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Power-Management Strategies For A Grid-Connected PV-FC Hybrid Systems

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***Abstract*—This paper presents a method to operate a grid connected hybrid system. The hybrid system composed of a Pho- tovoltaic (PV) array and a Proton exchange membrane fuel cell (PEMFC) is considered. The PV array normally uses a maximum power point tracking (MPPT) technique to continuously deliver the highest power to the load when variations in irradiation and temperature occur, which make it become an uncontrollable source. In coordination with PEMFC, the hybrid system output power becomes controllable. Two operation modes, the unit-power control (UPC) mode and the feeder-flow control (FFC) mode, can be applied to the hybrid system. The coordination of two control modes, the coordination of the PV array and the PEMFC in the hybrid system, and the determination of reference parameters are presented. The proposed operating strategy with a flexible operation mode change always operates the PV array at maximum output power and the PEMFC in its high efficiency performance band, thus improving the performance of system operation, en- hancing system stability, and decreasing the number of operating mode changes.**

***Index Terms*—Distributed generation, fuel cell, hybrid system, microgrid, photovoltaic, power management.**

I. INTRODUCTION

Renewable energy is currently widely used. One of these resources is solar energy. The photovoltaic (PV) array normally uses a maximum power point tracking (MPPT) technique to continuously deliver the highest power to the load when there are variations in irradiation and temperature. The disadvantage of PV energy is that the PV output power depends on weather conditions and cell temperature, making it an uncontrollable source. Furthermore, it is not available during the night. In order to overcome these inherent drawbacks, alternative sources, such as PEMFC, should be installed in the hybrid system. By changing the FC output power, the hybrid source output becomes controllable. However, PEMFC, in its turn, $(P_{FC}^{low} \div P_{FC}^{up})$ works only at a high efficiency within a specific power range . The hybrid system can either be connected to the main grid or work autonomously with respect to the grid-connected mode or islanded mode, respectively. In the grid-connected mode, the hybrid source is connected to the main grid at the point of common coupling (PCC) to deliver power to the load. When load demand changes, the power supplied by the main grid and hybrid system must be properly changed.

The power delivered from the main grid and PV array as well as PEMFC must be coordinated to meet load demand. The hybrid source has two control modes: 1) unit-power control (UPC) mode and feeder-flow control (FFC) mode. In the UPC mode, variations of load demand are compensated by the main grid because the hybrid source output is regulated to reference power. Therefore, the reference value of the hybrid source output must be determined. In the FFC mode, the feeder flow is regulated to a constant, the extra load demand is picked up by the hybrid source, and, hence, the feeder reference power must be known. The proposed operating strategy is to coordinate the two control modes and determine the reference values of the UPC mode and FFC mode so that all constraints are satisfied. This operating strategy will minimize the number of operating mode changes, improve performance of the system operation, and enhance system stability.

DISTRIBUTED GENERATION:

Distributed generation, also called on-site generation, dispersed generation, embedded generation, decentralized generation, decentralized energy or distributed energy generates electricity from many small energy sources. Currently, industrial countries generate most of their electricity in large centralized facilities, such as fossil fuel (coal, gas powered) nuclear or hydropower plants. These plants have excellent economies of scale, but usually transmit electricity long distances and negatively affect the environment. Most plants are built this way due to a number of economic, health & safety, logistical. For example, coal power plants are built away from cities to prevent their heavy air pollution from affecting the populace. In addition, such plants are often built near collieries to minimize the cost of transporting coal. Hydroelectric plants are by their nature limited to operating at sites with sufficient water flow. Most power plants are often considered to be too far away for their waste heat to be used for heating buildings. Distributed generation is another approach. It reduces the amount of energy lost in transmitting electricity because the electricity is generated very near where it is used, perhaps even in the same building. This also reduces the size and number of power lines that must be constructed. Typical distributed power sources in a Feed-in Tariff (FIT) scheme have low maintenance, low pollution and high efficiencies. In the past, these traits required dedicated operating engineers and large complex plants to reduce pollution. However, modern embedded systems can provide these traits with automated operation and renewables, such as sunlight, wind and geothermal. This reduces the size of power plant that can show a profit

