the gas/liquid interface ($mol.cm^{-2}$), which can be calculated as:

$$C_{O2} = \frac{P_{O2}}{5.08\times10^{6}\times\exp(-\frac{498}{T})} \quad (4)$$

Ohmic over voltage ξ_{ohmic} results from the resistance of the polymer membrane in electron and proton transfer and it can be written as following:

$$\xi_{ohmic} = -I.R_m \quad (5)$$

The resistance R_m is given by:

$$R_m = \frac{r_m \times t_m}{A} \quad (6)$$

Where r_m is membrane resistivity (Ωcm) to proton transfer, t_m is membrane thickness (cm), and A *is* cell active area (cm^2). Membrane resistivity depends strongly on membrane humidity and temperature, and can be described by the following empirical expression:

$$r_m = \frac{181.6\left[1+0.03(I/A)+0.0062\left(\frac{T}{303}\right)^2 (I/A)^{2.5}\right]}{\left[\lambda-0.634-3(I/A)\right]\exp\left[4.18(T-303/T)\right]} \quad (7)$$

Where λ is the membrane water content. The membrane water content is a function of the average water activity a_m as following:

$$\lambda = \begin{cases} 0.043+17.81a_m-39.85a_m^2+36a_m^3 & 0<a_m\le1 \\ 14+1.4(a_m-1) & 1<a_m\le3 \end{cases} \quad (8)$$

The average water activity is related to the anode water vapor partial pressure $P_{v,an}$ and the cathode water partial vapor pressure, $P_{v,ca}$ as following:

$$a_m = \frac{1}{2}(a_{an}+a_{ca}) = \frac{1}{2}\frac{P_{v,an}+P_{v,ca}}{P_{sat}} \quad (9)$$

The saturation pressure of water, P_{sat}, can be calculated by the following empirical expression:

$$\log_{10} P_{sat} = -2.1794 + 0.02953T - 9.1813\times10^{-5}T^2 + 1.4454\times10^{-7}T^3 \quad (10)$$

The value of λ varies between 0 and 14, equivalent to the relative humidity of 0% and 100% under supersaturated conditions. However, the maximum possible value of λ can be as high as 23. In addition, λ is influenced by the membrane preparation procedure, the relative humidity of the feed gas and the membrane age. In this paper, λ is considered as an adjustable parameter with a possible value between 0 and 23. Concentration over voltage ξ_{con} results from the concentration gradient of reactants as they are consumed in the reaction. The equation for concentration over voltage is given by:

$$\eta_{con} = \frac{RT}{nF}\ln(1-\frac{I}{i_L A}) \quad (11)$$

Where i_L is the limiting current, defined as the maximum rate at which a reactant can be supplied to an electrode.

The fuel cell model parameters are listed in Table 1. Figure 1. demonstrates that thefuel cell has anonlinearbehavior, amaximumpoint, as namely MPP and alsoshow that MPPvarieswithtemperatureso MPPT control system is employed to track MPP of FC.

TABLE 1. The FC model parameters [3].

Parameter	Value	Parameter	Value
$F (Ckmol^{-1})$	96484600	ξ_2	0.00354
$R (jkmol^{-1}K)$	8314.47	ξ_3	7.8×10^{-8}
N	35	ξ_4	-1.96×10^{-4}
$A (cm^2)$	232	$i_L (Acm^{-2})$	2
$t_m (cm)$	0.0178	$P_{H2} (Atm)$	3
ξ_1	-0.944	$P_{O2} (Atm)$	1

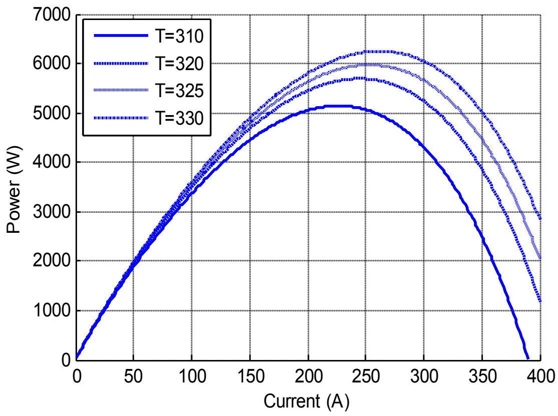

Figure 1. $P_{FC} - I_{FC}$ curves of FC in different temperatures and λ=11.

