# Hydrogen Generation/Pressure Enhancement Using FC and ANN Based MPPT Assisted PV System

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***Abstract*— In this paper, two systems based on renewable energy sources are considered for the generation of $H_2$ by electrolysis process of water. A compressor system is used for enhancing the generated $H_2$ pressure for both the considered systems. Firstly, a PEMFC is utilized for electrical power generation, and to drive the compressor system. Generated $H_2$ pressure is again feed to PEMFC operation itself. The electrical power generated by PEMFC is used to assist the induction motor (IM) driven compressor system to enhance the $H_2$ pressure. Secondly, an artificial neural network (ANN) based maximum power point tracking (MPPT) technique assisted solar photovoltaic (PV) system is utilized for the same purpose. The dynamic modeling of PEM fuel cell, MPPT assisted solar PV system, electrolyzer, $H_2$ storage tank and compressor has been done by using MATLAB/Simulink environment. The performance of the PEMFC and solar PV power assisted induction motor driven $H_2$ compressor system has been investigated in detail.**

***Keywords*— electrolyzer; green power generation; hydrogen storage; proton exchange membrane fuel cell (PEMFC); renewable energy; solar PV system;***

## I. Introduction

Nowadays, fossil fuels such as coal, oil and gases are used to generate the electrical energy to prosper the human life however rate of consumption of fossil fuels is increasing faster enough to deplete these [1]. Due to this reason, the renewable energy (RE) sources such as, solar photovoltaic (PV) system, wind power generation, fuel cell (FC), micro turbine (MT) and mini hydro potential etc. are receiving considerable attention.

Solar PV technology converts only 30-40% sunlight directly into electricity. Solar PV system is a primary source of power generation for rural and agricultural applications. With the advancement of solar technology, various maximum power point tracking (MPPT) techniques have been developed to achieve maximum power through solar PV system. In literature review, various MPPT techniques are implemented and investigated with satisfactory performance e.g. incremental conductance (IC), Perturb & observe (PO), Fuzzy logic controller (FLC) and artificial neural network (ANN) MPPT techniques [2-3].

The FC is an electrochemical device which produces electricity by supplying $H_2$ reactant at the electrode. In this paper, PEMFC is considered due to low operating temperature in the range of (60-100)°C[4]. Today, $H_2$ fuel cells offer tremendous potential to produce electrical power for distributed generation (DG) systems and electrical vehicles.

## II. System Description

In this paper, two approaches are designed for $H_2$ pressure generation. Furthermore, the system is described using following components: (a) RE sources (i) PEMFC (ii) Artificial neural network based MPPT assisted solar PV system (b) DC-DC and DC-AC power converters (c) Electrolyzer (d) $H_2$ storage tank (e) Induction motor driven $H_2$ compressor system, which is powered by PEMFC and solar PV system separately, and shown in Fig. 1(a)-(b) as,

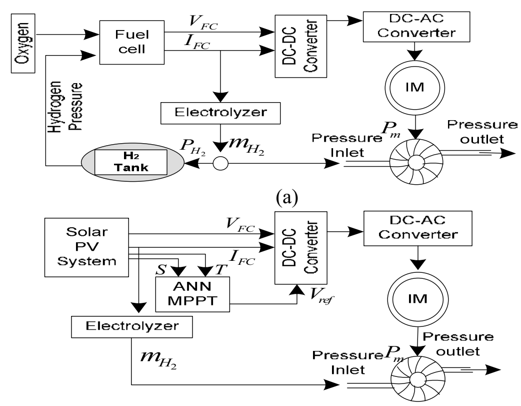


Fig. 1 (a) PEMFC (b) PV power assisted IM driven compressor system.

