Reliable Designing of Stand-alone PV/FC Hybrid System

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ABSTRACT:
Application of renewable energy sources has shown a perfect potential as a form of contribution to conventional power generation systems. This paper presents a hybrid system based on photovoltaic (PV) module and PEM (proton exchange membrane) fuel cell (FC) with the aim of selling electricity to distribution network (DN) and improving its reliability. In this paper, moreover supplying the load electricity of system, the proposed hybrid system is capable to sale electricity to DN and by electricity injection causes DN reliability improvement. The revenue from selling electricity to DN is considered as the system profit (SP). An optimization is applied to maximize the SP using GAMS environment. This study claims that moreover load electricity provision, electricity can also be sold to DN by proposed hybrid system and reliability of DN in load supplement can be increased by injecting the electricity to it.

KEYWORDS: Photovoltaic Module, PEM Fuel Cell, Sale Electricity, Distribution Network, GAMS environment

1. INTRODUCTION

The application of renewable energy sources is increasingly growing since demand of electrical energy is increasing due to population growth and industrialization. Meanwhile, the sources of fossil fuels are reducing [1].

Distribution lines cause significant losses in which weak voltage regulation and low quality and Low reliability are the drawbacks of generating energy in conventional method. The drawbacks can be removed by local energy generation using renewable energy sources, like PV, FC and Wind turbine. This kind of energy generation is called Distributed Generation (DG). Some advantages of DG are Low Distribution Losses, Better Power Quality and High Reliability. When different kinds of renewable energy sources come together, they generate a Hybrid Distributed Generation System (HDGS). PV generator is one of the proposed sources in HDGS. PV is one of renewable energy systems which has always been in the spotlight and in recent years it has been increasingly expanded on business affairs. PV directly converts solar radiation energy to electrical energy and considers weather condition and Level of solar radiation the amount of generating energy changes. A PV generator has some drawbacks as well which are as follows [2]:

PV output voltage versus current follows a nonlinear relation and The PV output power varies with solar radiation. This generated power variation causes disturbance for the utility or connected users. No power generation has been feasible for night hours. Lack of control for generating power in PV caused it not to be able to schedule in generation for different periods which is one of the obstacles in business improvements in this technology.

When PV connected with a suitable auxiliary energy source, above drawbacks can be reduced or solved. The auxiliary energy sources that can work in connection with PV are FC, Wind Turbine, Battery and Diesel Generator. Battery is only a low load solution. Wind Energy is clean and renewable, but its reliability is low. The diesel Generator offers a compact size and high energy density, but it's not clean and renewable and its running cost is very high. FC converts chemical energy to Electrical energy and the amount of power generation can be controlled by regulating the fuel provided for it (Natural Gas/hydrogen). FC is an eco-friendly which owns a higher energy density and also can generate power as long as the fuel is supplied. FC suffers from running cost, but because of higher conversion efficiency, its performance is better compared to a Diesel Generator [3].

FC system is capable of generating controlled energy in different periods and can be coupled with PV as an auxiliary source. Hence, FC acts as a source of Energy storage to compensate the intermittent in power generating of PV; As a result, it makes the scheduling of electrical generating possible. Increased profits of generating electrical energy and increasing reliability in providing electrical demand of the consumers are the advantages of simultaneous application of PV and FC. From the current discussion, we can conclude that an HDGS System consists of PV and FC sources will result in an optimal HDGS which is capable of providing clean and reliable power round o'clock [3].

Investigating the studies, we have observed that problem of optimal application in PV and FC in all papers has been with the view of power electronic in order to provide the load power demand (peak-shaving) and load reliability improvement. This problem has never been investigated on the view of selling electricity from hybrid system to DN and improving the reliability of DN. In this paper, a hybrid PV/FC system is presented by simultaneous and optimal applications PV and FC. The aim of this study has been maximizing the SP. Moreover load electricity provision, the proposed hybrid system can also sell electricity to DN that by injecting the electricity to it, its reliability in consumer load supplement will increase.

2. PROPOSED HYBRID SYSTEM MODELING

Mathematical modeling of PV/FC hybrid system is presented. Proposed system consists of PV and PEMFC with one electrolyzer (EL) and hydrogen storage tank (HST). The block diagram of proposed system is depicted in Fig. 1.

