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Electric Power Management for a Grid Connected Renewable Energy Sources

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ABSTRACT
Operation of a grid connected hybrid system for renewable energy sources has been presented. The hybrid system composed of a photovoltaic (PV) array and a proton exchange membrane fuel cell (PEMFC) is considered. The operation modes used in the hybrid system are unit-power control (UPC) and the feeder-flow control (FFC) modes. In the UPC mode, variations of load demand are compensated by the main grid because the hybrid source output is regulated to reference power. Renewable energy is currently widely used because fossils are known to endanger the environment. 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 temperature. The disadvantage of PV energy is that the PV output power depends on weather conditions and cell irradiation and temperature, making it an uncontrollable source. Moreover, the sun is not available during the night. In order to overcome these inherent drawbacks, alternative sources, such as PEMFC in the hybrid system are used. By changing FC output power, the hybrid source output becomes controllable. Therefore, the reference value of the hybrid source output is 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. Thus the hybrid system can maximize the generated power when load is heavy and minimizes the load shedding area.

Key Words: *Fuel cell, hybrid system, micro grid, photovoltaic, unit power control, power management.*

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I. INTRODUCTION

Although the conventional fossil fuel energy sources meet most of the world's energy demand today, they are being depleted rapidly and are not renewable. In addition, their combustion products are causing the greenhouse effect and pollution which are posing great danger to our environment and eventually endangering the entire planet. The renewable energy sources (solar, wind, tidal, plasma-wte, geothermal etc.) are gaining more attention as alternative energy sources. Among the renewable energy sources, the photovoltaic (PV) energy has been widely utilized in low power applications. It is also the most promising candidate for research and development for large scale users as the fabrication of low cost PV devices become a reality.

Photovoltaic generators which directly convert solar radiation into electricity have a lot of significant advantages such as being inexhaustible and pollution free, silent, with no rotating parts, and with size-independent electric conversion efficiency. Due to harmless environmental effect of PV generators, they are replacing electricity generated by other polluting methods and even more popular for electricity generation in rural areas. With increasing penetration of solar photovoltaic devices, various anti-pollution apparatus can be operated by solar PV power. From an operational point of view, a PV power generation experiences large variations in its output power due to intermittent weather conditions. Those phenomena may cause operational problems at the power station, such as excessive frequency deviations. In many regions of the world, the fluctuating nature of solar radiation means that purely PV power generators for off grid applications must be large and thus expensive. One method to overcome this problem is to integrate the photovoltaic plant with other power sources such as diesel, fuel cell (FC), or battery back-up.

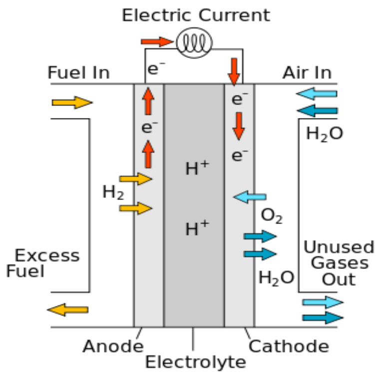


Fig. 1.0 Scheme of a proton-conducting fuel cell

A fuel cell is a device that converts the chemical energy from a fuel into electricity through a chemical reaction of positively charged hydrogen ions with oxygen or another oxidizing agent.[1]. Fuel cells are different from batteries in that they require a continuous source of fuel and oxygen or air to sustain the chemical reaction. Fuel cells can produce electricity continuously for as long as these inputs are supplied. There are many types of fuel cells, but they all consist of an anode, a cathode and an electrolyte that allow positively charged hydrogen ions (or protons) to move between the two sides of the fuel cell, Fig. 1. The anode and cathode contain catalysts that cause the fuel to undergo oxidation reactions that generate positive hydrogen ions and electrons. The hydrogen ions are drawn through the electrolyte after the reaction. At the same time, electrons are drawn from the anode to the cathode through an external circuit, producing direct current electricity. Individual fuel cells produce relatively small electrical potentials, about 0.7 volts, so cells are "stacked", or placed in series, to create sufficient voltage to meet an application's requirements [2]. The fuel cell market is growing, and Pike Research has estimated that the stationary fuel cell market will reach 50 GW by 2020.[3].
The fuel cell back-up power supply is a very attractive option to be used with an intermittent power generation source like PV power because the fuel cell power system is characterized with many attractive features, such as efficiency, fast load-response, modular production and fuel flexibility, [13]. Its feasibility in co-ordination with a PV system has been successfully realized for both grid-connected and stand-alone power applications, [15]. Due to the fast responding capability of the fuel cell power system, [16], a photovoltaic-fuel cell (PV-FC) hybrid systemmay be able to solve the photovoltaic inherent problem of intermittent power generation. Environmental impacts of the fuel cell power generation are relatively small in contrast to other fossil fuel power sources. Since chemical reactions inside the fuel cell stack are accomplished by catalysts, it requires a low sulphur-content fuel. Low-emission characteristics of the fuel cell power system may allow some utilities to offset the costs of installing additional emission control equipment.