. DISTRIBUTED ENERGY SYSTEMS

Today, new advances in technology and new directions in electricity regulation encourage a significant increase of distributed generation resources around the world. As shown in Fig. the currently competitive small generation units and the incentive laws to use renewable energies force electric utility companies to construct an increasing number of distributed generation units on its distribution network, instead of large central power plants. Moreover, DES can offer improved service reliability, better economics and a reduced dependence on the local utility. Distributed Generation Systems have mainly been used as a standby power source for critical businesses. For example, most hospitals and office buildings had stand-by diesel generation as an emergency power source for use only during outages. However, the diesel generators were not inherently cost-effective, and produce noise and exhaust that would be objectionable on anything except for an emergency basis.

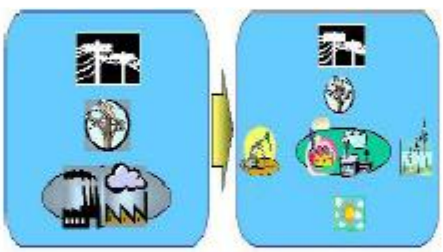

Fig.1large central power plant and distributed energy systems

Meanwhile, recently, the use of Distributed Energy Systems under the 500 kW level is rapidly increasing due to recent technology improvements in small generators, power electronics, and energy storage devices. Efficient clean fossil fuels technologies such as micro-turbines and fuel cells, and environmentally friendly renewable energy technologies such as solar/photo voltaic, small wind and hydro are increasingly used for new distributed generation systems.

PROBLEM STATEMENTS

DES technologies have very different issues compared with traditional centralized power sources. For example, they are applied to the mains or the loads with voltage of 480 volts or less; and require power converters and different strategies of control and dispatch. All of these energy technologies provide a DC output which requires power electronic interfaces with the distribution power networks and its loads. In most cases the conversion is performed by using a voltage source inverter (VSI) with a possibility of pulse width modulation (PWM) that provides fast regulation for voltage magnitude. Power electronic interfaces introduce new control issues, but at the same time, new possibilities. For example, a system which consists of micro-generators and storage devices could be designed to operate in both an autonomous mode and connected to the power grid. One large class of problems is related to the fact that the power sources such as micro turbines and fuel cell have slow response and their inertia is much less. It must be remembered that the current power systems have storage in generators' ine rtia, and this may result in a slight reduction in system frequency. As these generators become more compact, the need to link them to lower network voltage is significantly increasing. However, without any medium voltage networks adaptation, this fast expansion can affect the quality of supply as well as the public and equipment safety because distribution networks have not been designed to connect a significant amount of generation. Therefore, a new voltage control system to facilitate the connection of distributed generation resources to distribution networks should be developed.

In many cases there are also major technical barriers to operating independently in a standalone AC system, or to connecting small generation systems to the electrical distribution network with lower voltage, and the recent research issues includes:

1. Control strategy to facilitate the connection of distributed generation resources to distribution networks.
2. Efficient battery control.
3. Inverter control based on only local information.
4. Synchronization with the utility mains.
5. Compensation of the reactive power and higher harmonic components.
6. Power Factor Correction.
7. System protection.
8. Load sharing.
9. Reliability of communication.
10. Requirements of the customer.

DES offers significant research and engineering challenges in solving these problems. Moreover, the electrical and economic relationships between customers and the distribution utility and among customers may take forms quite distinct from those we know today. For example, rather than devices being individually interconnected in parallel with the grid, they may be grouped with loads in a semi-autonomous neighborhood that could be termed a micro grid is a cluster of small sources, storage systems, and loads which presents itself to the grid as a legitimate single entity. Hence, future research work will focus on solving the above issues so that DES with more advantages compared with tradition large power plants can thrive in electric power industry.