3. THE PROPOSED WATER CYCLE ALGORITHM BASED MPPT

Water cycle algorithm is a new method for engineering problems solving. In this algorithm sea is the best value and stream or river as initial population, adjoined to sea (the best value) at last [15].

Proposed algorithm has ability to find maximum or minimum value of function with high speed and accuracy also reduces the probability of staying in local optimum points which is a good feature of this algorithm. So in this paper, this algorithm is applied to determine MPP of fuel cell.

Water cycle algorithm consists of some steps. The first step is initial formation of raindrops. The second step is calculation of cost or value of each raindrop. The third step is joining of streams and rivers to sea, when the values of the sea, rivers and streams are become equal, the raining stage will be start, which is the main feature of this algorithm in comparison with other optimization methods that avoid getting trapped in local optimum points. Number of rivers and streams are initially considered.

Certainly, the number of rivers and streams are selected to provide an effective performance of algorithm. For example, if a large number of rivers are selected, effect of raining step is reduced.

3.1. Initial formation of raindrops

Similar to optimization methods, WCA consists of a number of initial guesses called raindrops. Each guess is a solution of the problem of a $1\times N_{var}$ array, where N_{var} is dimension of optimization problem, shown in Equation (12). The solution arrays create a population of raindrops matrix shown in Equation (13).

$$Raindrop_i = X_i = [x_1, x_2, \ldots, x_{Nvar}] = unifrand\ (varmin, varmax, 1, Nvar) \qquad (12)$$

Where *unifrand* is uniformly distributed random number between *varmin* (lower bound of *x*) and *varmax* (upper bound of *x*).

$$Population\ raindrops = \begin{bmatrix} raindrop_1 \\ \ldots\ldots\ldots\ldots \\ raindrop_i \\ \ldots\ldots\ldots\ldots \\ raindrop_{N_{pop}} \end{bmatrix} \qquad (13)$$

Where N_{pop} is number of raindrops and population raindrops is initial population.

The cost of each raindrop is calculated by the following expression:

$$C_i = Cost_i = P_{FC} = N \times V_{cell} \times I_{FC} \qquad (14)$$

Where C_i is the cost function.

Eqs. (1-11) show that P_{FC} is a function of I_{FC}. Equation (12) is initial random population of I_{FC} instead of X_i. Initial population of I_{FC} is random numbers. In this paper, *P-I* curve of FC is function cost for optimization problem. The sea is chosen as the best raindrop. Then, rivers are chosen as a number of good raindrops, total of sea and rivers are called N_{sr}. The rest of the raindrops are considered as streams that flow to the rivers and sea.

3.2. Flowing to the sea

All rivers and streams end up in seas, therefore, the new position for streams and rivers may be given as [15]:

$$X^{new}_{stream} = X_{stream} + rand \times C \times (X_{river} - X_{stream}) \qquad (15)$$

$$X^{new}_{river} = X_{river} + rand \times C \times (X_{sea} - X_{river}) \qquad (16)$$

Where *C* is a number between 1 and 2 as the best value for *C*. Rand is distributed random number between 0 and 1. If the value of a stream is better than the value of its connecting river, the position of stream and river must change. Namely, stream becomes river and vice versa. Also rivers and sea similarly swap.

3.3. Evaporation and Raining

In order to avoid getting trapped in local optima, evaporation and raining process is proposed [15]. This is specific prominence for WCA in comparison to other optimization algorithms. Evaporation process ends if the following criterion is met:

$$|X_{sea} - X_{river}| < d_{max} \qquad (17)$$

Where d_{max} is a number near to 0. The value of d_{max} automatically decreases according to following:

$$d^{new}_{max} = d_{max} - (d_{max}/maxiteration) \qquad (18)$$

After the evaporation process ends, the raining process begins.

In the raining process, the new raindrops flow toward streams in the different locations. Equation (19) is used to determine new location of streams.

$$X^{new}_{stream} = X_{sea} + \sqrt{u} \times randn(1, N_{var}) \qquad (19)$$

Where u is the rate of search near the sea and *randn* is the normally distributed random number.