II. POWER MANAGEMENT FOR DISTRIBUTED GENERATION

Distributed generation (DG), also called On-site generation, Dispersed generation, Embedded generation, decentralized generation or Distributed energy resource (DER) systems are small-scale power generation or storage technologies (typically in the range of 1 kW to 10,000 kW)[9] used to provide an alternative to or an enhancement of the traditional electric power system. DER systems typically are characterized by high initial capital costs per kilowatt [10]. DER systems also serve as storage device and are often called Distributed energy storage systems (DESS) [11], [12], and generates electricity from many small energy sources.
Today, new advances in technology and new directions in electricity regulation encourage a significant increase of distributed energy resources around the world, [4]. 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, [5]. 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 pollution. Fuel cells are also well used for distributed generation applications, and can essentially be described as batteries which never become discharged as long as hydrogen and oxygen are continuously provided. The hydrogen can be supplied directly, or producedfrom natural gas, or liquid fuels such as alcohols, or gasoline. Each unit ranges in size from 1 – 10,000 KW or larger MW size, [6]. Even if they offer high efficiency and low emissions, today's costs are high. Phosphoric acid cell are commercially available in the range of the 200 kW, while solid oxide and molten carbonate cells are in a pre-commercial stage of

development. The polymer electrolyte membrane (PEM) fuel cells are available in the range of greater than 200 KW. A Distributed Energy Resource (DER) unit includes a Distributed Generation (DG) unit, a Distributed Storage (DS) unit, or a hybrid of DG and DS units, [4], [5].
Micro-grids are modern, localized, small-scale grids, contrary to the traditional, centralized electricity grid (macro-grid). Micro-grids can disconnect from the centralized grid and operate autonomously, strengthen grid resilience and help mitigate grid disturbances, [8]. They are typically low-voltage AC grids, often use diesel generators, and are installed by the community they serve. Micro-grids increasingly employ a mixture of different distributed energy resources, such as solar hybrid power systems, which reduce the amount of emitted carbon significantly. 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, [7]. A Power Management System (PMS) assigns references for real and reactive power components of DER units within a micro-grid to:

Share real/reactive-power among DER units,
Rapidly respond to small-signal and large-signal disturbances,
Determine final operating conditions of DER units to balance power and restore
micro-grid frequency,
Assist in re-synchronization of an autonomous micro-grid to the main grid.

III. GRID CONNECTED PV-FC HYBRID SYSTEM COMPONENTS

In hybrid power systems, a number of power generators and storage components are combined to meet the energy demand of remote or rural area, or even a whole community, [6]. In addition to PV generators, diesel generators, wind generators, small hydro plants and plasma wte plants; other sources of electrical energy can be added as needed to meet the energy demand in a way that fits the local geography and other specifics. Before developing a hybrid electric system for a specific site, it is essential to know the particular energy demand and the resources available at that site.
In this section, a brief technical description of some different hybrid power system configurations is considered. It also includes notes about hybrid power system topologies, modularization, and standardization. In order to meet the over load conditions the hybrid systems are the best choice. These hybrid systems are interconnecting with conventional grid at the point of common coupling through dc-ac inverters. The first hybridization step is taken by adding a PV generator or a wind turbine generator to such conventional power generation systems, but the disadvantage of PV energy is that the PV output power depends on weather conditions and cell temperature, making it an uncontrollable source and it is not available during the night times. Furthermore wind energy is also an uncontrollable source.
In order to overcome these inherent drawbacks, alternative sources, such as fuel cell should be installed in the hybrid system. By changing the FC output power, the hybrid source output becomes controllable. As the power has to be supplied continuously, these generators must run continuously to meet any instantaneous deficit caused by load increase or renewable resource fluctuations. Moreover integration of a storage medium enhances the renewable energy usability. The diesel generator in this system is replaced by a fuel cell system. The fuel cell system is used as a back-up generator, when the batteries reach the minimum allowable charging level and the load exceeds the power produced by the PV generator. A significant advantage of the fuel cell as a back-up generator over the diesel or petrol generator is the high conversion efficiency of the fuel cell. Whereas a 1kW diesel generator achieves total efficiencies between 8-15%, a similar fuel cell system can achieve up to 50% efficiency when operated with H_2 and O_2. The system consists of a PV-FC hybrid source with the main grid connecting to loads at the point of common coupling (PCC) as shown in Fig. 1.1.

