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A Fuzzy-Based PI Controller for Power Management of a Grid-Connected PV-SOFC Hybrid System

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Abstract: Solar power generation is intermittent in nature. It is nearly impossible for a photovoltaic (PV) system to supply power continuously and consistently to a varying load. Operating a controllable source like a fuel cell in parallel with PV can be a solution to supply power to variable loads. In order to coordinate the power supply from fuel cells and PVs, a power management system needs to be designed for the microgrid system. This paper presents a power management system for a grid-connected PV and solid oxide fuel cell (SOFC), considering variation in the load and solar radiation. The objective of the proposed system is to minimize the power drawn from the grid and operate the SOFC within a specific power range. Since the PV is operated at the maximum power point, the power management involves the control of SOFC active power where a proportional and integral (PI) controller is used. The control parameters of the PI controller K_p (proportional constant) and T_i (integral time constant) are determined by the genetic algorithm (GA) and simplex method. In addition, a fuzzy logic controller is also developed to generate appropriate control parameters for the PI controller. The performance of the controllers is evaluated by minimizing the integral of time multiplied by absolute error (ITAE) criterion. Simulation results showed that the fuzzy-based PI controller outperforms the PI controller tuned by the GA and simplex method in managing the power from the hybrid source effectively under variations of load and solar radiation.

Keywords: distributed generation; fuel cell; fuzzy logic controller; hybrid system; power management; photovoltaic

1. Introduction

Renewable energy sources such as wind turbines and photovoltaics (PV) have gained prominence in generating electricity due to environmental concerns. A reduction in CO_2 emission and the combustion of fossil fuels are among the main benefits of using these sources. At the end of 2014, renewable energy sources contributed to 22.8% of global electricity production [1]. During the period of 2009–2014, the annual growth rate of solar PV capacity was higher among other renewable energy sources. Solar PV can supply a local load that is referred to as a microgrid system. The microgrid can operate in parallel with the grid or in islanded mode. In grid-connected mode, depending on both the generation and load demand, the microgrid absorbs or supplies power from/to the grid. The main challenge of using PV is its dependence on the solar radiation level. Thus, it is nearly impossible to satisfy a variable load since the output power from the PV varies. In order to overcome this shortcoming, a controllable source such as a fuel cell can be installed and operate in parallel with the PV. Fuel cells are chosen because of their (i) high energy conversion; (ii) zero emission of pollutant gases; (iii) noiseless operation; and (iv) high reliability. Among other fuel cell technologies, the solid oxide fuel cell (SOFC) is an attractive option for distributed generation applications. Practical application of SOFC in power production is reported in [2]. In this paper, a 100 kW SOFC unit was installed and operated for more than 15,000 h at a power plant in Westervoort, Netherlands, proving the point that SOFC is reliable enough for commercial power generation.

A microgrid system consisting of PV and SOFC can operate in grid-connected or islanded mode. During grid-connected operation, the system should be managed well in order to coordinate power generation between PV and SOFC, and at the same time ensure that load demand is fulfilled. In this context, an efficient power management system is required. If the total power from the hybrid system is less than the load demand, the microgrid imports power from the grid. If the power produced from the hybrid source is more than the load demand, the excess power is injected into the grid. Since SOFC is a controllable source, its output power should be regulated to its reference value specified by the power management system. The microgrid power management system assigns a reference set point for the generation units. Therefore, the generation unit should have appropriate control schemes for their voltage source inverter (VSI) in order to position its output power to the reference points assigned by power management systems. It is necessary for a control scheme to attain fast response and maintain system stability during sudden changes.

In [3] a power management strategy is developed for a hybrid system consisting of PV and a proton exchange membrane fuel cell (PEMFC) supplying power to a variable load. The authors developed a detailed model of PV, PEMFC and electrolyser. The authors used an artificial neural network (ANN) for maximum power point tracking (MPPT). They claimed that the ANN for MPPT produced the best results for real weather conditions. Here the PEMFC is seen as a secondary generator which works when PV power is absent. This paper deals only with the management of the hybrid system, which operates in an islanded mode. Similar work was carried out in [4], where two intermittent sources (PV and wind) along with a fuel cell were used to deliver DC load. They employed fuzzy logic control to achieve maximum power tracking for wind and PV. The hybrid system was operating in islanded mode. In [5], a power management strategy for a grid-connected PV-FC hybrid source was presented where the hybrid sources were operating in unit power control and feeder flow control modes. The strategy is to operate PV at MPPT and the fuel cell within its power range and reduce the number of switches between the two control modes. In [3,6] a power management system is proposed for a hybrid system consisting of PV-FC operated in islanded mode. However, the authors did not mention the controller used or the selection of parameters for the controller. In [7], a differential evolution algorithm was used to find the optimal control parameters for a PI controller. The robustness of the controller was evaluated only for the SOFC system operating in parallel with the grid. A fuzzy logic controller for tuning the PI controller parameters was designed in [8] specifically for inverter reactive power control. In [9] a PI tuning method is proposed for the energy management of a DC microgrid grid. The tuning of the PI controller used a swarm variant of hybrid mean variance mapping optimization. Although they used optimization to tune the controller's parameters, it may be difficult to implement this in real time. An optimal controller was presented in [10] for a grid-connected microgrid operation considering changes in the load. In this work, the control parameters were tuned using the particle swarm optimization (PSO) technique. The operating range of the distributed source, a constraint, was not considered, and the robustness of the controller was demonstrated for a single step change in the load. In addition, the reference set point which was given as an input to distributed generator's (DG) control was fixed. From the above references, it can be confirmed that many researchers focused on the design of power management for the operation of hybrid systems. However, there is very limited research that focuses on the selection of control parameters for the distributed generator's (DG) real power controllers. Moreover, most of it only considers cases where DG output is constant. Hence, there is a need to look into this matter, which will be addressed in this paper.