3.4. Convergence criteria In this paper, maximum number of iterations (*maxiteration*) is used as a convergence criterion. If it was satisfying, the best I_{FC} and P_{FC} are presented as output of algorithm then V_{ref} is equal to P_{FC} divided in to I_{FC}. P_{FC} is optimized with attention to I_{FC} to get the next V_{ref} and when P_{FC} is equal to MPP, V_{ref} is fixed until FC situation or WCA inputs changes.
The used WCA parameters in this paper are listed in Table 2. and flowchart of the proposed MPPT method is shown in Figure 2.

TABLE 2. WCA parameters for MPPT of PEMFC.

Parameter	Value	Parameter	Value
N_{pop}	10	*maxiteration*	50
N_{sr}	3	*C*	2
Dmax	0.001	*U*	0.1
N_{var}	1	------	-------

4. A BRIEF STUDY OF OTHER MPPT METHODS

4.1. P&O MPPT In a conventional P&O MPPT algorithm, the operating voltage of fuel cell is perturbed and the power variation is observed. If power variation is positive, this means that the operating point has moved closer to the MPP and, therefore, the operating voltage must be further perturbed in the same direction, otherwise, if power variation is negative, the operating point has moved away from the MPP and, therefore, the direction of the operating voltage perturbation must be reversed [3,4]. Flowchart of P&O algorithm has been brought in Figure 3. In this Figure C is step of perturbation.

4.2. Voltage based MPPT The voltage and current based MPPT techniques express that there is a liner relation between voltage in MPP and $V_{o.c}$[11].

$$V_{mp}=K_v\times V_{o.c} \qquad (20)$$

Where $K_v$is the constant "voltage factor". $V_{o.c}$ is fuel cell voltage when I_{FC} is zero. The flowchart of VMPPT method shows in Figure 4(a). In Figure 4(b). K_v ($K_v=V_{mp}$ / $V_{o.c}$)has been brought in different temperature.

4.3. Current based MPPT In the CMPPT technique, the fuel cell current corresponding to maximum power (I_{mp}) is considered proportional to the short current (I_{sh}) [11].

$$I_{mp}=K_i\, I_{sh} \qquad (21)$$

where $K_i$is the constant "current factor". The flowchart of CMPPT method shows in Figure 5(a). Figure 5(b). show computed values of the current factor ($K_i=I_{mp}$ / I_{sh})versus different temperature.

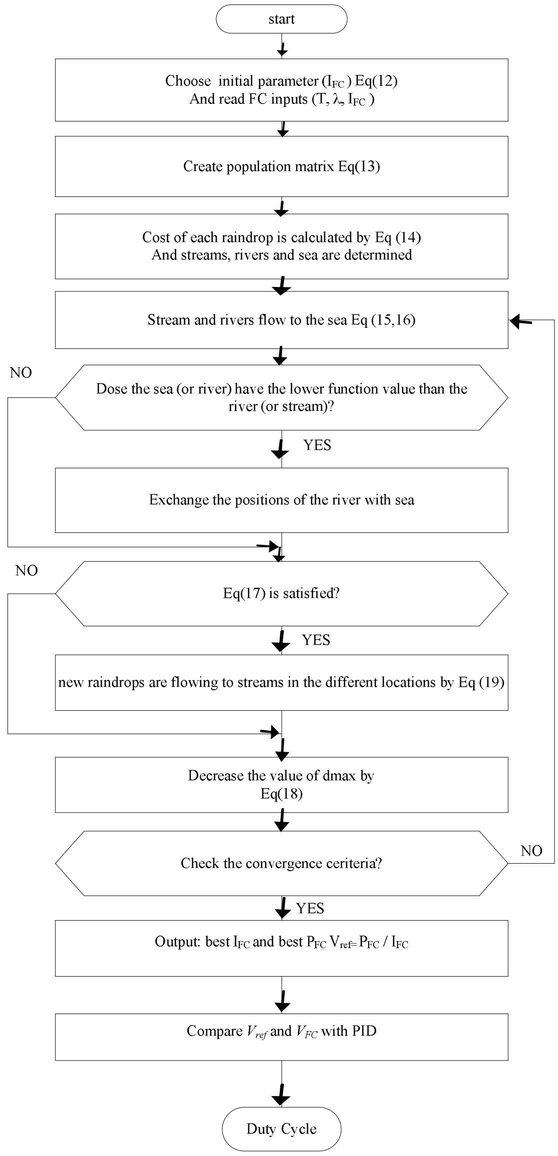

Figure 2. Flowchart of the proposed MPPT.