### A. Renewable energy sources

#### (i) Proton exchange membrane fuel cell (PEMFC)

PEMFC voltage ($V_{fc}$), can be expressed using Eq. (1). The no load voltage, known as Nernst voltage ($E$) is reduced by three categories of voltage drop as,

$$V_{fc} = E - V_{act} - V_{conc} - V_{ohm} \quad (1)$$

The Nernst equation is expressed using Eq. (2) [5] as,

$$E = E_0 + \left(\frac{RT}{nF}\right)\ln\left(\frac{(P_{H_2})(P_{O_2})^{\frac{1}{2}}}{(P_{H_2O})}\right) \quad (2)$$

Hydrogen, oxygen flow pressure and water pressure can be expressed in Eq. (3) and (4) [5] as,

$$P_{H_2} = \left(\frac{m_{H_2} R_{H_2}}{V_{anode}} T\right) \quad \text{and} \quad P_{O_2} = \left(\frac{m_{O_2} R_{O_2}}{V_{cathode}} T\right) \quad (3)$$

$$P_{H_2O} = \left( \frac{\left(m_{H_2O}\right)^{\frac{1}{2}} Q_{H_2O}}{k_{cathode}} \right) \quad (4)$$

The activation drop ($V_{act}$) can be represented by Tafel's equation which gives the activation drop is shown in Eq. (5) as,

$$V_{act} = -\varsigma_1 + \varsigma_2 T - \varsigma_3 T\left[\ln(I)\right] + \varsigma_4\left[\ln(Conc.O_2)\right] \quad (5)$$

Where, $\varsigma_1, \varsigma_2 \ldots\ldots \varsigma_4$ are constants. The oxygen concentration $(Conc.O_2)$ is given as a function of stack temperature shown in Eq. (6) as,

$$Conc.O_2 = \frac{P_{O_2}}{5.08\times10^6 \times \exp^{\left(\frac{-498}{T}\right)}} \quad (6)$$

The concentration voltage drop $(V_{conc})$ is explained in Eq. (7) as,

$$V_{conc} = \ell_1 - \ell_2 (T - 273) e^{(\ell_3 I)} \quad (7)$$

Here the coefficients $\ell_1, \ell_2$ and $\ell_3$ vary with temperature [6]. The ohmic voltage drop ($V_{ohm}$) is almost linear in nature and obtained using Eq. (8) as,

$$V_{ohm} = IR_{mem} \;\; \& \;\; R_{mem} = \frac{t_m}{\sigma} \quad (8)$$

Where, $R_{mem}$ is membrane resistance, $t_m$ is membrane thickness and $\sigma$ is conductivity.

*(ii) Solar PV system*

The solar PV cell voltage ($V_C$) is function of photocurrent, can be determined by load current and depends upon the solar irradiation, explained in Eq. (9) as,

$$V_C = \frac{AkT_C}{e}\ln\left(\frac{I_{ph} + I_o - I_c}{I_o}\right) - R_s I_c \quad (9)$$

The solar cell operating temperature $T_c$ varies as a function of solar irradiation level $S_c$ and ambient temperature $T_a$ affects the cell voltage $V_c$ and cell photo current $I_c$. These effects are also incorporated in the model by the temperature coefficients $C_{TV}$ and $C_{TI}$ are expressed using Eq. (10) [7] as,

$$C_{TV} = 1 + \beta(T_a - T_x) \;\; \& \;\; C_{TI} = 1 + \frac{\gamma_T}{S_C}(T_x - T_a) \quad (10)$$

The correction factor is expressed using Eq. (11) as,

$$C_{SV} = 1 + \beta_T \alpha_S (S_x - S_c) \;\; \& \;\; C_{SI} = 1 + \frac{1}{S_c}(S_x - S_c) \quad (11)$$

Where, $S_c$ is the reference solar irradiation and $S_x$ is new irradiation level at operating condition. Using correction factors $C_{TV}$, $C_{TI}$, $C_{SV}$ and $C_{SI}$ [7], the new values of the cell voltage $V_{cx}$ and photo current $I_{phx}$ are given by Eq. (12) as,

$$V_{cx} = C_{TV} C_{SV} V_C \;\; \& \;\; I_{phx} = C_{TI} C_{SI} I_{ph} \quad (12)$$

*(iii) Artificial neural network MPPT*

Artificial neural network (ANN) architecture is specified to determine the suitable output for the non-linear and complex systems [8]. The simple architecture of ANN is shown in Fig. 2 as,

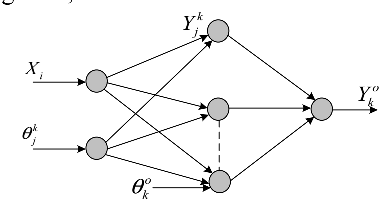


Fig 2. Three layers artificial neural network structure.