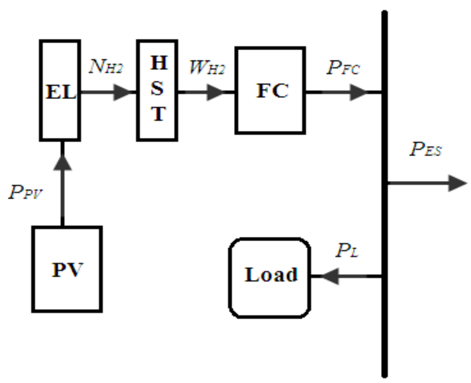

Fig. 1. The block diagram of case study system.

In this system, with receiving solar radiation, PV generates necessary power for generating hydrogen for EL, and then the generated hydrogen is delivered into the tank and stored under pressure. Based on load power demand and maximizing the SP, some of hydrogen is used by FC and the rest is stored in the tank under pressure. It's worthwhile to mention that the amount of hydrogen stored in the tank is so effective in the amount of SP and that the amount of hydrogen storage depends on tank pressure.

2.1. PV system modeling

The energy of solar radiation converts to electrical energy using PV. The temperature and solar radiation of PV changes bring about changes in voltage level and output power. The output power of PV based on temperature and solar radiation changes is given as follows [4]:

$$P_{PV} = V_{PV} I_{PV} \quad (1)$$

$$V_{PV} = V_{ref} + (-\beta\Delta T - R_s(\alpha(\frac{G}{G_{ref}})\Delta T + (\frac{G}{G_{ref}} - 1)I_{SC})) \quad (2)$$

$$I_{PV} = I_{ref} + (\alpha(\frac{G}{G_{ref}})\Delta T + (\frac{G}{G_{ref}} - 1)I_{SC}) \quad (3)$$

Where, $P_{PV,}$ V_{PV} and I_{PV} refer to power, voltage and current of PV module. G and G_{ref} represent the solar radiation in operational condition and solar radiation in standard condition (1000W/m2, AM 1.5, 25 degree C). I_{SC} is pv module short circuit current. α and β are Current and voltage change temperature coefficients and ΔT refers to PV temperature variation [°K]. V_{ref} and I_{ref} refer to voltage and current of PV cell in standard condition. It should be mentioned that in this paper, temperature changes are ignored.

2.2. PEMFC system modeling

FC converts oxygen and hydrogen chemical energy to electrical energy. The amount of output voltage in each cell is little, so some cells connected in series to gain a bigger output voltage and that is called FC stack. The performance of FC is described by polarization curve and in a constant state which shows FC voltage based on the current. Three basic areas which affect the overall polarization are ohmic, activation and concentration polarization [5].

The mentioned factors are cell voltage drops which change the cell potential from ideal behavior. FC output voltage is mentioned in polarization curve calculated by:

$$V_{FC} = E_{nernst} - V_{act} - V_{ohmic} - V_{con} \quad (4)$$

Where, V_{act}, V_{ohmic} and V_{con} refer to activation, Ohmic and concentration voltage drop and E_{nernst} is open circuit and lossless voltage in FC can be calculated as follows:

$$E_{nernst} = 1.229 - 0.85 \times 10^{-3}(T - 298.15) + 4.3085 \times 10^{-5} T \left\lfloor \ln(P_{H_2}) + 0.5 \ln(P_{O_2}) \right\rfloor \quad (5)$$

Where, T refers to FC Operation temperature [°K]. P_{H2} and P_{O2} are Partial pressure of hydrogen and oxygen [atm].

A. Ohmic polarization

Ohmic polarization shows that ohmic voltage drop occurs due to resistive losses in the cell which is caused by resistance against electrons and ions movement.

The ohmic voltage drop can be defined as follows:

$$V_{ohmic} = I_{FC}(R_M + R_C) \quad (6)$$

Where, I_{FC} refers to FC current. R_C is resistance of FC electrodes against electrons movement which is constant and R_M is FC membrane resistance against ions passing, which can be calculated by [6]:

$$R_M = \rho_M (\frac{\ell}{A}) \quad (7)$$

$$\rho_M = \frac{181.6(1+0.03(I_{FC}/A)+0.062(T/303)^2(I_{FC}/A)^{2.5})}{((\varphi-0.634-3(I_{FC}/A))\exp(4.18((T-303)/T)))} \quad (8)$$

Where, ρ_M is the cell membrane specific resistivity (Ω.m), A is cell active area (cm^2) and ℓ is membrane thickness (cm).