Fuzzy logic is mathematical tool which provides solutions for a complex problem where there is no well-defined mathematical formulation. Mamdani and Takagi Sugeno interface fuzzy systems are commonly used for control applications. An application of a mamdani interface system is found in [11] where a fuzzy-based speed governor was designed for a mini hydro power plant that supplies varying load. In [12] an adaptive fuzzy logic controller was designed using a mamdani interface system for load frequency control of a small hydro plant. Some applications of Takagi Sugeno fuzzy systems are presented in [13,14]. In [13], a Takagi Sugeno fuzzy system is designed to efficiently control static synchronous compensator (STATCOM) installed in a power system network under various disturbances. The voltage and frequency of an isolated wind turbine controlled by a Takagi Sugeno fuzzy logic controller considering variation in wind speed and load power can be found in [14]. A fuzzy logic system integrated with an optimization technique to provide fast and robust results has been presented in [15–18]. In [15], a fuzzy-logic–genetic-algorithm model is developed to estimate monthly solar radiation. The results presented in [15] indicate that the fuzzy–genetic model more accurately estimates the monthly solar radiation than an artificial neural network (ANN) and neuro fuzzy model. The application of a fuzzy-based controller to tune the PI control parameters for a hybrid electric vehicle application is found in [16]. A cuckoo-search-optimization-based fuzzy logic controller is developed in [17] to operate a hybrid system consisting of PV, battery and diesel generator in standalone mode. PSO used to tune the membership function of a fuzzy controller for solar PV MPPT control is carried out in [18]. Application of fuzzy logic to solve diverse engineering problems can be found in the literature; however, the application of fuzzy to find the PI controller parameters for a DG used in a power management problem is very limited.

In this paper, a power management algorithm is developed for a grid-connected PV-SOFC hybrid system, taking into consideration variation in the load and solar radiation. When the system is in operation, the power management system facilitates PV to operate at the maximum power point, minimizing the power drawn from the grid and operating the fuel cell within its operating efficiency. The control of the power from the hybrid source is possible by controlling the power output from the SOFC system. Here, a PI controller is employed to control the active power flow from the SOFC system. A fuzzy logic system, genetic algorithm and simplex are designed to obtain the optimal control parameters (K_p and T_i) for the PI controller, taking into consideration variation in the load and solar radiation. The integral of time multiplied by absolute error (ITAE) criterion is used to evaluate the performance of the controllers. The SOFC operates within a specific power range (PFCmin, PFCmax). The simulation model of the grid-connected PV-SOFC was built in PSCAD software.

2. System Description

The proposed microgrid incorporates two electronically-interfaced distributed generators (DG) connected through a three-phase voltage source converter (VSC). A 100 kW SOFC is the primary power source. Since minimizing the power drawn from the grid is considered as one of the objectives, the SOFC is sized to the peak load where the fuel cell is able to supply power to the variable load in the absence of PV. The load demand varies throughout 24 h. A 200 kW PV is also connected where the available power is injected into the microgrid system with a unity power factor. The microgrid operates in grid-connected mode.

2.1. Hybrid Grid-Connected PV-SOFC System

The microgrid system considered here consists of a 200 kW PV array and 100 kW SOFC connected to the point of common coupling through a 0.4/11 kV transformer (Figure 1). The system is grid-connected and operates in parallel with variable load.

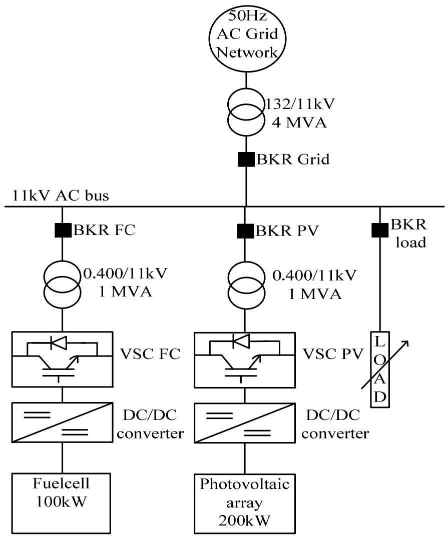


Figure 1. Grid-connected hybrid system.

2.2. PV Array Model

An electrical equivalent of solar cell is modeled by connecting a current source anti-parallel with a diode which is shown in Figure 2 [19].

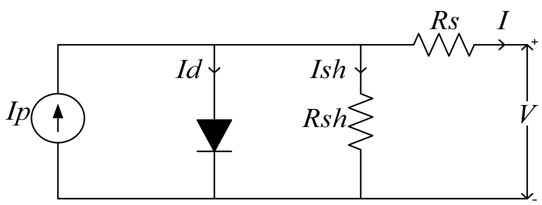


Figure 2. Equivalent circuit of single diode solar cell.

When solar radiation falls on a solar cell, a DC photo current (I_p) is generated. I_p varies proportionally with changes in solar radiation. Applying Kirchhoff's current law to the equivalent circuit gives [20],

$$I = I_p - I_d - I_{sh} \tag{1}$$

The diode current (I_d) can be calculated as,

$$I_d = I_o[\exp\left(\frac{V+IR_s}{nkT_c/q}\right) - 1] - \left(\frac{V+IR_s}{R_{sh}}\right) \tag{2}$$

I_o is the dark current and can be calculated as,

$$I_o = I_{oref}\left(\frac{T_c{}^3}{T_{cref}{}^3}\right)\exp\left[\left(\frac{1}{T_{cref}} - \frac{1}{T_c}\right)\right]\frac{qe_g}{nk} \tag{3}$$

where,

I_{oref}: dark current at T_{cref};
k: Boltzman constant;
e_g: band gap energy;
T_{cref}: reference cell temperature;
T_c: cell temperature;
q: electron charge;

n: diode ideality factor.

I_p depends on solar radiation and temperature and can be expressed as,

$$I_p = I_{SCref} \frac{G}{G_{ref}} \left[1 + \alpha_t \left(T_c - T_{cref}\right)\right] \quad (4)$$

where,

G_{ref}: reference solar radiation;
α_t: temperature coefficient of photo current.

PV cells are connected in series/parallel combination to make the PV module. The PV modules are arranged in series and in parallel combination to generate the required electrical power. A 200 kW PV plant is built by connecting 40 strings in parallel where each string contains 20 modules in a series. The electrical specifications of the PV module is obtained from [21].