SYSTEM DESCRIPTION

A. Structure of Grid-Connected Hybrid Power System The system consists of a PV-FC hybrid source with the main grid connecting to loads at the PCC as shown in Fig. 2. The photovoltaic [3], [4] and the PEMFC [5], [6] are modelled as nonlinear voltage sources. These sources are connected to dc–dc converters which are coupled at the dc side of a dc/ac inverter. The dc/dc connected to the PV array works as an MPPT controller. Many MPPT algorithms have been proposed in the literature, such as incremental conductance (INC), constant voltage (CV), and perturbation and observation (P&O).

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The P&O method has been widely used because of its simple feedback structure and fewer measured parameters [7]. The P&O algorithm with power feedback control [8]–[10] is shown in Fig. 2. As PV voltage and current are determined, the power is calculated. At the maximum power point, the derivative (dP/dV) is equal to zero. The maximum power point can be achieved by changing the reference voltage by the amount of ΔV_{ref}.

B. PV Array Model

The mathematical model [3], [4] can be expressed as

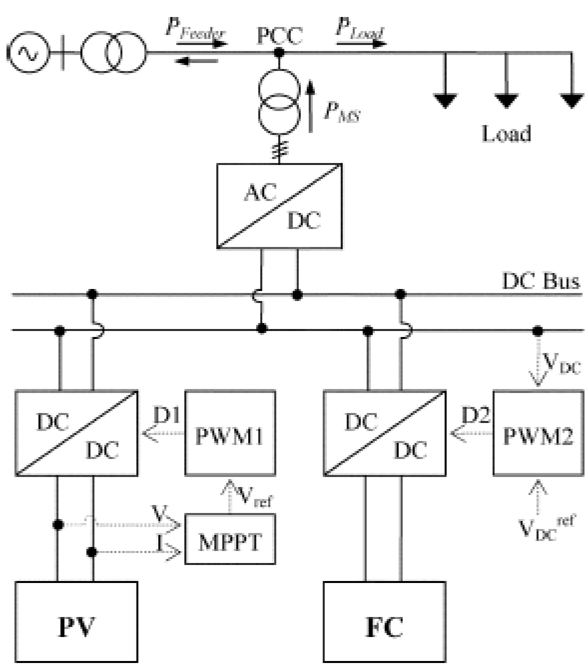
$$I = I_{\mathrm{ph}} - I_{\mathrm{sat}} \left\{ \exp\left[\frac{q}{AKT}(V + IR_s) \right] - 1 \right\}.$$

Above equation shows that the output characteristic of a solar cell is nonlinear and vitally affected by solar radiation, temperature, and load condition. Photocurrent I_{ph} is directly proportional to solar radiation G_a

$$I_{\mathrm{ph}}(G_a) = I_{\mathrm{sc}} \frac{G_a}{G_{\mathrm{as}}}.$$

The short-circuit current of solar cell I_{sc} depends linearly on cell temperature

$$I_{\mathrm{sc}}(T) = I_{scs}[1 + \Delta I_{\mathrm{sc}}(T - T_s)].$$



Fign 3 :Grid-connected PV-FC hybrid system

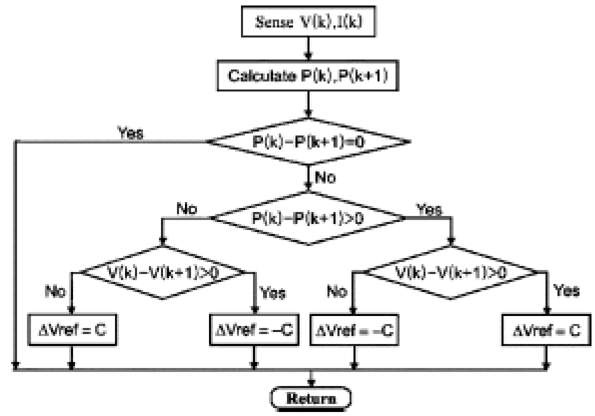


Fig. . P&O MPPT algorithm

Thus, I_{ph} depends on solar irradiance and cell temperature

$$I_{\mathrm{ph}}(G_a, T) = I_{scs} \frac{G_a}{G_{\mathrm{as}}}[1 + \Delta I_{\mathrm{sc}}(T - T_s)].$$