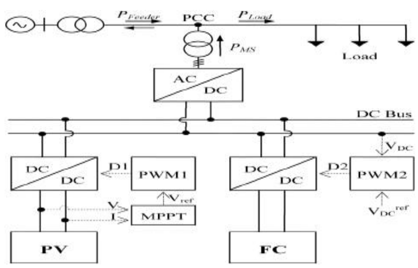


Fig.1.1 Grid-connected PV-FC hybrid system

The system consists of photovoltaic cell and the photo exchange membrane fuel cell (PEMFC) 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 a maximum power point tracking (MPPT) controller. In this

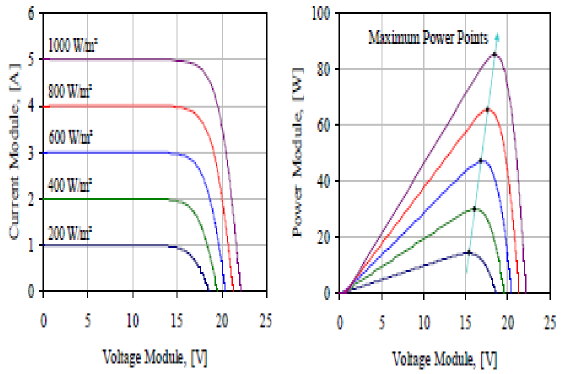
section, a brief description of the system components will be given to make the grid connected PV-FC hybrid system easy to understand.
Photovoltaic power generation employs solar panels composed of a number of cells containing a photovoltaic material. The basic material for almost all the photovoltaic cells existing in the market, high purified silicon (Si), is obtained from sand or quartz. Materials presently used for photovoltaic include mono-crystalline silicon, polycrystalline silicon, amorphous silicon, cadmium telluride, and copper indium selenite/sulphide. The crystalline-Si technology is commonly used as a reference, or baseline, for the solar power generation technology. Due to the growing demand for renewable energy sources, manufacturing of solar cells and photovoltaic arrays have advanced considerably in recent years.

3.1.IV Characteristics of a Photovoltaic Module

The performance characteristics of a photovoltaic module depend on its basic materials, manufacturing technology and operating conditions. Figure 2 shows typical current-voltage (I-V) and power-voltage (P-V) curves of a BP 585 High Efficiency Mono-crystalline Photovoltaic Module according to the variation of solar radiation level and cell temperature. Three points in these curves are of particular interest:
1. Short circuit point, where the voltage over the module is zero and the current is at its maximum (short circuit current Isc).
2. Maximum power point or MPP, where the product of current and voltage has its maximum (defined by (Impp * Vmpp).
3. Open circuit point, where the current is zero and the voltage has its maximum (open circuit voltage Voc).
The measurements taken for obtaining an I-V curve depend on controlling the load current. At open circuit, when no load current is generated, a first characteristic value can be measured; the open circuit voltage Voc. Decreasing the load fed by the photovoltaic module leads to a decreasing voltage V with an increasing current I. In other words, by increasing the load current from zero to its maximum value, the operating point moves from the open circuit voltage at zero current to the short circuit current Isc at zero voltage. The series of all measured pairs (V, I) yields the characteristic I-V curve of the module.

3.2. MAXIMUM POWER POINT TRACKING (MPPT)

The position of the maximum power points on the PV generator characteristic depends strongly on the solar radiation and the cells temperature, as shown in Fig. 2.
It is used to adjust the actual operating voltage and current of the PV generator so that the actual power approaches the optimum value as closely as possible.
Operation of the PV generator at its MPPT involves matching the impedance of the load to that of the generator. For this purpose, an electronic device, normally a power conditioning unit, capable of performing the function of a MPPT has to be connected between PV generator and the load. Therefore, a tracking of the MPP is only meaningful, if components for processing are available and the tracking of the working point does not bring additional energy losses and at small additional costs.