B. Activation polarization

Activation polarization shows activation voltage drops in FC anode and cathode electrodes. These drops are caused by the slow reactions on the surface of electrodes which are calculated by:

$$V_{act} = -\left\lfloor \xi_1 + \xi_2 T + \xi_3 T \ln(C_{O_2}) + \xi_4 T \ln(I_{FC}) \right\rfloor \quad (9)$$

Where ξ_1, ξ_2, ξ_3 and ξ_4 are parameters corresponding to V_{act} and C_{O_2} is oxygen concentration rate on the catalyst surface which can be described as follows:

$$C_{O_2} = \frac{P_{O_2}}{5.08 \times 10^6 \exp(-\frac{498}{T})} \quad (10)$$

C. Concentration polarization

Concentration polarization shows voltage drop due to reduction in density of reaction materials which is called mass transport losses. To determine voltage drop model in mass transport or concentration voltage drop, maximum current density must be gained (J_{max}). Voltage drop corresponding to mass transport can be calculated by [7]:

$$V_{con} = -B \ln(1 - \frac{J}{J_{max}}) \quad (11)$$

Where B is a constant (RT/2F) and J refers to current density of cell.

Considering all FCs voltage drops and for n cells which are connected in series by forming a stack, output power of FC stack is defined as follows:

$$P_{FC} = N_{FC} \cdot V_{FC} \cdot I_{FC} \quad (12)$$

Where N_{FC} represents the number of cells in series and V_{FC} and I_{FC} refer to fuel cell voltage and current.

D. PEMFC current

The FC current I_{FC} can be determined as a function of hydrogen flow rate to FC and can be obtained by [8-9]:

$$I_{FC} = (\frac{2F}{N_{FC}})(\frac{W_{H_2}}{M_{H_2}}) \quad (13)$$

Where, W_{H2} is hydrogen molar flow rate delivered to FC, M_{H2} is hydrogen molar mass and F refers to Faraday's constant [C/kmol].

2.3. EL system modeling

Water by EL can be decomposed into its elementary components. This process is done by passing electrical current between two electrodes that are separated by an aqueous electrolyte. The rate of hydrogen production in an EL is directly proportional to electrical current which is given by [10-13]:

$$N_{H_2} = \frac{\eta_F n_c I_{EL}}{2F} \quad (14)$$

Where, η_F refers to faraday efficiency. n_c *is* number of EL cells in series and I_{EL} *is EL* current.

The ratio between the real and theoretical maximum amount of hydrogen which is produced in the EL is called faraday efficiency and defined by:

$$\eta_F = 96.5 e^{(\frac{0.09}{I_{EL}} - \frac{75.5}{I_{EL}^2})} \quad (15)$$

2.4. HST system Modeling

Physical hydrogen storage is one of the storage techniques that use tank to store compressed hydrogen. After compressing under high pressure, the hydrogen molar flow which is required by PEMFC is sent from the HST. The model of HST is described according to (16) [10] and using the ratio of hydrogen flow to the tank, it directly obtained the tank pressure.

$$P_b - P_{bi} = z\left(\frac{(N_{H_2} - W_{H_2})RT_b}{M_{H_2}V_b}\right) \tag{16}$$

Where, P_b and P_{bi} refer to pressure of HST and Initial pressure of the HST [Pa], respectively. R is universal (Rydberg) gas constant [J (kmol °K)$^{-1}$]. Z refers to compressibility factor as a function of tank pressure. T_b and V_b represent HST operating temperature [°K] and volume [m^3], respectively.

3. OPTIMIZATION AND OBJECTIVE FUNCTION

PV and FC optimal application with the aim of maximizing SP gained from generating electrical energy by proposed hybrid system, presenting algorithm for optimal utilization from FC with the aim of maximizing SP, Load and DN reliability improvement are the aims of this paper. Equations from (1) to (16) represent the mathematical formulation of case study system. The planning problem is formulated as mixed integer nonlinear programming (MINLP) in GAMS environment [14], with an objective function for maximizing the SP due to selling electricity to DN.

The objective function can be defined by (17):

$$Maximize\ System\ profit = \sum_{t=1}^{24} P_{ES}(t)$$

(17) Where, $P_{ES}(t)$ represents the electricity sold to DN (Wh) from proposed hybrid system and can be defined by:

$$P_{ES}(t) = P_{FC}(t) - P_{Load}(t) \tag{18}$$

Where, $P_{FC}(t)$ and $P_{Load}(t)$ refer to electricity generated by PEMFC and load electricity demand, respectively.

3.1. Constraints

Optimization problem constraints are as follows:

$$P_{FC}(t) > P_{Load}(t) \tag{19}$$

$$P_{FC}(t)_{,min} < P_{FC}(t) < P_{FC}(t)_{,max} \tag{20}$$

Where, $P_{FC}(t)_{,min}$ and $P_{FC}(t)_{,max}$ refer to minimum and maximum output power of FC, respectively.