The MPPT controller connected to the DC/DC converter of PV always captures the maximum power from a solar cell. MPPT algorithms such as incremental conductance (IC), perturbation and observation (P&O), and constant voltage are the common techniques found in the literature. Among these techniques, the IC algorithm is the simplest and most effective technique that is used widely. The IC algorithm is the fastest in MPPT under rapid weather changing conditions and the power oscillation is negligible at the maximum power point [22]. For this reason, the IC algorithm method is used in this work.

2.3. SOFC Model

The SOFC is a distributed generator (DG) technology that generates power from chemical reactions. The advantages of using SOFC over other fuel cells are long term stability and fuel flexibility; the electrical efficiency of a typical SOFC power plant can reach up to 70% [23]. A grid-connected SOFC developed using PSCAD software is presented in [24]. The output fuel cell stack voltage considering ohmic loss is given by [25],

$$V = No\left[Eo + \frac{RT}{2F}\left(\ln \frac{p_{H_2} p_{O_2}^{0.5}}{p_{H_2O}}\right)\right] - rI_{fc} \quad (5)$$

where,

I_{fc}: fuel cell current;
R: universal gas constant;
T: absolute temperature in kelvin;
P_{H_2}, P_{O_2} and P_{H_2O}: partial pressure of hydrogen, oxygen and water;
r: representation of ohmic loss in ohm;
F: Faraday's constant;
E_o: ideal standard potential;
N_o: number of cells in series in the stack.

The utilization factor and temperature of the stack are critical operating variables of SOFC. The utilization factor is the ratio between fuel consumed to total fuel input and the range of the utilization factor should be 80–90% [26]. For this work, the utilization factor is taken as a constant value of 85% and the operating temperature is kept constant at 1273 K [26]. The parameters of the 100 kW SOFC power plant are obtained from [27].

3. Proposed Operating Strategy of Hybrid System

The hybrid system supplies power at a variable load throughout the day. The power management system coordinates DG output (in this case PV and SOFC) in order to supply the variable load. In this operating strategy, the power from SOFC is regulated to its reference value. To coordinate the PV-SOFC operation, an appropriate reference value must be set to the operating constraints of the DGs. Once the SOFC operating limit is known, the operating strategy depends on load variation and PV output power. When hybrid power supplies the load in grid-connected mode, the power balance equation is given by,

$$P_{PV} + P_{FC} + P_{GRID} = P_{LOAD} \tag{6}$$

Since the power drawn from the grid (P_{GRID}) incurs costs, the P_{GRID} has to be minimized. Therefore the value of P_{GRID} is set to zero.

$$P_{PV} + P_{FC} = P_{LOAD} \tag{7}$$

The operating limit of SOFC output power is given as follows,

$$P_{HYref} = P_{PV} + P_{FCref} \tag{8}$$

In Equation (7), when PV output (P_{PV}) varies, the balance power is compensated by SOFC (P_{FC}). The fuel cell supplies power based on its reference value (P_{FCref}). Therefore, the total power from the hybrid generators is regulated to its reference value (P_{HYref}). The reference of the hybrid system is given by,

$$P_{HYref} = P_{PV} + P_{FCref} \tag{9}$$

Figure 3 shows the operating strategy of a fuel cell when P_{PV} equals zero. The references for fuel cell and hybrid system generation are given in Equations (10) and (11), respectively.

$$P^i_{FCref} = P^i_{Load},\ i = 0,\ 1,\ 2,\ 3,\ \ldots\ n \tag{10}$$

$$P^i_{HYref} = P^0_{PV} + P^i_{FCref},\ i = 0,\ 1,\ 2,\ 3,\ \ldots\ n \tag{11}$$

In the absence of P_{PV} generation, only the fuel cell has to supply power to the varying load. For example, when load demand increases from $P_{Load\,1}$ to $P_{Load\,2}$, the change in the load is assigned as the fuel cell reference set point ($P_{FCref\,2}$). Therefore, the SOFC delivers the required power ($P_{FC\,2}$) following the reference set point. Since the PV is absent, the total power generated from the hybrid source is equal to $P_{FCref\,2}$. In this way, if the load demand reaches the maximum value $P_{Load\,n}$, which is 100 kW, fuel cell generation is also increased to its maximum capacity $P_{FC\max}$ following its reference $P_{FCref\,n}$. For load increment or decrement, the change in P_{FCref} and P_{HYref} is shown in Figure 3. It should be noted that $P_{Load\,0}$ is the load demand equal to or less than 20 kW. Here, the power from the SOFC is fixed at $P_{FC\min}$ i.e., 20 kW.

When P_{PV} is greater than zero, the operating strategy depends on PV output power and load variation. PV power and load variation are time dependent. In the case when PV power is available but less than the load, the SOFC supplies the deficit in power and the power from the grid is maintained at zero in order to reduce the cost for the power drawn from the utility grid. Therefore the target hybrid reference power is given as,

$$P_{HYref}(t) = P_{PV}(t) + P_{FCref}(t) + P_{Grid}(t) \tag{12}$$

where,

$$P_{FCref}(t) = P_{Load}(t) - P_{PV}(t),\ P_{Grid}(t) = 0 \tag{13}$$

In the case where PV power is more than the load, the excess power is injected into the grid where the value will be negative. In this case the fuel cell power P_{FCref} is fixed to a minimum operating point ($P_{FC\min}$), that is, 20 kW in order to avoid the underused condition, as this will lead to unexpected high cell voltages. Then the target reference power is given as,

$$P_{HYref}(t) = P_{PV}(t) + P_{FCref}(t) + P_{Grid}(t) \tag{14}$$

where,

$$P_{FCref}(t) = 20\ \text{kW},\ P_{Grid}(t) = P_{Load}(t) - P_{PV}(t) \tag{15}$$

It should be noted that the P_{FC} is operated taking into consideration the constraint as stated in Equation (8). The complete control algorithm for the power management module is shown in Figure 4.