I_{sat} also depends on solar irradiation and cell temperature and can be mathematically expressed as follows:

$$I_{\mathrm{sat}}(G_a, T) = \frac{I_{\mathrm{ph}}(G_a, T)}{e^{\left(\frac{V_{\mathrm{oc}}(T)}{V_{\mathrm{t}}(T)}\right)} - 1}.$$

C. PEMFC Model

The PEMFC steady-state feature of a PEMFC source is assessed by means of a polarization curve, which shows the nonlinear relationship between the voltage and current density. The PEMFC output voltage is as follows [5]:

$$V_{\mathrm{out}} = E_{\mathrm{Nerst}} - V_{\mathrm{act}} - V_{\mathrm{ohm}} - V_{\mathrm{conc}}$$

Where E_{Nerst} is the “thermodynamic potential” of Nerst, which represents the reversible (or open-circuit) voltage of the fuel

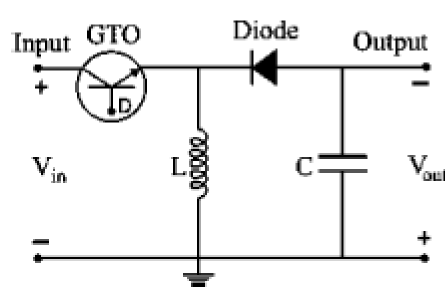


Fig. 4. Buck-boost topology.

cell. Activation voltage drop V_{act} is given in the Tafel equation

$$V_{\mathrm{act}} = T[a + bln(I)]$$

Where a, b are the constant terms in the Tafel equation (in volts per Kelvin)The overall ohmic voltage drop can be expressed as

$$V_{\mathrm{ohm}} = IR_{\mathrm{ohm}}.$$

The ohmic resistance R_{ohm} of PEMFC consists of the resistance of the polymer membrane and electrodes, and the resistances of the electrodes. The concentration voltage drop V_{conc} is expressed as

$$V_{\mathrm{conc}} = -\frac{RT}{zF} ln\left(1 - \frac{I}{I_{\mathrm{limit}}}\right).$$

MPPT Control

Many MPPT algorithms have been proposed in the literature, such as incremental conductance (INC), constant voltage (CV), and perturbation and observation (P&O). The two algorithms often used to achieve maximum power point tracking are the P&O and INC methods. The INC method offers good performance under rapidly changing atmospheric conditions. However, four sensors are required to perform the computations. If the sensors require more conversion time, then the MPPT process will take longer to track the maximum power point. During tracking time, the PV output is less than its maximum power. This means that the longer the conversion time is, the larger amount of power loss [7] will be. On the contrary, if the execution speed of the P&O method increases, then the system loss will decrease. Moreover, this method only requires two sensors, which results in a reduction of hardware requirements and cost. Therefore, the P&O method is used to control the MPPT process..

In order to achieve maximum power, two different applied control methods that are often chosen are voltage-feedback control and power-feedback control [8], [9]. Voltage-feedback control uses the solar-array terminal voltage to control and keep the array operating near its maximum power point by regulating the array's voltage and matching the voltage of the array to desired voltage. The drawback of the voltage-feedback control isits neglect of the effect of irradiation and cell temperature. Therefore, the power-feedback control is used to achieve maximum power .The P&O MPPT algorithm with a power-feedback control [9], information [10] is shown in Fig. 2. As PV voltage and current are determined, the power is calculated. At the maximum power point, the derivative (dP/dV) is equal to zero. The maximum power point can be achieved by changing the reference voltage by the amount of ΔV_{ref}

In order to implement the MPPT algorithm, a buck-boost dc/dc converter is used as depicted in Fig. 3.