(a) Influence of solar radiation (cell temperature T_j = 25°C)

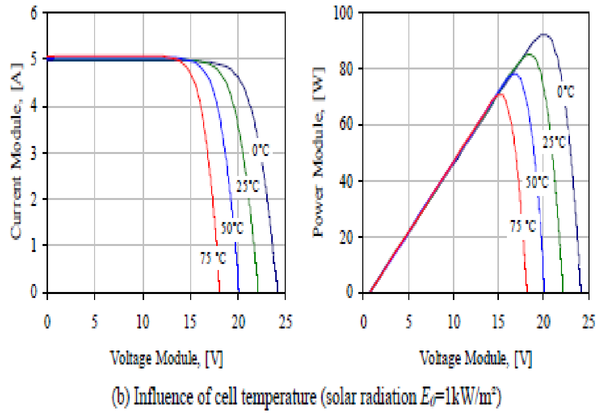


Fig.2.I-V Characteristics of Monocrystalline PV Module

MPPT controller algorithm

Many MPPT direct method algorithms have been proposed in the literature, such as incremental conductance (INC), constant voltage (CV), and perturbation and observation (P&O), Gradient descent method, Multi-unit Optimization Method with Identical Units. The P&O method has been widely used because of its simple feedback structure and fewer measured parameters. P&O algorithm is widely used in MPPT because of their simple structure and high reliability. They operate by periodically perturbing & incrementing & decrementing the array terminal voltage and comparing the PV output power with that of the previous perturbation cycle. If the power is increasing, the perturbation will continue in the same direction in the next cycle, otherwise the perturbation direction will be reversed. This means the array terminal voltage is perturbed for every MPPT cycle. Therefore, when the optimum power is reached, the P&O algorithm will oscillate around it, resulting in a loss of PV power, especially in cases of constant or slowly varying atmospheric conditions. The flow chart of the implemented algorithm is shown in Figure.3.

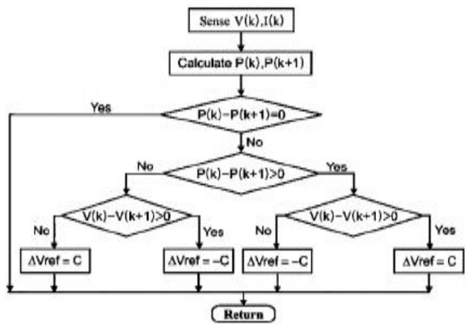


Fig. 3.0 P&O MPPT flow chart

The algorithm reads the value of current and voltage from the solar PV module. Power is calculated from the measured voltage and current. The value of voltage and power at k^{th} instant are stored. Then next values at $(k+1)^{th}$ instant are measured again and power is calculated from the measured values. The power and voltage at $(k+1)^{th}$ instant are subtracted with the values from k^{th} instant. In the power voltage curve of the solar PV module, it is inferred that in the right hand side curve where the voltage is almost constant and the slope of power voltage is negative ($dP/dV<0$) whereas in the left hand side, the slope is positive, ($dP/dV>0$).Therefore the right side of the curve is for the lower duty cycle(nearer to zero) whereas the left side curve is for the higher duty cycle(nearer to unity).

3.2 Design of Buck-Boost Converter

The buck-boost converter consists of one switching device (GTO) that enables it to turn on and off depending on the applied gate signal. The gate signal for the GTO can be obtained by comparing the saw tooth waveform with the control voltage. The change of the reference voltage 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 point is tracked and delivered to the AC side via a DC/AC inverter.

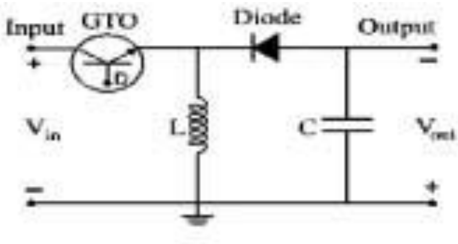


Fig. 4.0 BuckBoost converter

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

$$L > \frac{(1 - D)2R}{2f} \qquad C > \frac{D}{Rf(\Delta V/Vo)} \quad \ldots\ldots \quad (3.1)$$

WhereD is Duty cycle, f is Switching frequency, R isGas constant, 8.3143 J/(mol.K) and ΔV/Vo is voltage repples.

IV. OPERATIONS OF THE HYBRID SYSTEM

T he control modes in the micro grid include unit power control (UPC), feeder flow control (FFC), and mixed control mode. The two control modes were first proposed by [10]. 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.

As mentioned before, the purpose of the operating algorithm is to determine the control mode of the hybrid source and the reference value for each control mode so that the PV is able to work at maximum output power and the constraints (PEMFC lower limit of high efficiency band P^{L}_{FC}, PEMF Cupper limit of high efficiency band, P^{U}_{FC} and Feeder maximum power, P^{M}_{F}) are fulfilled. Once the constraints are known, the control mode of the hybrid source (UPC mode and FFC mode) depends on load variations and the PV output.