The input-output of ANN are shown in Eq. (13) as,

$$y_j^h = f\left(\sum_{i-1}^{N} W_{ji} X_i + \theta_j^h\right), \quad y_k^o = f\left(\sum_{j=1}^{Nh} W_{kj} Y_j^h + \theta_k^o\right) \quad (13)$$

## III. Power Electronics Interface

A DC-DC boost converter is used to enhance the DC voltage and supplied suitable DC power to the load [9]. The duty ratio of DC-DC boost converter is expressed by Eq. (14) as,

$$Duty \;\; Ratio = 1 - \frac{V_{in}}{V_{out}} \quad (14)$$

This generated DC power is fed to the PWM inverter for AC load. This PWM inverter is an insulated gate bipolar transistor (IGBT) based current controlled voltage source converter (CC-VSC) [9].

## IV. Electrolyzer and $H_2$ Storage tank

### *A. Electrolyzer system*

An electrolyzer is an electrochemical device, which decompose water into hydrogen and oxygen [10]. The production rate of $H_2$ in an electrolyzer cell is directly proportional to the transfer rate of electrons at the electrodes, which in turn equivalent to the electrical current in the circuit, as expressed in Eq. (15), and the ratio between the actual and the theoretical maximum amount of $H_2$ produced in electrolyzer is known as Faraday efficiency, which is also expressed in Eq. (15) as,

$$m_{H_2} = \frac{\eta_F N i_e}{2F} \;\; \& \;\; \eta_F = 96.5\left(e^{\frac{0.09}{i_e} - \frac{75.5}{i_e^2}}\right) \quad (15)$$

The Eq. (15) is utilized to design electrolyzer system in MATLAB/Simulink environment.

### *B. Hydrogen storage tank*

The dynamics of $H_2$ storage tank system can be expressed in Eq. (16) as,

$$P_b - P_{bi} = \frac{ZN_{H_2}RT_b}{m_{H_2}V_b} \tag{16}$$

All the auxiliary components such as pumps, valves, and fans are ignored for both these dynamic systems.

## V. IM Driven $H_2$ Compressor System

Three phase induction motor model in q-d arbitrary reference frame is expressed using Eq. (17)-(20) [11] as,

$$v_{qs} = r_s i_{qs} + \omega\lambda_{ds} + p\lambda_{qs} \tag{17}$$

$$v_{ds} = r_s i_{ds} - \omega\lambda_{qs} + p\lambda_{ds} \tag{18}$$

$$v_{qr} = r_r i_{qr} + (\omega - \omega_r)\lambda_{dr} + p\lambda_{qr} \tag{19}$$

$$v_{dr} = r_r i_{dr} - (\omega - \omega_r)\lambda_{qr} + p\lambda_{dr} \tag{20}$$

The electromagnetic torque $T_e$ is expressed in Eq. (21) as,

$$T_e = \left(\frac{3}{2}\right)\left(\frac{P}{2}\right)\left(\lambda_{ds}i_{qs} - \lambda_{qs}i_{ds}\right) \tag{21}$$

The useful equations for designing the compressor system are expressed in Eq. (22)-(24). The inlet and outlet temperature of the compressor are $T_1$ and $T_2$ [12]. The change in temperature is expressed as,

$$\Delta T = T_2 - T_1 = \frac{T_1}{\eta_C}\left(\left(\frac{P_2}{p_1}\right)^{\frac{\gamma-1}{\gamma}} - 1\right) \tag{22}$$

The specific heat capacities and mechanical power $(P_m)$ required for compressor operation are expressed in Eq. (23) as,

$$\gamma = \frac{C_p}{C_v} \quad \& \quad \eta_C = \frac{T_2^{'} - T_1}{T_2 - T_1} \quad \& \quad P_m = C_p \Delta T m \tag{23}$$

Finally outlet pressure of compressor can be expressed in Eq. (24) as,

$$P_2 = P_1\left(1 + \frac{P_m \times \eta_C}{\dot{m} \times C_p \times T_1}\right)^{\frac{1}{0.286}} \tag{24}$$

Where, $C_p$ = 1004 $JKg^{-1}K^{-1}$ and $m$ is rate of gas flow constant.