The parameters L and C in the buck-boost converter must satisfy the following conditions [11

$$L > \frac{(1-D)^2 R}{2f} \quad ; \quad C > \frac{D}{Rf(\Delta V/V_{\mathrm{out}})}.$$

The buck-boost converter consists of one switching device (GTO) that enables it to turn on and off depending on the applied gate signal D . The gate signal for the GTO can be obtained by comparing the saw tooth waveform with the control voltage [7]. The change of the reference voltage ΔV_{ref} obtained by MPPT algorithm becomes the input of the pulse width modulation (PWM). The PWM generates a gate signal to control the buck-boost converter and, thus, maximum power is tracked and delivered to the ac side via a dc/ac inv

CONTROL OF THE HYBRID SYSTEM

The control modes in the micro grid include unit power control, feeder flow control, and mixed control mode. The two control modes were first proposed by Lasserter [12]. In the UPC mode, the DGs (the hybrid source in this system) regulate the voltage magnitude at the connection point and the power that source is injecting. In this mode if a load increases anywhere in the micro grid, the extra power comes from the grid, since the hybrid source regulates to a constant power. In the FFC mode, the DGs regulate the voltage magnitude at the connection point and the power that is flowing in the feeder at connection point . With this control mode, extra load demands are picked up by the DGs, which maintain a constant load from the utility viewpoint. In the mixed control mode, the same DG could control either its output power or the feeder flow power. In other words, the mixed control mode is a coordination of the UPC mode and the FFC mode. Both of these concepts were considered in [13]–[16]. In this paper, a coordination of the UPC mode and the FFC mode was investigated to determine when each of the two control modes was applied and to determine a reference value for each mode. Moreover, in the hybrid system, the PV and PEMFC sources have their constraints. Therefore, the reference power must be set at an appropriate value so that the constraints of these sources are satisfied. The proposed operation strategy presented in the next section is also based on the minimization of mode change. This proposed operating strategy will be able to improve performance of the system's operation and enhance system stability.

B. Overall Operating Strategy for the Grid-Connected Hybrid System

It is well known that in the microgrid, each DG as well as the hybrid source has two control modes: 1) the UPC mode and 2) the FFC mode. In the aforementioned subsection, a method to determine $P_{\mathrm{MS}}^{\mathrm{ref}}$ in the UPC mode is proposed. In this subsection, an operating strategy is presented to coordinate the two control modes. The purpose of the algorithm is to decide when each control mode is applied and to determine the reference value of the feeder flow when the FFC mode is used. This operating strategy
must enable the PV to work at its maximum power point, FC

output, and feeder flow to satisfy their constraints. If the hybrid source works in the UPC mode, the hybrid output is regulated to a reference value and the variations in load are matched by feeder power. With the reference power proposed Subsection A, the constraints of FC and PV are always satisfied. Therefore, only the constraint of feeder flow is considered. On the other hand, when the hybrid works in the FFC mode, the feeder flow is controlled to a reference value $P_{\text{feeder}}^{\text{ref}}$