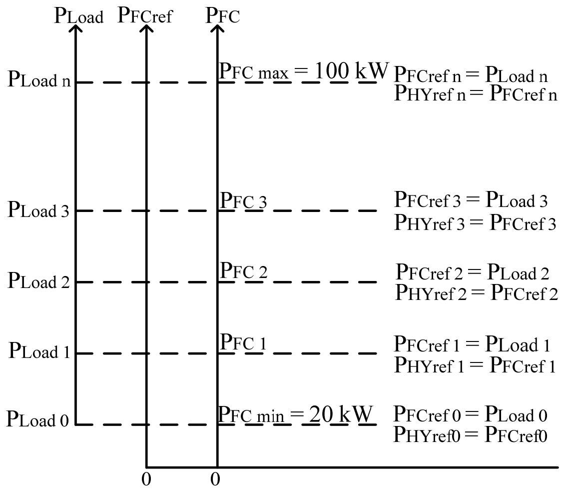


Figure 3. Operating strategy of fuel cell when $P_{PV}{}^0$ = 0.

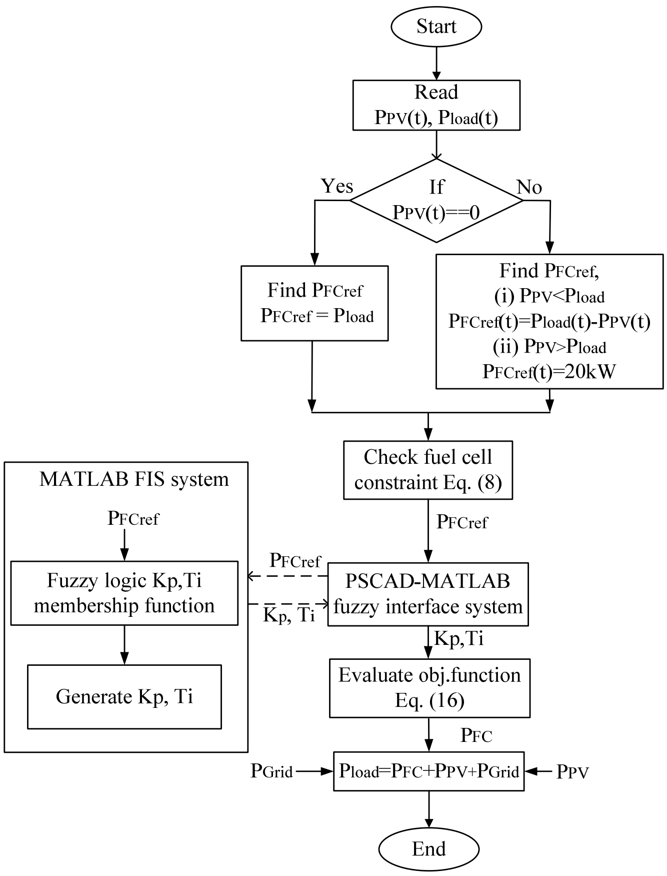


Figure 4. Control algorithm for power management system.

4. Methodology

4.1. Control of SOFC Voltage Source Inverter (VSI)

The voltage and active power flow from the inverter output is regulated by adjusting the modulation index and phase angle of the inverter, respectively. Regulating the inverter terminal voltage determines the reactive power flow as well. During the operating strategy, the fuel cell reference value can be achieved by controlling fuel cell power to the desired level. The PI controller is employed for better dynamic response. In this paper, PI controllers are utilized to generate the modulation index and phase angle. From Figure 5, the active power from the fuel cell output is controlled by controlling its direct sequence component. From the meter installed at the inverter output, the actual output power is calculated and is compared with its reference, which is produced from the power management system. The error signal of the active power is given as the input to the PI controller. The controller generates a reference direct axis component from the error signal and is fed into dq0 to abc transformation block. Finally the control signals for the inverter are generated by the pulse width modulation (PWM) technique.

This work focuses on implementing fuzzy logic to generate appropriate control values for a real power controller where the real power error signal is given as an input to the MATLAB-fuzzy interface system (FIS) system. The FIS system in turn generates the appropriate proportional gain (K_p) and integral time constant (T_i) which are then used as input for the PI controller. Here, the SOFC reference set point (P_{FCref}) is generated from the power management system module.

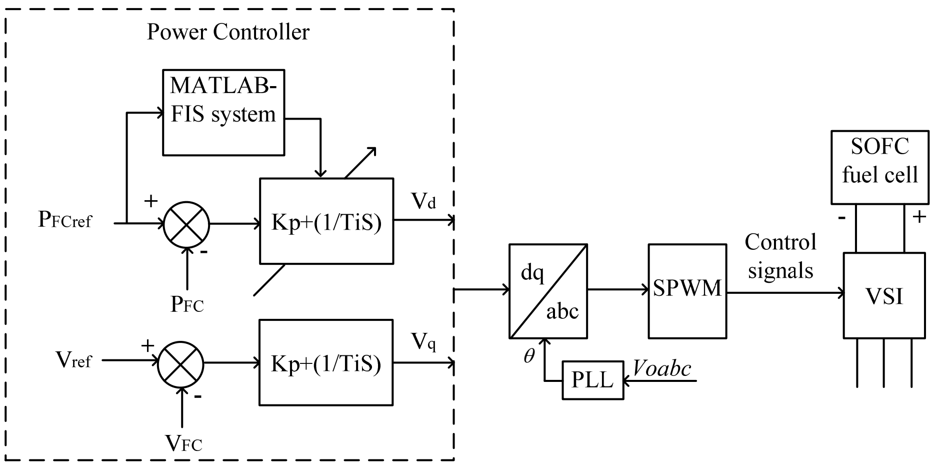


Figure 5. Solid oxide fuel cell (SOFC) active power control.

The PI controller used in the SOFC active power control should be robust in nature when the system is operating under dynamic changes such as PV output and load. Therefore, optimal operation of the PI controller is necessary. The optimal values for the real power controller K_p and T_i is determined using a fuzzy logic controller. For comparison, the GA and simplex method were also used to determine the control parameters of the PI controller. In this work, the controller's objective function is to minimize the error using the ITAE performance criterion. The advantage of using the ITAE performance criterion is that it produces smaller overshoot and oscillations [28]. The mathematical expression for the ITAE criterion is given as:

$$J = \int_{0}^{\infty} (t.|e(t)|).dt \tag{16}$$

where,

t: time;

$e(t)$: the difference between reference power and the actual fuel cell power.