## VI. Results and Discussion

### A. Performance of PEMFC powered $H_2$ pressure generation

The performance of MATLAB/Simulink model of PEMFC powered $H_2$ pressure generation is investigated. The results are obtained for the following cases,

- V-I characteristics of FC system
- Performance of FC system
- Performance of electrolyzer and IM driven compressor

MATLAB/Simulink model of PEMFC powered $H_2$ generation system is shown in Fig. 3. The obtained V-I characteristic of FC system is shown in Fig. 4 , in which all the voltage drops are shown clearly. The FC voltage, current and power are obtained as 320.12V, 8.46 and 2708.21W respectively, shown in Fig. 5. The output of DC-DC converter and PWM inverter output voltage are same as 640.20V, as shown in Fig. 6.

In Fig. 7, the torque, rotor speed and mechanical power of PEMFC based system are shown, with their values of 10.93 Nm, 188 rad/sec and 2054W respectively. The $H_2$ pressure, generated by electrolyzer is 22.19 atm., and IM assisted compressor system is utilized to enhance the $H_2$ pressure up to 76.25 atm.

### B. Performance of solar PV powered $H_2$ pressure generation

The performance of MATLAB/Simulink model of ANN based MPPT assisted solar PV powered $H_2$ pressure generation is investigated, and shown in Fig. 8. The following results are obtained as,

- V-I characteristics of PV system at different operating parameters
- Performance of solar PV system
- Performance of electrolyzer and IM driven compressor system

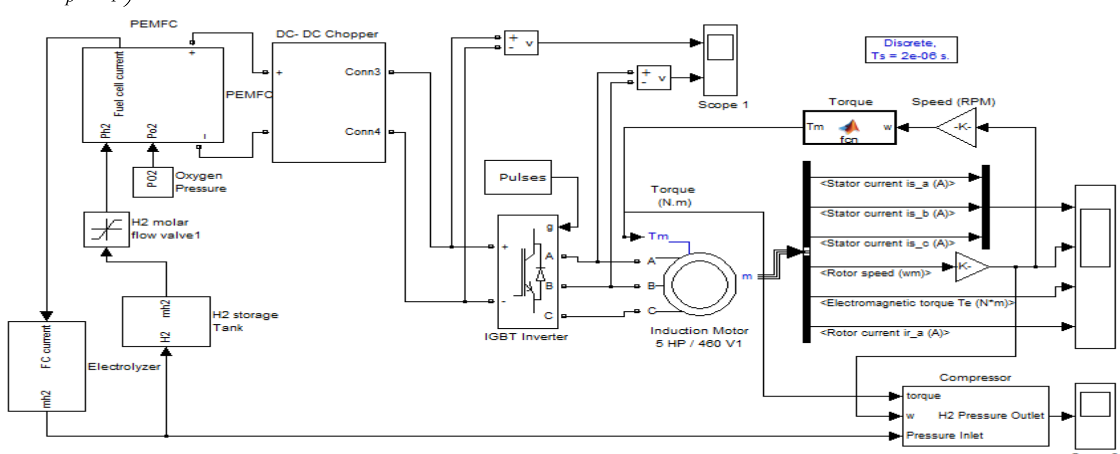


Fig 3. MATLAB/Simulink model of PEMFC powered hydrogen generation system.

The V-I characteristics of solar PV system at different operating environmental conditions are shown in Fig. 9(a)-(d).