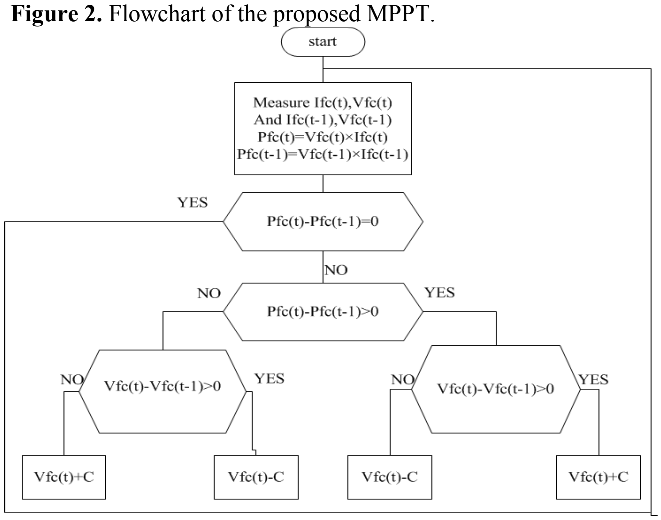

Figure 3. P&O algorithm.

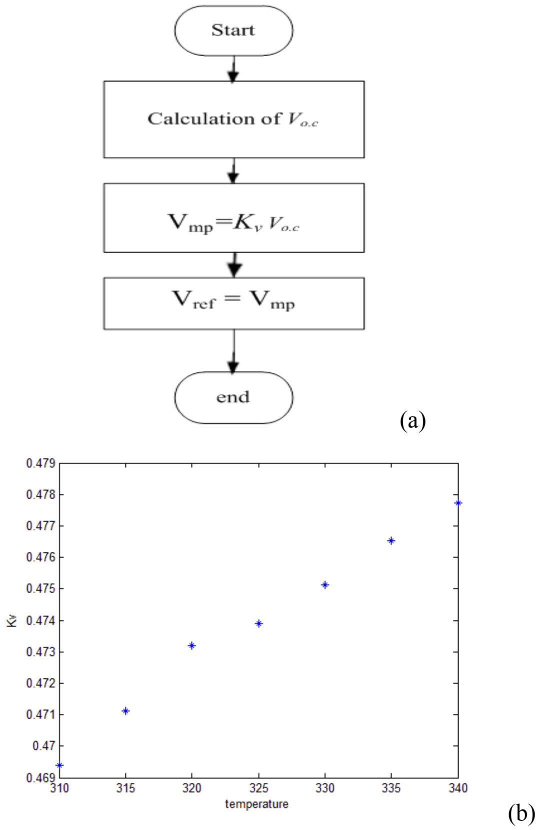

Figure 4. flowchart of VMPPT (a) and Voltage factor (K_v) versus temperature (b).

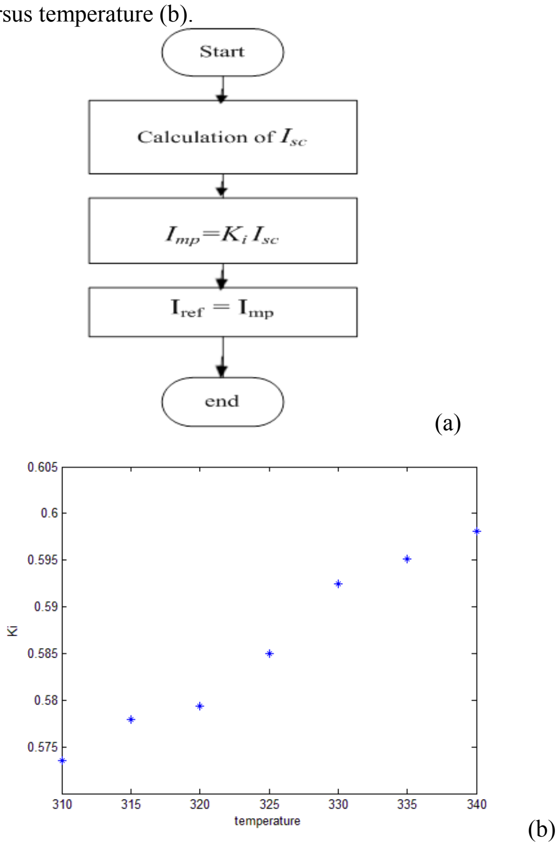

Figure 5. Flowchart of CMMPT (a) and Voltage factor (K_i) versus temperature (b)