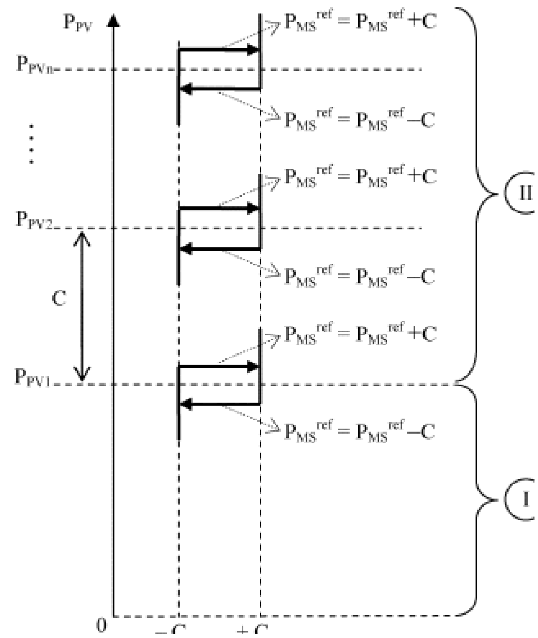


Fig. 6: Hysteresis control scheme for □ control

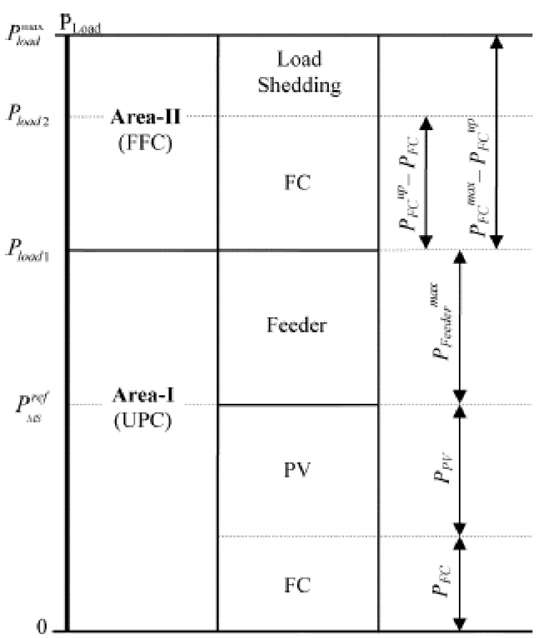


Fig. 7. Overall operating strategy for the grid-connected hybrid system.

and, thus, the hybrid source will compensate for the load variations.

In this case, all constraints must be considered in the operating algorithm. Based on those analyses, the operating strategy of the system is proposed as demonstrated in Fig. 7. The operation algorithm in Fig. 7 involves two areas (Area Iand Area II) and the control mode depends on the load power. If load is in Area I, the UPC mode is selected. Otherwise, the FFC mode is applied with respect to Area II. In the UPC area, the hybrid source output is . If the load is lower than , the redundant power will be transmitted to the main grid. Otherwise, the main grid will send power to the load side to match load demand. When load increases, the feeder flow will increase correspondingly. If feeder flow increases to its maximum , then the feeder flow cannot meet load demand if the load keeps increasing. In order to compensate for the load demand, the control mode must be changed to FFC with respect to Area II. Thus, the boundary between Area I and Area

$$P_{\text{Load1}} = P_{\text{Feeder}}^{\max} + P_{\text{MS}}^{\text{ref}}.$$

When the mode changes to FFC, the feeder flow reference must be determined. In order for the system operation to be seamless, the feeder flow should be unchanged during control mode transition. Accordingly, when the feeder flow reference is set at $P_{\text{feeder}}^{\max}$, then we haveconference on computer as a tool,

$$P_{\text{Feeder}}^{\text{ref}} = P_{\text{Feeder}}^{\max}.$$

In the FFC area, the variation in load is matched by the hybrid source. In other words, the changes in load and PV output are compensated for by PEMFC power. If the FC output increases to its upper limit and the load is higher than the total generating power, then load shedding will occur. The limit that load shedding

$$P_{\text{Load2}} = P_{\text{FC}}^{\text{up}} + P_{\text{Feeder}}^{\max} + P_{\text{PV}}.$$

Equation (25) shows that P_{load2} is minimal when PV output is at 0 kW. Then

$$P_{\text{Load2}}^{\min} = P_{\text{FC}}^{\text{up}} + P_{\text{Feeder}}^{\max}.$$