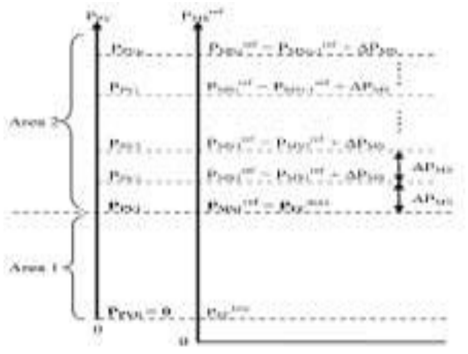


Fig. 5.0 Operation strategy of hybrid source in the UPC mode

4.1.OPERATING STRATEGY FOR THE HYBRID SYSTEM IN THE UPC MODE

Herewe determinehow the hybrid source works in the UPC mode. This algorithm allows the Photovoltaic(**PV**) towork at its maximum power point, and the FC to work within its high efficiency band. In the UPC mode, the Hybrid source reference power, $\mathbf{P^{ref}_{MS}}$regulates the output to the reference value. Then the photovoltaic output power,$\mathbf{P_{PV}}$ and PEMFC output power, $\mathbf{P_{FC}}$ are related to the hybrid source reference power by

$\mathbf{P_{PV} + P_{FC} = P^{ref}_{MS}}$.. (4.1)

Equation (4.1) shows that the variations of the PV output will be compensated for by the FC power and, thus, t hetotal power will be regulated to the reference value. However, the FC output must satisfy its constraints and, h enceP$^{ref}_{MS}$ must be set at an appropriate value. Fig. 5 shows the operation of the hybrid source in UPC mode to determine P$^{ref}_{MS}$.

The algorithm includes two areas: Area 1 and Area 2.

In Area 1, Ppv is less than Ppv1, and then the reference power $P^{ref}_{MS1}$is set at $P^{U}_{FC}$where

$$\mathbf{P_{PV} = P^{U}_{FC} - P^{L}_{FC}} \ldots\ldots (4.2)$$

$$\mathbf{P^{ref}_{MS1} = P^{U}_{FC}} \quad \ldots\ldots (4.3)$$

If PV output is zero, then equation (4.1) deduces $\mathbf{P_{FC}}$ to be equal to$\mathbf{P^{U}_{FC}}$. If the **PV** output increases to PPV1,then from equations (4.1) and (4.2), we obtain $\mathbf{P_{FC}}$ equal to $\mathbf{P^{L}_{FC}}$. In other words, when the **PV** output varies from zero to PPV1, then FC output will change from $\mathbf{P^{U}_{FC}}$ to$\mathbf{P^{L}_{FC}}$. As a result, the constraints for the FC output always reach Area 1. It is noted that the reference power of the hybrid source during the UPC modeis fixed at aconstant $\mathbf{P^{U}_{FC}}$. Area 2 is for the case in which PV output power is greater than PPV1. As examined earlier, when the PV output increases to PPV1, the FC output will decreaseto its lower limit$\mathbf{P^{L}_{FC}}$. If **PV** output keeps increasing, the FCoutput will decrease below its limit $\mathbf{P^{L}_{FC}}$. In this case, to operate the PV at its maximum power point and the FCwithin its limit, the reference power must be increased. If PV output is larger than PPV1,the reference power will beincreased by the amount of $\Delta \mathbf{P_{MS}}$, and we obtain

$$\mathbf{P^{ref}_{MS2}} = \mathbf{P^{ref}_{MS1}} + \Delta \mathbf{P_{MS}} \quad \ldots\ldots (4.4)$$

Similarly if **PPV** is greater than **PPV2** the FC output becomes less than its lower limit and the reference power will thus beincreased by the amount of $\Delta \mathbf{P_{MS}}$. In other words, the reference power remains unchanged and equal toP^{ref}_{MS2} if PPV is less than PPV2 and greater than PPV1 where $\mathbf{P_{PV2} = P_{PV1}} + \Delta \mathbf{P_{MS}}$ … (4.5)

It is noted that $\Delta \mathbf{P_{MS}}$is limited so that with the new reference power, the FC output must be less than its upper Limit $\mathbf{P^{U}_{FC}}$. Then, we have .. $\Delta \mathbf{P_{MS}} \le \mathbf{P^{U}_{FC} - P^{L}_{FC}}$ .... (4.6)

In general, if the **PV** output is between **PPVi** and **PPVi-1** and, then we have

$$\mathbf{P^{ref}_{MSi} = P^{ref}_{MSi-1} + P_{MS}} \quad \ldots\ldots (4.7)$$

$$\mathbf{P_{PVi} = P_{PVi-1}} + \Delta \mathbf{P_{MS}} \ldots \quad (4.8)$$

Equations (4.7) and (4.8) show the method of finding the reference power when the **PV** output is in Area2. Therelationship between P^{ref}_{MSi} and PPVi is obtained by using (4.2), (4.3), and (4.8) in (4.7) and then

$$\mathbf{P^{ref}_{MSi} = P_{PVi} + P^{M}_{FC}} \quad i=2, 3, 4 \ldots\ldots (4.9)$$

The determination of$\mathbf{P^{ref}_{MS}}$in Area 1 and Area 2 can be generalized by starting the index from 1. Therefore,

if the**PV** output**PPVi-1** $\le$ **PPV** $\le$ **PPVi** , i=1, 2,3. . .