5. SIMULATION RESULTS AND DISCUSSION

In order to investigate performance of the proposed method, a system consisting of one PEMFC, one DC/DC boost converter, one resistance load, one MPPT module and one PID controller is considered. Simulations are performed in MATLAB/SIMULINK. The diagram of system is shown in Figure 6. In this section, characteristics of the proposed method are compared with the P&O, the VMPPT and CMPPT methods. WCA algorithm determines the reference voltage V_{ref} then PID controller is employed to reduce the error between the actual FC voltage and V_{ref} by changing of the DC/DC converter duty cycle. The switching frequency of DC/DC boost converter is equal to 10 KHz, K_P (Proportional coefficient of PID) is equal to 0.4 and K_I (Integral coefficient of PID) is taken as value of 2. High value for K_I increases stability of the system. Inductance of boost converter (L) is equal to 10 *mH*, and resistance of load is equal to 1 Ω.

5.1. Investigation of the proposed MPPT Performance

In order to investigate the performance of the proposed method, three following cases are considered:

Case study I: FC normal operation
Case study II: Step change in the FC temperature
Case study III: Step change in the FC membrane water content

Case study I: Normal operating conditions

In this case, membrane water content (λ) and temperature (T) are constant and are equal to 10 and 320 °*K*, respectively. The simulation results of this case are shown in Figures 7. and 8. Figure 7(a). shows the FC power (P_{FC}) and Figure 7(b). shows the variations of P_{FC} versus FC current. Figure 8(a). shows the FC voltage (V_{FC}) and reference voltage corresponding to FC maximum power (V_{ref}). Figure 8(b). also shows V_{FC} versus FC current. The power corresponding to maximum power is 5217 W in the proposed method for given λ and T. Actual value of maximum power of FC is 5219 W. ($\delta P_{FC}/\delta I_{FC}=0$) is used to calculate the actual values of maximum power points. For more information refer to [17]. Thus, accuracy of the proposed method to determine maximum power point is 99.96%. V_{FC} corresponding to V_{FC} in MPP in Figure 8(b). is 23.378 volt. These results show that the proposed method track MPP with high accuracy and good performance.

Case study II: Fast variation of the FC temperature

In order to show the fuel cell MPPT control system's responses to step changes of the FC temperature, it is assumed that the membrane water content is constant and equal to 11 while the temperature variation is 310, 330 and 320 at first, second and third seconds of simulation. The system is at first operating in the temperature $T = 310$ *K*. At this temperature, the optimal power is 5141 kW. At t = 1 s, the temperature is increased to 330 K. The optimal power corresponding to this temperature is 6250 kW. Once again, at t = 2 s, the temperature is decreased to 320 K. At this temperature, the optimal power is 5693 kW. Simulation results for this case study are shown in Figures 9. and10. The simulations the proposed MPPT method are compared for P&O, VMPPT and CMPPT. The time evolution of P_{FC}has been also brought in Figure 10. Besides, the performance of the proposed MPPT method has been compared with P&O, VMPPT and CMPPT in Figure 10. Table 3. presents the numerical comparison between the proposed MPPT approach and the other mentioned approach under fast variation of the Fuel Cell temperature in constant membrane water content. Also Table 3. reveal that proposed method has high accuracy to find new MPP under step change of the fuel cell temperature.

From these results one can conclude that the proposed has been able to make the closed loop system to reach the new set points caused by the variation of the fuel cell temperature, satisfactorily.

Also these results shows, the WCA-based MPPT has better performance (less response time and less oscillation) in compare with three other mentioned method.