To increase the robustness of the controller, the optimization is performed on all hourly data for the entire day, which means that the ITAE index is optimized for 24 different operating points. Therefore, Equation (14) is rewritten for 24 different operating points. The objective function is given as,

$$J = \sum_{n=0}^{24} \int_{0}^{\infty} (t.|e(t)|).dt, \ n = 0, 1, 2, \ldots 24 \tag{17}$$

4.2. Proposed Fuzzy-Based PI Controller Model

The fuzzy-based PI controller was modeled in the PSCAD environment using the SOFC-fuzzy interface system (FIS). Figure 6 shows a block diagram of the fuzzy-logic-based PI control. A FORTRAN subroutine was written in PSCAD to interface with the MATLAB engine.

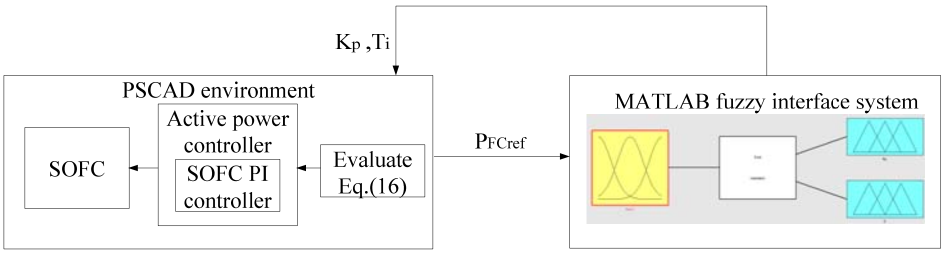
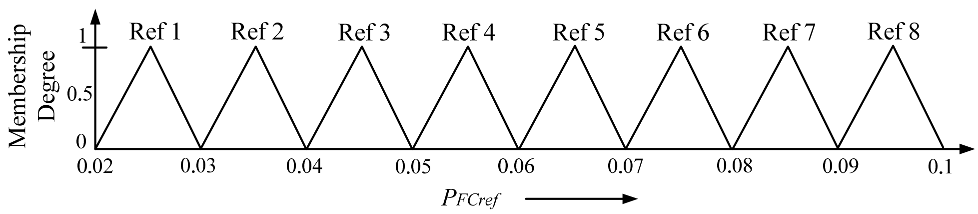
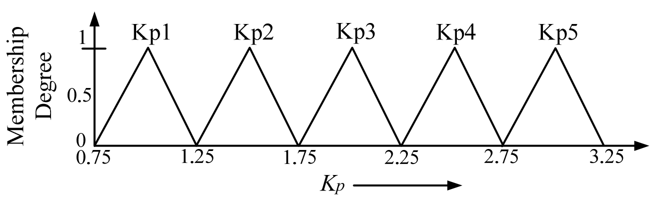


Figure 6. Block diagram for fuzzy-based proportional and integral (PI) control.

The MATLAB-FIS system has one input (P_{FCref}) and two outputs (K_p and T_i). The FIS system receives P_{FCref} as the input signal, and depending on the input signal an appropriate control parameter is sent back to the SOFC active power controller in the PSCAD environment. The FIS system consists of three important steps: (i) fuzzification; (ii) rule base mechanism; and (iii) defuzzification. As a first step, a set of input data (P_{FCref}) are converted into a fuzzy set using a membership function. A membership function is used in the fuzzification and defuzzification process where the set of non-fuzzy inputs is mapped to fuzzy sets. For this work, a triangular membership function was constructed for P_{FCref}, K_p and T_i, given in Figure 7. The linguistic variables of input P_{FCref} are denoted as Ref 1 to Ref 8, shown in Figure 7a. The linguistic variables of the output are indicated as K_{p1} *to* K_{p5} for K_p in Figure 7b and T_{i1} *to* T_{i5} for T_i in Figure 7c, respectively.

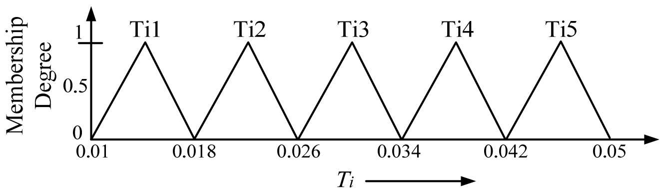


(**a**)



(**b**)

Figure 7. *Cont.*



(**c**)

Figure 7. (**a**–**c**) shows the membership function for P_{FCref}, K_p and T_i, respectively.

A rule-based mechanism was created to find the output variable for the given input. The fuzzy rule constructed for this work is shown in Table 1. The rule-based mechanism has a simple if–then statement with a condition and conclusion.

Table 1. Rules for fuzzy logic controller.

	P_{FCref}							
	Ref 1	**Ref 2**	**Ref 3**	**Ref 4**	**Ref 5**	**Ref 6**	**Ref 7**	**Ref 8**
K_p	K_{p1}	K_{p1}	K_{p2}	K_{p2}	K_{p3}	K_{p3}	K_{p4}	K_{p5}
T_i	T_{i1}	T_{i1}	T_{i2}	T_{i2}	T_{i3}	T_{i3}	T_{i4}	T_{i5}

With the help of the output membership function, the resulting fuzzy set is mapped to its output. The appropriate K_p and T_i from the FIS system is sent back to the PSCAD environment. The advantage of using fuzzy logic is that for any change in the P_{FCref}, a specific value for the PI controller parameters is produced. The methodology proposed in this paper is the design of a fuzzy controller to generate appropriate the real power PI controller control parameters considering ITAE as the performance criterion. The possible limitation of the proposed method is that the fuzzy controller solution is specifically for the ITAE performance criterion. However, the fuzzy controller may provide varying solutions if different performance criteria, such as integral absolute error (IAE), and integral square error (ISE), were used.

On the whole, a power management system for a grid-connected hybrid system consisting of solar PV and SOFC is proposed considering varying loads and solar radiation. In order to operate the SOFC efficiently within a specific power range and to deliver the power set by the reference set point, a fuzzy logic controller is also developed to generate appropriate control parameters for the PI controller. The performance of the controllers is evaluated by the minimizing ITAE criterion for a 24 h time period.