HST pressure (P_{HST}) must reach its maximum rate for once during 24 hours. Also following is HST pressure variation domain:

$$P_{min} \le P_{HST} \le P_{max} \tag{21}$$

Where, P_{min} and P_{max} refer to minimum and maximum pressure of HST, respectively.

3.2. System input data

System input data includes load electricity demand and solar radiation during 24 hours. The demand of load electricity during 24 hours is depicted in Fig. 2 and solar irradiance is shown in Fig. 3.

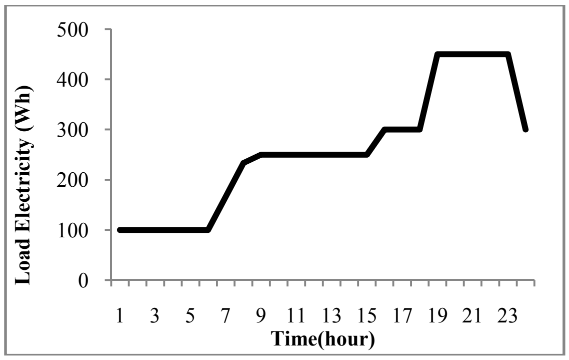

Fig. 2. Load electricity demand during 24 hours.

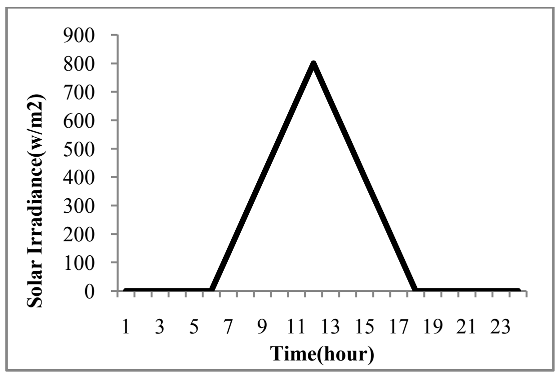

Fig. 3. solar irradiance during 24 hours.

4. OPTIMIZATION RESULTS AND DISCUSSION

The rate of hydrogen production by EL, consumed hydrogen by PEMFC and stored hydrogen in HST are shown in Fig. 4. According to Fig. 4, with receiving the PV power by EL, hydrogen is produced from 6 to 18. But in remaining hours it is not capable to produce hydrogen due to lack of solar radiation. Load needs electricity during all hours and the aim of selling electricity to DN must be considered in these hours.

Being under pressure in tank, some amount of produced hydrogen is delivered to FC and the rest is stored when hydrogen production is stopped. According to curve related to tank stored hydrogen, it is clear that amount of hydrogen is positive from 6 to 17. This means that in these hours hydrogen is produced, some amount of hydrogen is also stored in tank more over consuming hydrogen by FC. In other words, the tank is filling hydrogen which happens at 17. But from 17 onwards, with reducing the level of hydrogen production and stopping production process, the storing no longer happens in tank and only FC uses hydrogen stored in the tank. This is visible in negative values in Fig. 4. As mentioned earlier, the maximum load demand is from 17 to 23 in which some more hydrogen is extracted from the tank and delivered to FC as shown in Fig. 4.

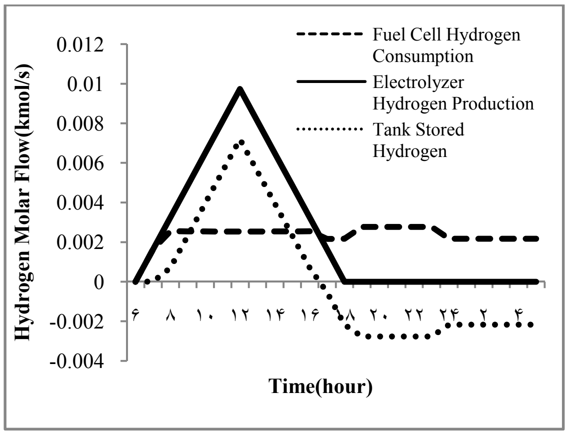

Fig. 4. Produced hydrogen by EL, consumed hydrogen by FC and tank hydrogen storage.

Tank pressure variations are depicted in Fig. 5. As it can be observed, being filled of hydrogen, tank pressure reaches its maximum amount which equals 2atm at 17, for once during 24 hours. But from 17 onwards, with reducing hydrogen production and stopping production process, storing in tank is stopped and stored hydrogen is consumed by FC. In this situation tank pressure curve continues smoothly.