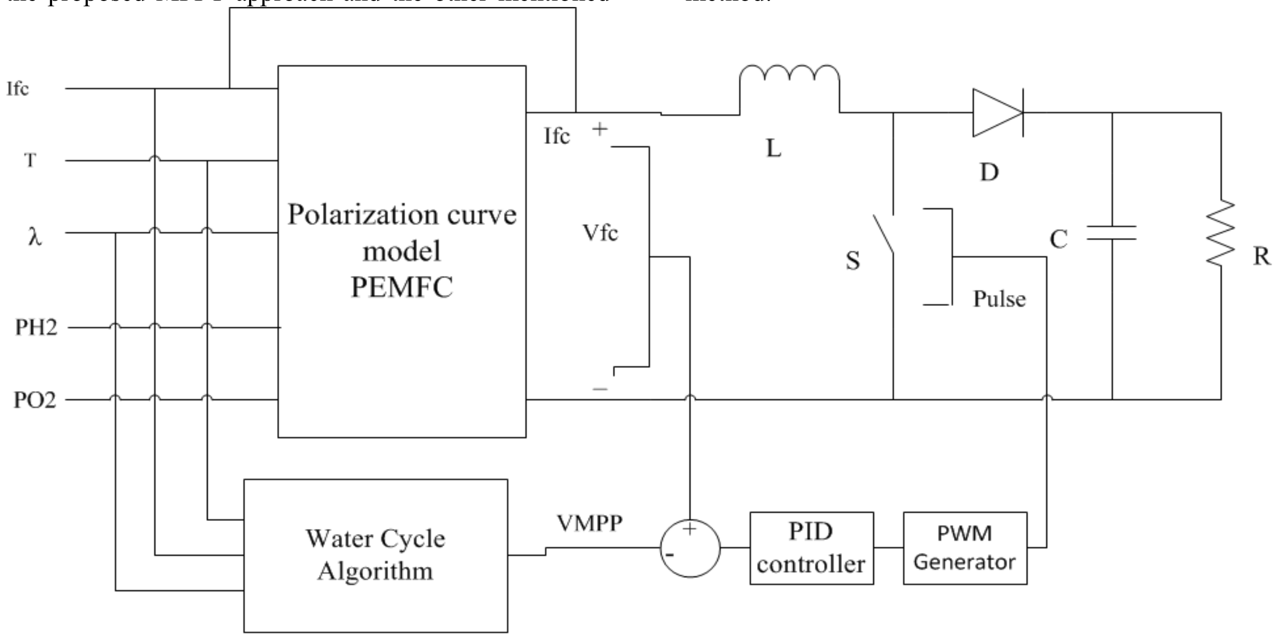

Figure 6. Proposed MPPT schematic.

Case study III: Fast variation of the FC membrane water content

In this case it is assumed that the temperature is equal to 320 ˚K and membrane water content is varied 10, 12 and 11 respectively. The simulation results of this case are shown in Figures 11. and 12. The system is first operating at λ=10. At this λ the optimal power is 5219 kW. At t = 1 s, λ is increased to 12. At this λ the optimal power is 6156 kW. At t = 2 s, λ is decreased to 11. At this λ the optimal power is 5693 kW. Simulation results for this case study are shown in Figures 11. and 12. The simulation is done for the proposed MPPT method and P&O, VMPPT and CMPPT methods. The power corresponding to MPP1, 2 and 3 in Figure 11. are 5217 W, 6150 W and 5690 W, respectively. The results show that the proposed MPPT method has high accuracy and reliability in comparison with the other mentioned methods, in tracking of the maximum power point in different membrane water content, Small settling time, no overshoot are the good features of the proposed MPPT method.

6. CONCLUSIONS

In order to optimize the operation of FC, it is necessary to enforce the FC system to operate in maximum power point (MPP). A WCA-based MPPT method is proposed and its characteristics are compared with three other methods (P&O, VMPPT, and CMPPT). The analyses and simulations are performed on a system including a PEMFC, a boost DC/DC converter and a load resistance. The results show that the proposed MPPT method has high accuracy, fast response and better performance especially in the fast variation of fuel cell input in compare with other mentioned methods.