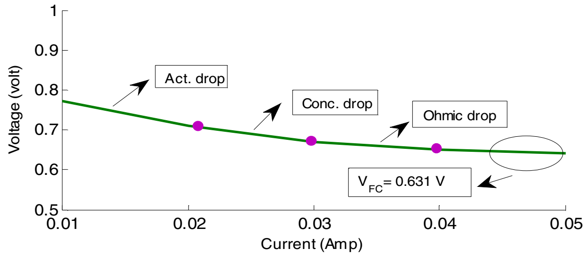


Fig 4. Typical V-I characteristics of FC system.

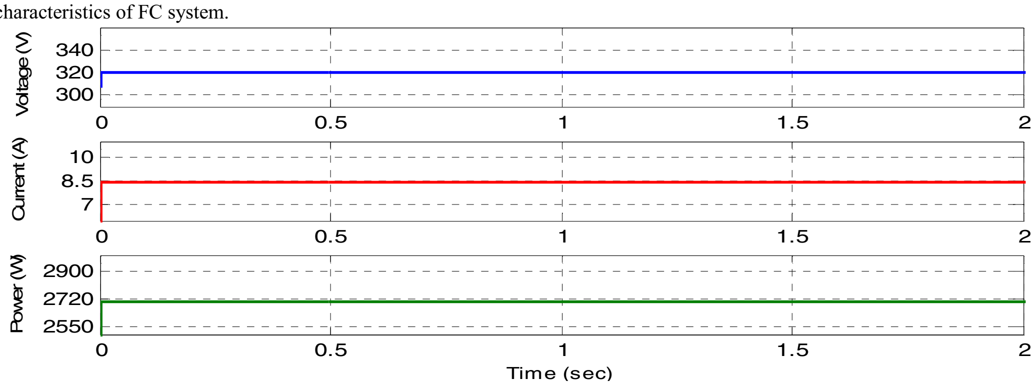


Fig 5. FC voltage, current, power.

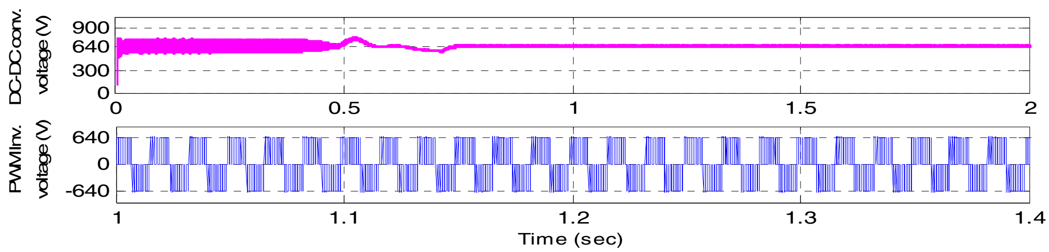


Fig 6. DC-DC converter and PWM inverter voltage.