From the beginning, FC has always worked in the high efficiency band and FC output has been less than $P_{\text{FC}}^{\text{up}}$. If the load is less than , $P_{\text{load2}}^{\min}$ load shedding is ensured not to occur. However, in severe conditions, FC should mobilize its availability, $P_{\text{FC}}^{\max}$, to supply the load. Thus, the load can be higher and the largest load is

$$P_{\text{Load}}^{\max} = P_{\text{FC}}^{\max} + P_{\text{Feeder}}^{\max}.$$

,

If FC power and load demand satisfy (27), load shedding will never occur. Accordingly, based on load forecast, the installed power of FC can be determined by following (27) to avoid load shedding. Corresponding to the FC installed power, the width of Area II is calculated as follows

$$P_{\text{Area-II}} = P_{\text{FC}}^{\max} - P_{\text{FC}}^{\text{up}}.$$

In order for the system to work more stably, the number of mode changes should be decreased. As seen in Fig. 7, the limit changing the mode from UPC to FFC P_{Load1} is , which is calculated in (23). Equation (23) shows that depends on $P_{\text{Feeder}}^{\max}$ and $P_{\text{MS}}^{\text{ref}}$, $P_{\text{Feeder}}^{\max}$. is a constant, thus depends on $P_{\text{MS}}^{\text{ref}}$. Fig. 4 shows that in Area 2 $P_{\text{MS}}^{\text{ref}}$ depends on ΔP_{MS}. Therefore, to decrease the number of mode changes, changes $P_{\text{MS}}^{\text{ref}}$

TABLE I
SYSTEM PARAMETERS

Parameter	Value	Unit
P_{FC}^{low}	0.01	MW
P_{FC}^{up}	0.07	MW
P_{Feeder}^{max}	0.01	MW
ΔP_{MS}	0.03	MW