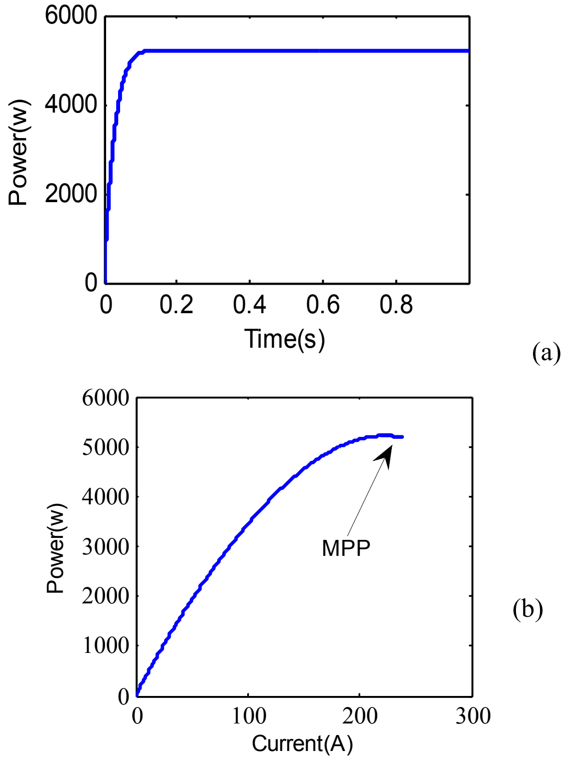

Figure 7. P_{FC} variations versus time (a) and current (b)in normal operation (λ =10 and T=320 °K).

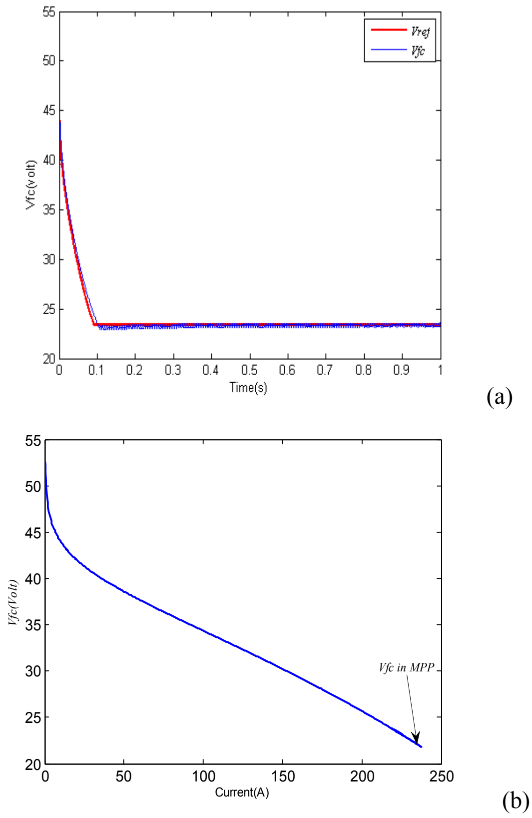

Figure 8. $V_{FC}$and V_{ref}(a) and V_{FC}- I_{FC}curves (b) under normal operation (λ =10 and T = 320 °K).

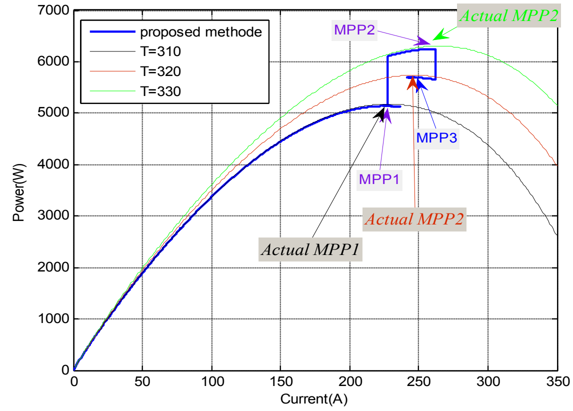

Figure 9. P_{FC} - I_{FC} curve in case study II (step change in temperature).