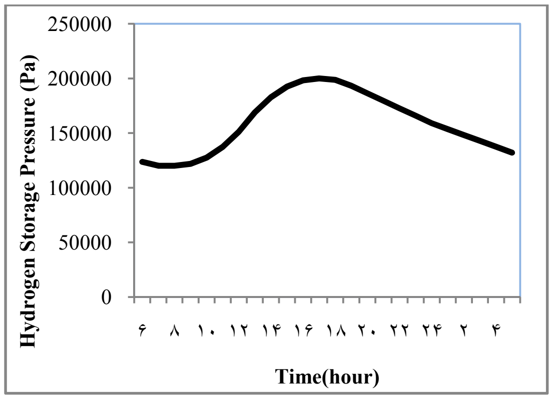

Fig. 5. The pressure variations of HST.

The generated electricity by PEMFC, sold electricity to DN and load electricity demand during 24 hours are shown in Fig. 6. PEMFC generates electricity proportional to factor like consumed hydrogen molar flow rate.

According to Fig. 6, it can be observed that maximum electricity is sold to network during 1 to 5 which is related to low load period. During 19 to 23 it is related to peak load period in which the generated electricity is only devoted to load provision which indicates system optimal performance. The results of optimization prove this claim that moreover providing load, electricity can also be sold by proposed hybrid system to DN.

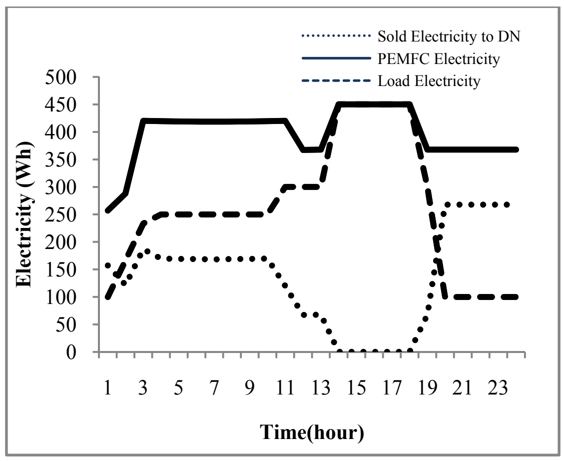

Fig. 6. The generated electricity by FC, Sold electricity to DN and load electricity demand during 24 hours.

5. CONCLUSION

In this study a proposed hybrid PV/FC system consists of PV module, PEMFC, EL and HST was optimized. The objective function in this study was considered maximizing the sale electricity to DN. Based on the results, during 24hours, moreover supply the load electricity, selling electricity to network is done (except peak time). As shown as in optimization results, SP was dependent on stored hydrogen molar flow rate in HST that was a system reserve electrical energy and also reserve duration, when PV module is not able to generate the power for EL and hydrogen generation.

Also being filled of hydrogen in HST and maximize its pressure for once during 24 hours was very important to maximize SP. Optimization constraints were observed and there was no violation. The results prove this claim that moreover loads electricity provision, electricity can also be sold to DN by proposed hybrid system and by injecting the electricity to DN, its reliability can be increased in load supplement of consumers.

6. APPENDIX

Table 1. Typical MSX-120 PV module Parameters [15].

MSX-120 PV module Parameters	Value
Rated Power (P_{mpp})	120 Wp
Rated Voltage (V_{mpp})	17.1 V
Rated Current (I_{mpp})	7.0 A
Open Circuit Voltage (V_{OC})	21.3 V
Open Circuit Current (I_{SC})	7.6 A
Number of cells in FC stack (N)	30

Table 2. Typical FC parameter of 500W BCS stack [15].

Typical FC Parameters of 500W BCS Stack	Value
Cell active area (A)	64 cm^2
Maximal current density (*Jmax*)	469mA/ cm^2
Operation temperature (*T*)	333K
Membrane thickness (ℓ)	178 μm
Partial pressure of Hydrogen (P_{H2})	1atm
Partial pressure of oxygen (P_{O2})	0.2095atm
Equivalent resistance to proton conduction (R_C)	0.0003Ω
Parameter corresponding to V_{act} (ξ_1)	– 0.948
Parameter corresponding to V_{act} (ξ_2)	0.00286+0.0002ln(A) +0.000043ln(CH2)
Parameter corresponding to V_{act} (ξ_3)	0.000076
Parameter corresponding to V_{act} (ξ_4)	-0.000193
Membrane humidity (φ)	23
B	0.016 V
Faraday's constant (F)	96 484 600 C/kmol
Universal gas constant (R)	8314.47 J/(kmol K)

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