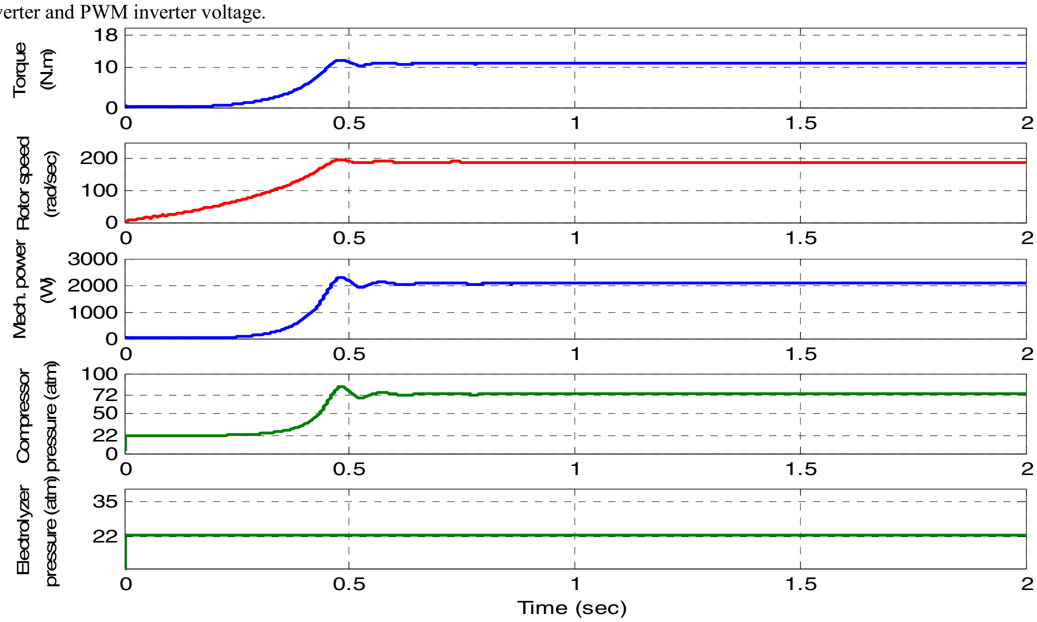


Fig. 7. Performance of PEMFC powered IM driven compressor system.

The solar PV voltage, current and power is 320.12V, 8.46 and 2708.21W respectively as shown in Fig. 10. The output voltages of DC-DC converter and PWM inverter integrated with ANN based MPPT assisted solar PV are same as 640.20V, shown in Fig. 11.

In Fig. 12, the torque, rotor speed and mechanical power of ANN based MPPT assisted solar PV system are shown, whose values are 10.93 Nm, 188 rad/sec and 2054W respectively. $H_2$ pressure, generated by electrolyzer is 22.196 atm. Induction motor assisted compressor is utilized to enhance the $H_2$ pressure up to 76.25 atm.

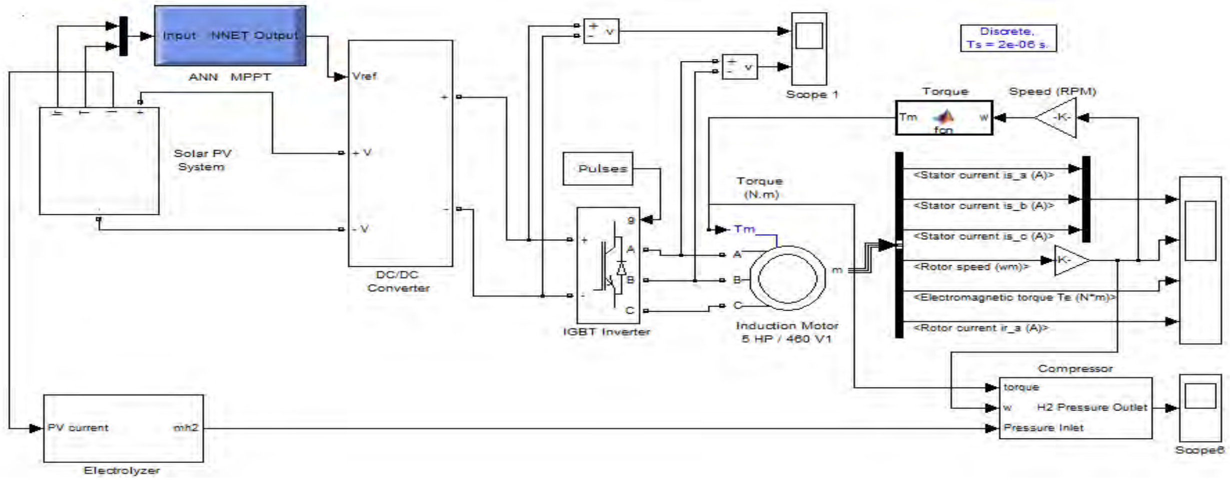

Fig 8. MATLAB/Simulink model of solar PV powered hydrogen generation system.