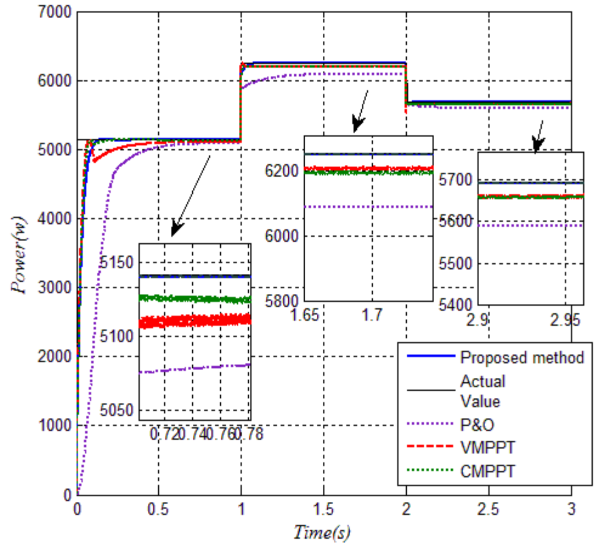

Figure 10. The time evolution of P_{FC} in case study II for the proposed MPPT method and other three methods.

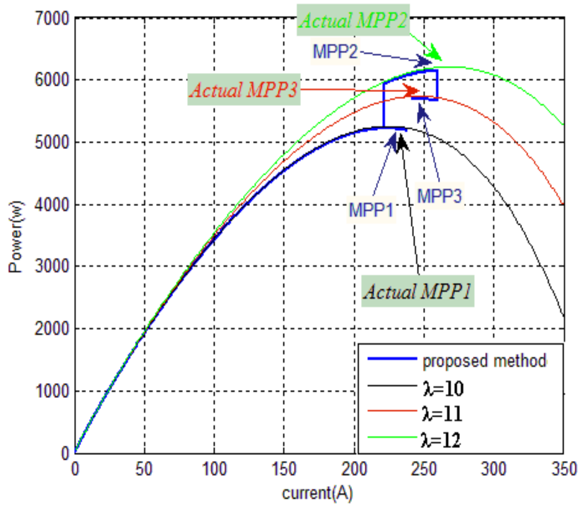

Figure 11. P_{FC} - I_{FC} curve in case study III (step change in λ).

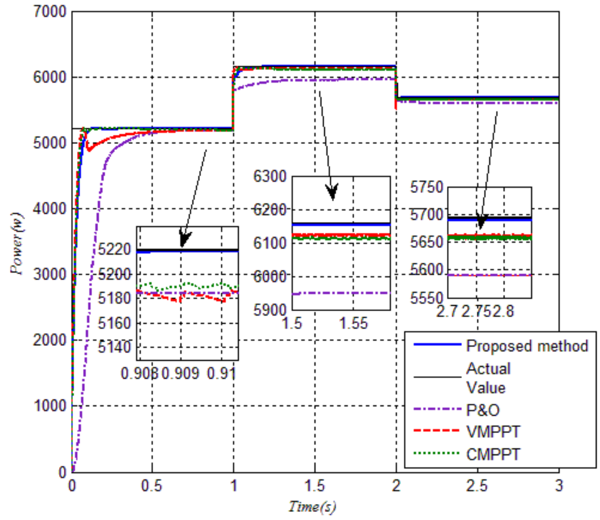

Figure 12. The time evolution of P_{FC} in case study III for the proposed MPPT method and other three methods.

TABLE 3. Numerical Comparison of computed *MPP* in case study II for the proposed MPPT method and other three methods.

Temperature(° K)	Actual Maximum Power of FC (W) [17]	Computed Maximum Power of FC (W)			
		Proposed method	P&O	VMPPT	CMPPT
330	6250	6246	6087	6205	6192
320	5693	5690	5592	5659	5658
310	5141	5139	5085	5114	5122

TABLE 4. Numerical Comparison of computed *MPP* in case study III for the proposed MPPT method and other three methods.

Membrane water content (λ)	Actual Maximum Power of FC (W) [17]	Computed Maximum Power of FC (W)			
		Proposed method	P&O	VMPPT	CMPPT
12	6156	6150	5949	6123	6113
11	5693	5690	5592	5659	5658
10	5219	5217	5186	5180	5191

7. ACKNOWLEDGEMENT

The authors thank Zanjan Regional Electric Company (ZREC) and Faculty of Engineering and Technology of Imam Khomeini International University for sponsoring this study.

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