5. Simulation Results

5.1. Optimization of Control Parameters

The objective of the SOFC active power controller is to deliver a power set by the reference (P_{FCref}), which is generated from the power management module. The control parameters of the controller are evaluated using the GA and simplex method. The PSCAD program is equipped with the optimum run search engine module, which enables us to perform successive simulations for a group of parameters. The group of parameters generated by the optimization algorithm is used for simulation program and simultaneously evaluates the objective function given in Equation (14). The GA and simplex method present in the optimum run module were used for this study. A generalized simulation flow for the GA and simplex method is presented in Figure 8. The search is terminated when the stopping criterion is met, that is, when the algorithm completes the maximum number of iterations.

The fuel cell reference set point (P_{FCref}) changes at regular intervals due to changes in load and PV input power. The PI controller parameters are optimized for the SOFC reference set points (P_{FCref}) for every hour. The final optimized values for different fuel cell reference set points are used for the simulation. Therefore the optimal parameters found using the GA or simplex method for different reference set points will be used throughout the simulation. The dynamic change in the controller parameters for the simplex and GA optimization methods for different fuel cell set points are shown in Figures 9 and 10, respectively.

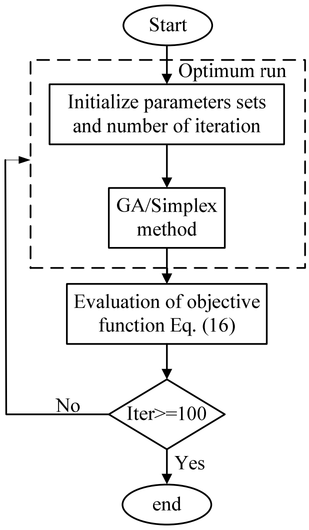


Figure 8. Generalized optimization flow using the optimum run module in PSCAD.

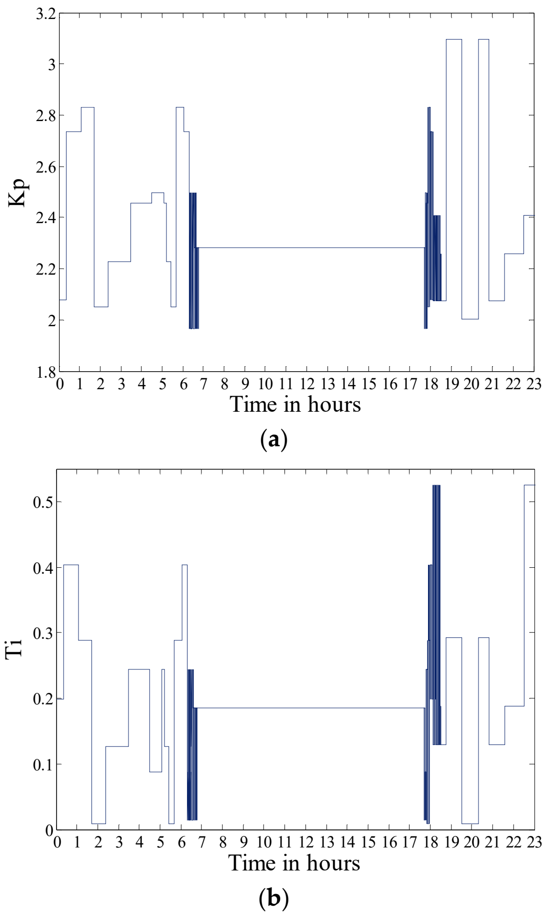
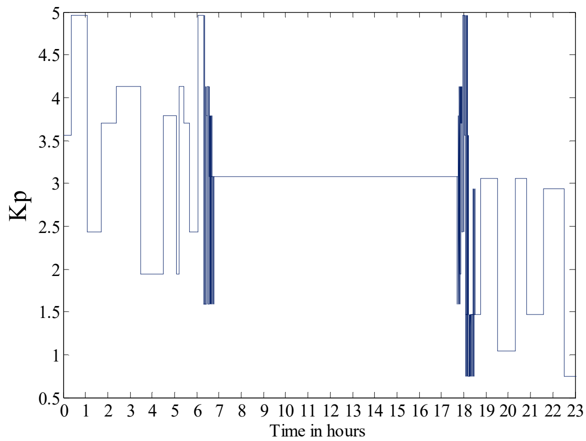
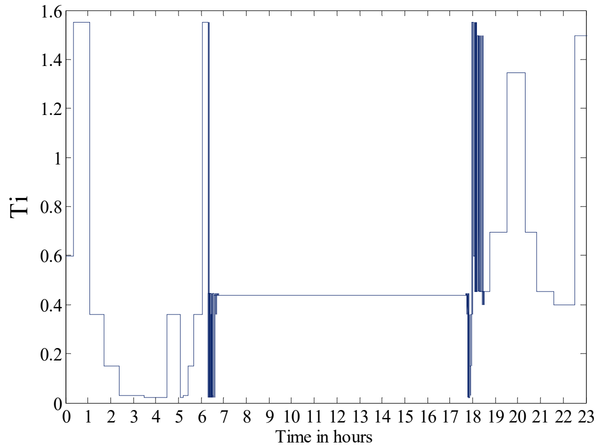


Figure 9. (**a**,**b**) show the variation of K_p and T_i respectively for different fuel cell controller set points using the simplex method.



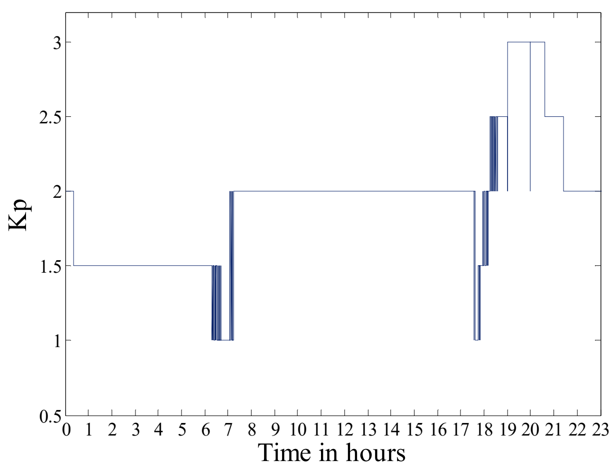
(**a**)



(**b**)

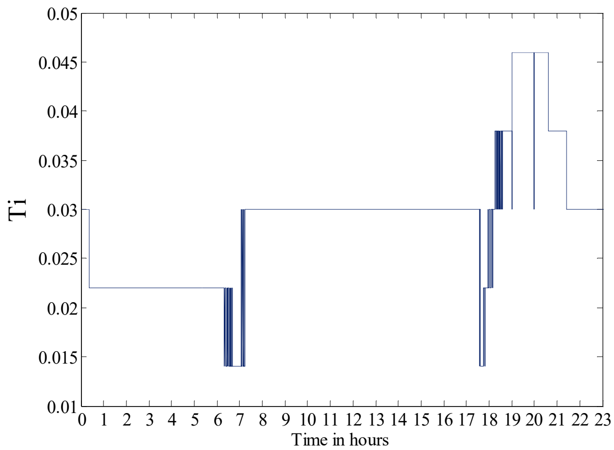
Figure 10. (**a**,**b**) show the variation of K_p and T_i respectively for different fuel cell controller set points using genetic algorithm (GA).