Then we have $\mathbf{P^{ref}_{MSi} = P_{PVi} + P^{M}_{FC}}$, **i=1, 2, 3 ... (4.10)**

$\mathbf{P_{PVi} = P_{PVi-1} + P_{MS}}$**, i=2, 3, 4 …... (4.11)**

it is noted that when i=1, PPV1 is given in (4.2), and

PPVi-1 = PPV0 =0……………….. (4.12)

In brief, the reference power of the hybrid source is determined according to the **PV** output power. If the **PV** output is in Area 1, the reference power will always be constant and set at$\mathbf{P^{U}_{FC}}$. Otherwise, the reference va luewill be changed by the amount ΔPMS, according to the change of **PV** power.

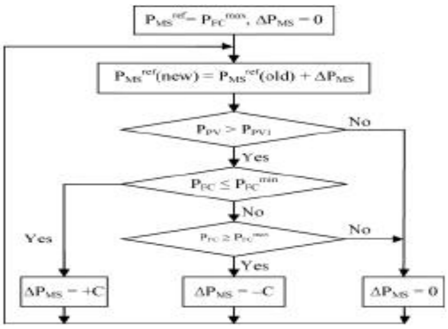


Fig. 6.0 Control algorithm in the UPC modeP^{ref}_{MS}automatically changing

The reference power of the hybrid source in Area 1 and Area 2 is determined by (4.10) and (4.12). , and areshown in (4.12), (4.2), and (4.6), respectively. Fig. 5 shows the control algorithm diagram for determining the reference power automatically.

The constant must satisfy equation (4.6). If C increases the number of change of$\mathbf{P^{ref}_{MS}}$will decrease andthus th
e performance of system operation will be improved.

However, C should be small enough so that thefrequency does not change over its limits, 5%.
In order to improve the performance of the algorithm, a hysteresis is included in the simulation model. Thehysteresis is used to prevent oscillation of the setting value of the hybrid system reference power $\mathbf{P^{ref}_{MS}}$ theboundary of change in $\mathbf{P^{ref}_{MS}}$the reference value will be changed continuously due tothe oscillations in PVmaximum power tracking. To avoid the oscillations around the boundary, a hyst
eresis is included and its controlscheme to control is depicted in Fig.6

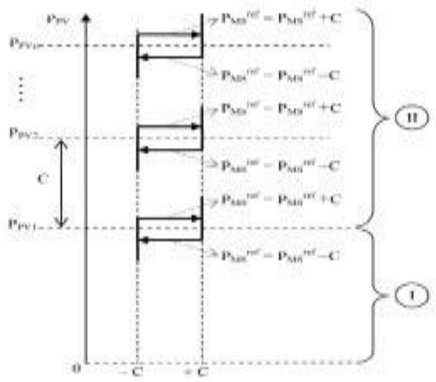


Fig. 7 Hysteresis control scheme forcontrol

This operating strategy must enable the PV to work at itsmaximum power point, FC output, and feeder flow to satisfy their constraints. If the hybrid sourceworks in the UPC mode, the hybrid output is regulated to areference value and the variations in load are matched byfeeder power. With the reference power propose
d inSubsection A, the constraints of FC and PV are always satisfied. Therefore, only the constraint of feeder flow isconsidered. On the other hand, when the hybrid works in the FFC mode, the feeder flow is controlled to a referencevalue and thus, the hybrid source will compensate for the load variations. In this case, all constr
aints must beconsidered in the operating algorithm. Based on those analyses, the operating strategy of the syste
m is proposedasdemonstrated in Fig. 8.