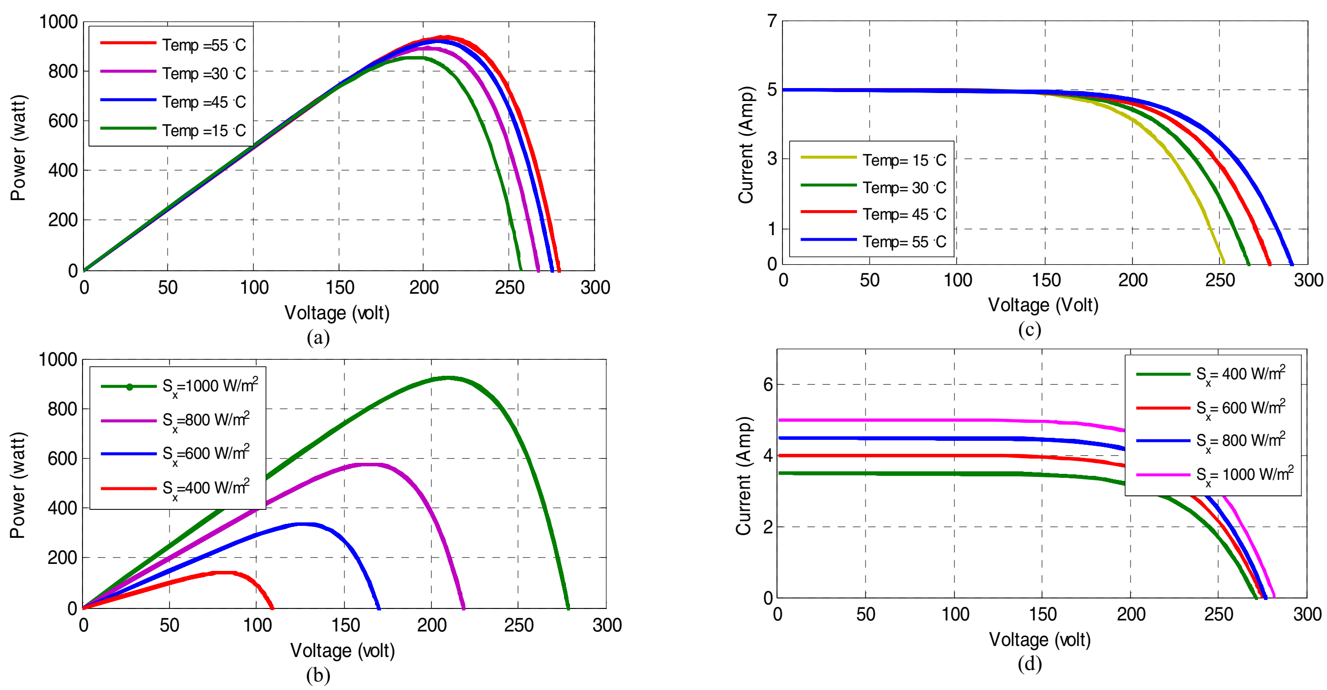

Fig. 9(a)-(d) Solar PV system characteristics at different environment conditions.

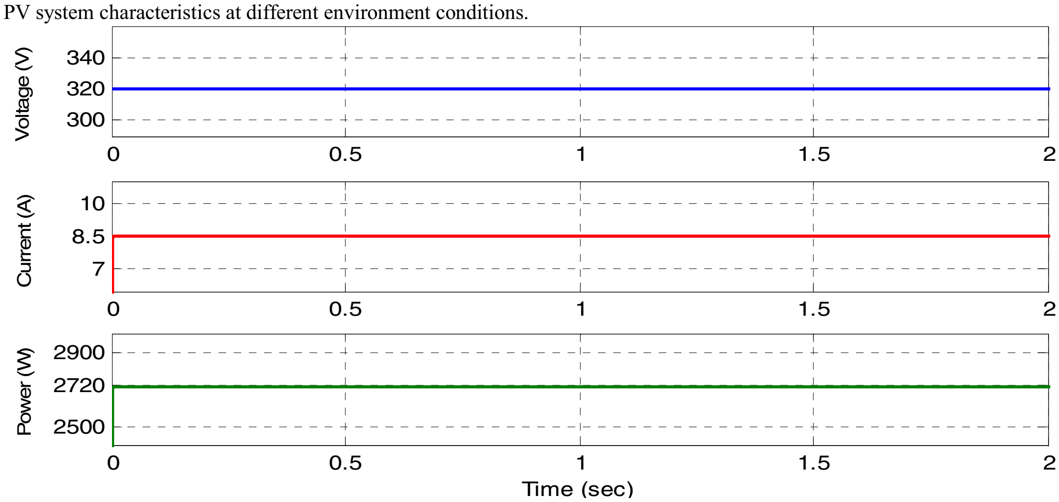

Fig. 10 Solar PV voltage, current and power.