The K_p and T_i generated by the FIS system is shown in Figure 11 for different values of input (P_{FCref}).



(**a**)

Figure 11. *Cont.*



(**b**)

Figure 11. (**a**,**b**) show the variation of K_p and T_i respectively for different fuel cell controller set points using the fuzzy-based PI controller.

The ranges of optimal control parameters for the PI controller were obtained using the GA, simplex method and fuzzy logic system are summarized in Table 2.

Table 2. Optimal K_p and T_i ranges found using the GA, simplex method and fuzzy logic control.

Method	**Control Parameter and Objective Function**		
	K_p	T_i	**ITAE**
GA	0.750–4.958	0.0217–1.550	7844.99311
Simplex	1.966–3.097	0.0087–0.5247	483.79171
PSCAD-MATLAB fuzzy logic control	1–3	0.013–0.047	73.3385

In Table 2, the objective function evaluated for the fuzzy logic controller is lower than the other methods. This proves that that fuzzy-logic-based PI controller is efficient. In addition, the controller's capability to dispatch SOFC power (P_{FC}) matching its reference value (P_{FCref}) can be seen in Figure 12.

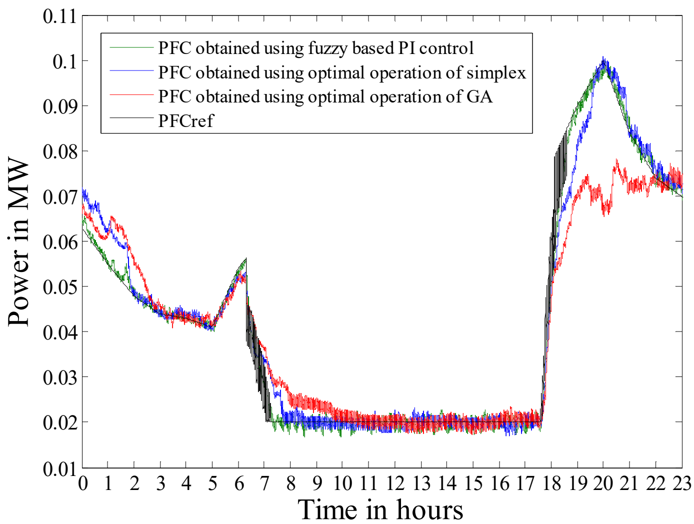


Figure 12. Comparison of SOFC power dispatch (P_{FC}) matching the reference (P_{FCref}) for the controllers.

The SOFC reference set point (P_{FCref}) is dependent on the change in load and PV generation. With reference to Figure 12, it can be seen that during the early morning hours when the PV power is zero, the fuzzy-based PI controller efficiently controls its power supply to the reference value for load changes. It should also be noticed in Figure 12 that the fuel cell reference changes suddenly between 6 a.m. to 7 a.m. due to the sudden increase in load demand from 40 kW to 54 kW, and during this time period the PV power is absent. SOFC controllers tuned by the GA, fuzzy and simplex method were capable of following the SOFC reference set point for the sudden load increase. Between 8 a.m. and 7 p.m. the fuel cell reference is regulated to 20 kW for two reasons (i) during this period PV power is available, and is more than sufficient to supply the varying load demand; and (ii) the fuel cell has to operate within its specific power limit. Between 7 a.m. and 8 a.m. the P_{FCref} is regulated to 20 kW, where the fuzzy controller follows the reference line exactly, but the controllers based on the GA and simplex method take time to settle at the reference value. Further, the fuzzy-based PI controller is more efficient after 7 p.m. that is, after sunset. After sunset, the load demand is taken care of by the SOFC. The fuzzy-based PI controller efficiently dispatches power from the SOFC to its reference value from 7 p.m., thereafter supplying the peak load at 9 p.m. On the other hand, the simplex method and GA-based PI controller was found to be less efficient in following the reference value. The fuzzy-logic-based PI controller's efficiency is tested during the absence of PV power.

Figure 12 shows that the SOFC controlled by a fuzzy-based PI controller is efficient where the fuel cell power (P_{FC}) follows the reference (P_{FCref}). It should be noted that in all the three controller types, the fuel cell is operating within its specific power range.

5.2. Application of Fuzzy-Based PI Controller for Power Management System

The results from the previous section confirmed that the fuzzy-based PI controller for SOFC active power control is more efficient. Therefore, a simulation of the power management system was carried out using the PSCAD-Matlab interface for the fuzzy-based PI controller for SOFC active power control for the hybrid system shown in Figure 1.

Load modeling is one of the important parts of a power system. Load varies throughout the day and in some hours of the day the load reaches its maximum value and/or minimum value. In this work, a variable residential load is modeled with a maximum load demand reaching up to 100 kW. The daily load pattern of a residential area from [29] is used for this work. The load pattern is scaled up to a maximum load demand of 100 kW; see Figure 13.

The simulation results for the power management strategy are shown in Figure 14. Figure 14a describes overall operating strategy of the hybrid system considering changes in load and solar radiation levels. The SOFC supplies power based on its reference value shown in Figure 12. Figure 14b shows the actual power generated from hybrid system which follows the reference.