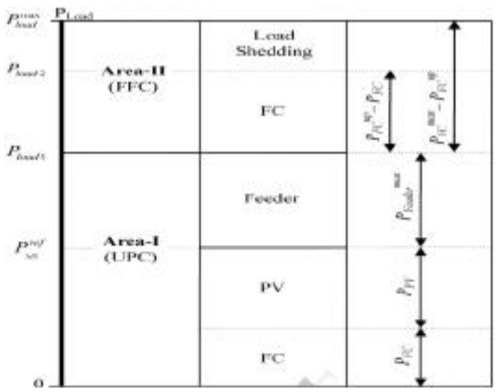


Fig. 8 Overall operating strategies for the grid-connected hybrid system

The operation algorithm involves two areas (Area I and 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. Inthe UPC area, the hybrid source reference output is $\mathbf{P^{ref}_{MS}}$. If the load is lower than$\mathbf{P^{ref}_{MS}}$, the redundant powerwill betransmitted to the main grid.b Otherwise, the main grid will send power to the load side to match load demand. Whenload increases, the feeder flow will increase correspondingly. If feeder flow increases to its maximum$\mathbf{P^{M}_{F}}$,then the feeder flow cannot meet load demand if the load keeps in
creasing. In order to compensate for the loaddemand, the control mode must be changed to FFC with respect

to Area II. Thus, the boundary between Area I andArea II is

$\mathbf{P_{L1} = P^{M}_{F} + P^{ref}_{MS}}$ .... (4.13)

when the mode changes to FFC, the feeder flowreference must be determined. In order for the system operation tobe seamless, the feeder flow should be u
changed during control modetransition. Accordingly, when the feederflow reference is set at P^{M}_{F}, then we have

$\mathbf{P^{ref}_{F} = P^{M}_{F}}$ .... (4.14)

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 ishigher than the total generating power, then load shedding will occur. The limit that load shedding will be reached is: $\mathbf{P_{L2} = P^{M}_{F} + P^{U}_{FC} + P_{PV}}$ .... (4.15)

Equation (4.15) shows that is minimal when PV output is at 0 kW. Then:

$\mathbf{P^{M}_{L2} = P^{U}_{FC} + P^{M}_{F}}$ .... (4.16)

Equation (4.16) means that if load demand is less than$\mathbf{P^{M}_{L2}}$, load shedding will never occur.

From the beginning, FC has always worked in the high efficiency band and FC output has been less. If the load is less than $\mathbf{P^{M}_{L2}}$then load shedding is ensured not to occur. However,in severe conditions, FC should mobilize its availability, to supply the load. Thus, the loadcan be higher and the largest load is

$\mathbf{P^{M}_{L}} = P^{M}_{FC} + \mathbf{P^{M}_{F}}$ .... (4.17)

If FC power and load demand satisfy equation (4.17), loadshedding will never occur. Accordingly, based on load forecast, the installed power of FC can be determined by following (4.17) to avoid load shed ding. Corresponding to the FC installed power; the width of Area II is calculated as follows:

$P_{Area\text{-}II} = P^{M}_{FC} - \mathbf{P^{U}_{FC}}$……………………………………………. (4.18)

In order for the system to work more stably, the number ofmode changes should be decreased. The limit changing the mode from UPC to FFC is PLoad1, which is calculated in equation (4.13). Equation (4.13) shows thatPLoad1 depends on $\mathbf{P^{M}_{F}}$and $\mathbf{P^{ref}_{MS}}$.$\mathbf{P^{M}_{F}}$is a constant, thus $\mathbf{P_{L1}}$ depends on $\mathbf{P^{ref}_{MS}}$. InArea 2 $\mathbf{P^{ref}_{MS}}$ depends on □ $\mathbf{P_{MS}}$. Therefore, to decrease the number of mode changes, $\mathbf{P^{ref}_{MS}}$changes must bereduced. Thus, □ $\mathbf{P_{MS}}$ must be increased. However □ $\mathbf{P_{MS}}$ must satisfy equation (4.6) and, thus, the minimized number of mode change is reached when □ $\mathbf{P_{MS}}$ is maximized: $\mathbf{P^{M}_{MS} = P^{U}_{FC} - P^{L}_{FC}}$ .... ……………………………………………(4.19)

V. RESULT OF GRID CONNECTED PV-FC HYBRID SYSTEM

The system consists of a PVFC hybrid source with the main grid connecting to loads atthe PCC. Thephotov oltaic and the PEMFC are modelledas nonlinear voltage sources. These sources are connected to DC/DC converters which are coupled at the DC side of a DC/AC inverter.

THE CASE WITHOUT HYSTERESIS

To verify the operating strategies the system parameters are shown in Table 5.1.

Table 5.1: System Parameters

Parameter	Value	Unit
$\mathbf{P^{L}_{FC}}$	0.01	MW
$\mathbf{P^{U}_{FC}}$	0.07	MW
$\mathbf{P^{M}_{F}}$	0.01	MW
□ $\mathbf{P_{MS}}$	0.03	MW

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}, $\mathbf{P^{ref}_{F}}$, $\mathbf{P^{ref}_{MS}}$ and the operating mode were determined by the proposed operating algorithm.