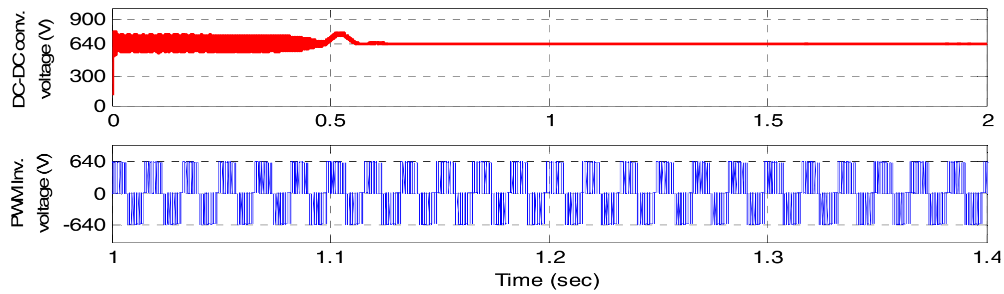


Fig. 11 DC-DC converter and PWM inverter voltage.

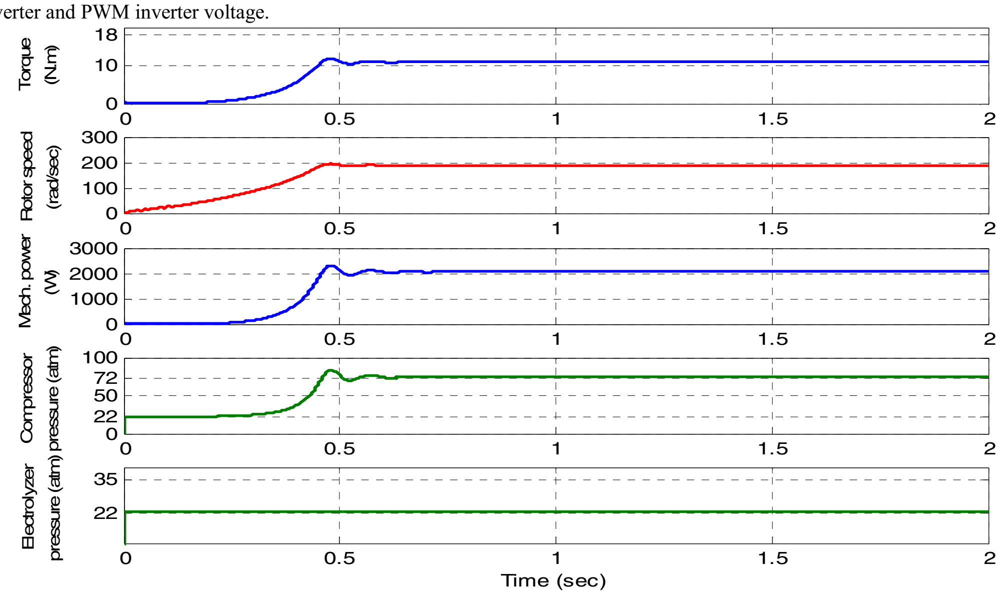


Fig. 12 Performance of ANN based MPPT assisted solar PV powered IM driven compressor system.

## VII. Conclusion

In this paper, two types of RE sources such as PEMFC and solar PV system are considered for $H_2$ pressure generation and power assisted IM to enhance $H_2$ pressure. The solar PV system is utilized and investigated for the same purpose as that of PEMFC system. It is observed that both the systems can be utilized separately in different environmental conditions. The operation of electrolyzer system is investigated and found satisfactory, for the storage of $H_2$ in the tank by electrolysis of water. The performance of both the systems has been investigated and it is observed that the system performance for both cases are found satisfactory. With the utilization of RE the system is more economic and these type systems have long life because during the day time, the solar PV based system and during night time the PEMFC based system can be employed.

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