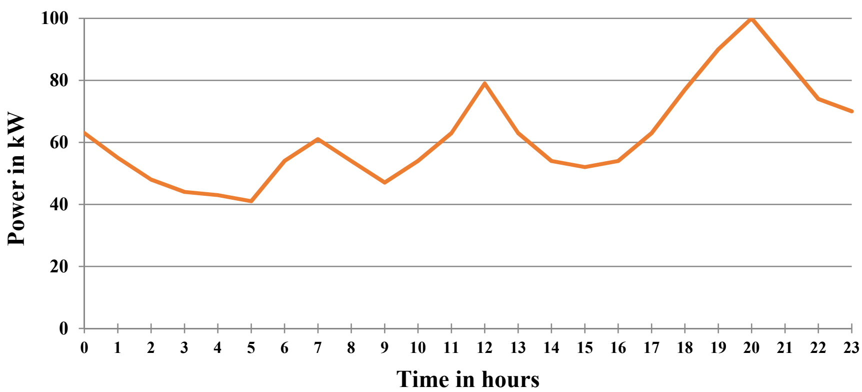


Figure 13. Daily load profile.

From Figure 14a it is clear that the power from the SOFC is well managed during the presence and absence of PV power. When PV power is zero in the early morning hours and after sunset in the evening, any change in the load is supplied by the SOFC. Since PV power is available during the day, it supplies the required power needed by the load. During the day, the excess power generated from the hybrid system is injected into the grid, where the power injection into the grid is indicated in the negative in Figure 14a. If the availability of PV power is less, the power deficit required by the load is taken care of by the SOFC. Here, the reference value for the SOFC is calculated as explained in Section 3 and is generated by the power management module.

During the entire period of operation of the hybrid system, the SOFC power P_{FC} changes based on the reference value P_{FCref} generated by the power management module, at the same time the PV array operates at the maximum power point. In addition, the power imported from the grid is almost zero, which can be established from Figure 14a, where the grid power is zero or negative during the entire operating time. From Figure 12 it is clear that the SOFC is operating within its operating range of 20 kW to 100 kW. With reference to these results, it is clear that the operating strategy is simple and that the fuzzy-based PI controller for SOFC active power control is more efficient.

It should also be noted that apart from the fuel cell, the proposed fuzzy based PI control can be applied to any electronically-interfaced controllable distributed energy source, such as battery energy systems or capacitors.

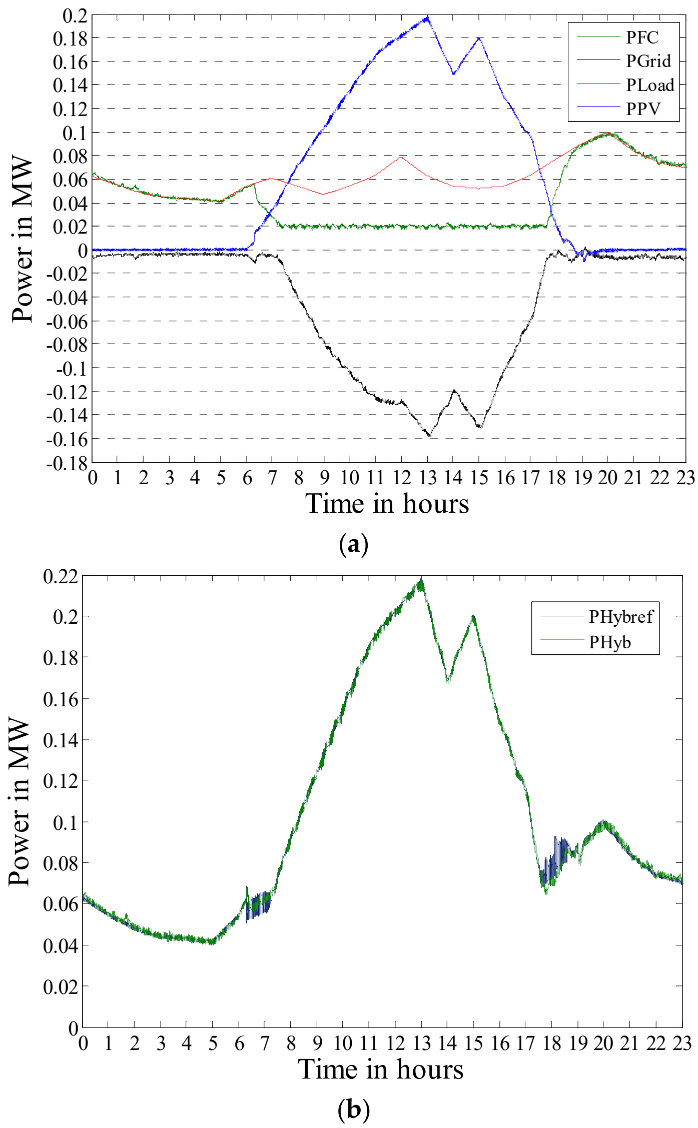


Figure 14. Simulation results of the power management system. (**a**) Overall system operating strategy; (**b**) Hybrid system reference and actual value.

6. Conclusions and Future Work

In this study, a power management strategy for a grid-connected hybrid PV-SOFC system supplying power at varying loads is presented. The optimal control parameters of the PI controller used in SOFC active power control were found using the GA and simplex method. In addition, a PSCAD-Matlab interface fuzzy-based PI controller was also designed to generate the optimal control parameters for changing input.

A comparison between the three methods was performed where the GA and simplex method SOFC active power controllers were found to be less efficient. The fuzzy-logic-based controller ensured that the output power from the SOFC followed the reference value accurately. Using this power management strategy, the following objectives were achieved: (i) the SOFC always operates within a specific power range; and (ii) the power drawn from the grid is zero at all times. Operating the SOFC within its specific operating range increases the efficiency of the fuel cell and also enhances the performance of the system. The hybrid system can increase its generation when the load is heavy and decrease its generation when the load is light. In brief, the grid-connected hybrid system works flexibly with this operating strategy. For further consideration, the proposed fuzzy logic will be implemented for (i) effective real power control of a battery bank; and (ii) voltage and reactive power control of controllable DGs.

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Author Contributions: Hazlie Moklis and Saad Mekhilef conceived and designed the experiments; Shivashankar Sukumar performed the experiments; Marayati Marsadek and Agileswari Ramasamy analyzed the data; Shivashankar Sukumar wrote the paper.

Conflicts of Interest: The authors declare no conflict of interest.

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