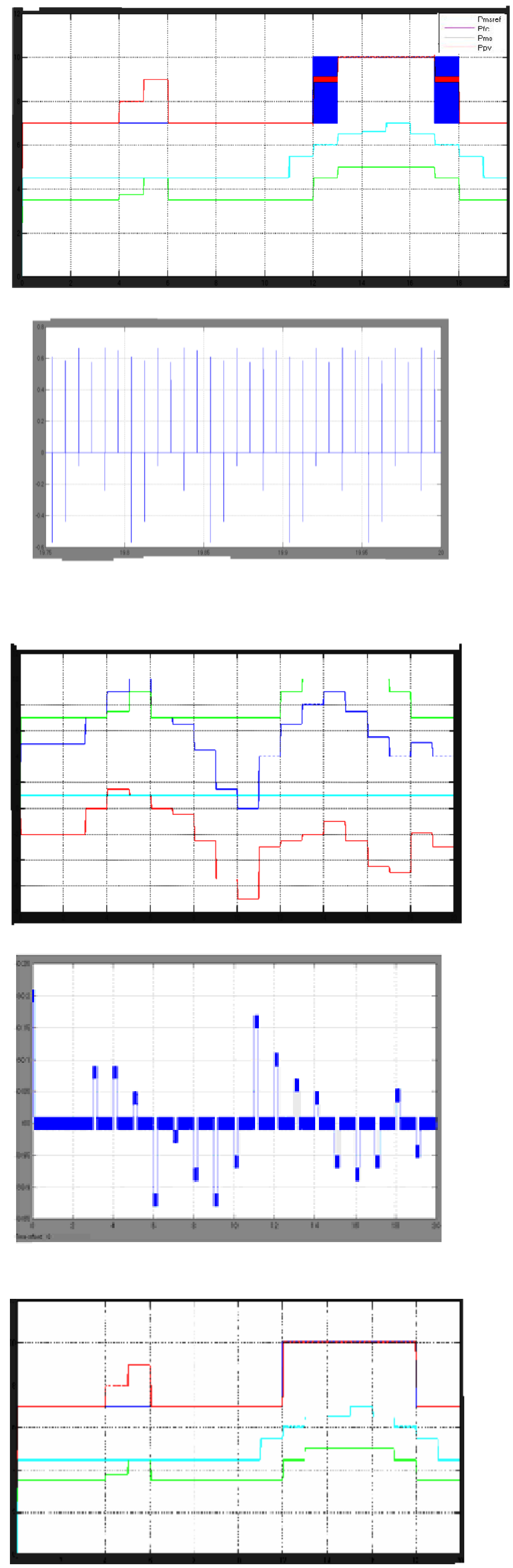
Simulation Results

A simulation was carried out by using the system model shown in Fig. 2 to verify the operating strategies. The system parameters are shown in Table I. In order to verify the operating strategy, the load demand and PV output were time varied in terms of step. According to the load demand and the change of PV output P_{FC}, $P_{\text{MS}}^{\text{ref}}$, $P_{\text{Feeder}}^{\text{ref}}$ and the operating mode were determined by the proposed operating algorithm. Fig. 8 shows the simulation results of the system operating strategy. The changes of P_{PV} and P_{Load} are shown in Fig. 8(a) (line) and Fig. 8(b) (, line), respectively. Based on P_{PV} and the constraints of P_{FC} shown in Table I, the reference value of the hybrid source output $P_{\text{MS}}^{\text{ref}}$ is determined as depicted in Fig. 8(a) (o line). From 0 s to 10 s, the PV operates at standard test conditions to generate constant power and, thus $P_{\text{MS}}^{\text{ref}}$, is constant. From 10 s to 20 s, P_{PV} changes step by step and, thus, $P_{\text{MS}}^{\text{ref}}$ is defined as the algorithm shown in Fig. 4 or 5. The PEMFC ouput P_{FC}, as shown in Fig. 8(a) (line), changes according to the change of P_{PV} and. P_{MS} Fig. 8(c) shows the system operating mode. The UPC mode and FFC mode correspond to values 0 and 1, respectively

.

Fig 8 :simulation out put with out hysteresis (a)operating strategy of whole system (b) change of operating modes(c) operating strategy of whole system with hysteresis(d) change of operating modes with hysteresis The operating strategy of the hybrid source

Fig:(a),(b),(c),(d)&(e)



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CONCLUSION

This paper has presented an available method to operate a hybrid grid-connected system. The hybrid system, composed of a PV array and PEMFC, was considered. The operating strategy of the system is based on the UPC mode and FFC mode. The purposes of the proposed operating strategy presented in this paper are to determine the control mode, to minimize the number of mode changes, to operate PV at the maximum power point, and to operate the FC output in its high-efficiency performance band. The main operating strategy, shown in Fig. 7, is to specify the control mode; the algorithm shown in Fig. 4 is to determine in the UPC mode .With the operating algorithm, PV always operates at maximum output power, PEMFC operates within the high-efficiency range $(P_{FC}^{low} \div P_{FC}^{up})$, and feeder power flow is always less than its maximum value (P_{Feeder}^{max}). The change of the operating mode depends on the current load demand, the PV output, and the constraints of PEMFC and feeder power. With the proposed operating algorithm, the system works flexibly, exploiting maximum solar energy; PEMFC works within a high-efficiency band and, hence, improves the performance of the system's operation. The system can maximize the generated power when load is heavy and minimizes the load shedding area. When load is light, the UPC mode is selected and, thus, the hybrid source works more stably.

The changes in operating mode only occur when the load demand is at the boundary of mode change ; otherwise, the operating mode is either UPC mode or FFC mode. Besides, the variation of hybrid source reference power is eliminated by means of hysteresis. In addition, the number of mode changes is reduced. As a consequence, the system works more stably due to the minimization of mode changes and reference value variation. In brief, the proposed operating algorithm is a simplified and flexible method to operate a hybrid source in a grid-connected microgrid. It can improve the performance of the system's operation; the system works more stably while maximizing the PV output power. For further research, the operating algorithm, taking the operation of the battery into account to enhance operation performance of the system, will be considered. Moreover, the application of the operating algorithm to a microgrid with multiple feeders and DGs will also be studied in detail.

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