The changes of $\mathbf{P_{PV}}$ and $\mathbf{P_{L}}$ are determined respectively. Based on the constraints shown in Table 5.1 the reference value of the hybrid source output was also determined. From 0 s to 10 s, the PV operates at standard test conditions to generate constant power and, thus $\mathbf{P^{ref}_{MS}}$ is constant. From 10 s to 20 s, P_{PV} changes step by step and, thus, $\mathbf{P^{ref}_{MS}}$ is defined as the algorithm (4.2). The PEMFC output power, P_{FC} changes according to the change of $\mathbf{P_{PV}}$ and $\mathbf{P_{MS}}$. In the system operating mode, the UPC mode and FFC mode correspond to values 1 and 0, respectively. From 4 s to 6 s, the system works in FFC mode and, thus, $\mathbf{P^{M}_{F}}$ becomes the feeder reference value $\mathbf{P^{ref}_{F.}}$ During FFC mode, the hybrid source output power changes with respect to the change of load demand. On the contrary, in the UPCmode, P_{MS} changes following $\mathbf{P^{ref}_{MS}}$. It can be seen that the system only works in FFC mode when the load is heavy. The UPC mode is the major operating mode of the system and, hence, the system works more stably, $\mathbf{P^{ref}_{MS}}$ changes continuously. This is caused by variations of P_{PV} in the MPPT process. As a result, P_{FC} and P_{MS} oscillate and are unstable. In order to overcome these drawbacks, a hysteresis was used to control the change of $\mathbf{P^{ref}_{MS}}$.

IMPROVING OPERATION PERFORMANCE WITH HYSTERESIS

The results, when hysteresis was included with the control scheme, indicate that from 12 s to 13 s and from 17 s to 18 s, the variations of hybrid source reference power, FC output, and feeder flow are eliminated and, thus, the system works more stably compared to a case without hysteresis.

VI. CONCLUSIONS

The main purpose of this work is to show that the operation of a grid connected PV-FC hybrid system can improve power management. The hybrid system, composed of a PV array and PEMFC, was considered. This has illustrated an available method to operate a hybrid grid-connected system. A comparison between different system operating strategies such as UPC mode and FFC mode are shown. The main conclusions and recommendations drawn from this work are summarized as follows:

The purposes of the proposed strategy 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 is to specify the control mode; the algorithm is to determine the reference power of hybrid system in the UPC mode. With the operating algorithm, PV always operates at maximum output power, PEMFC operates within the high-efficiency range and feeder power flow is always less than its maximum value. The change of the operating mode depends on the current load demand, 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 proposed operating algorithm is a simplified and flexible method to operate a hybrid source in a grid-connected micro grid. It can improve the performance of the system's operation; the system works more stably while the PV output power is maximized.

REFERENCES

[1] Khurmi, R. S. (2011), "Material Science book". Eds, 2011.

[2] Nice, Karim and Strickland, Jonathan. (2011) "How Fuel Cells Work: Polymer Exchange Membrane Fuel Cells". How Stuff Works, accessed 4 August 2011

[3] Prabhu, Rahul R. (2013). "Stationary Fuel Cells Market size to reach 350,000 Shipments by 2022". Renew India Campaign,13January2013 . Retrieved 2013-01-14.

[4] J.L. Del Monaco (2001), "The role of distributed generation in the critical electrical power infrastructure", in Proceedings of the Power Engineering Society Winter Meeting IEEE, vol. 1, 2001, 144-145.

[5] T.A. Short (2004)," Electric Power Distribution Handbook", CRC Press, 2004.

[6] S. Gilbert (2001)," The nation's largest fuel cell project, a 1MW fuel cell power plant deployed as a distributed generation resource, anchorage, Alaska project dedication 9 August 2000", in: Proceeding of the Rural electric Power Conference, 2001, pp. A4/1-A4/8

[7] J. A. Peças Lopes, C. L. Moreira, and A. G. Madureira (2006), "Defining control strategies for microgrids islanded operation," IEEE Trans. Power Syst., vol. 21, no. 2, May 2006, pp. 916-924.

[8] F. Katiraei and M. R. Iravani (2006), "Power management strategies for a microgrid with multiple distributed generation units," IEEE Trans.Power Syst., vol. 21, no. 4, Nov. 2006, pp. 1821–1831.

[9] NREL, (2002). "Using Distributed Energy Resources". http://www.nrel.gov. NREL. 2002. p. 1. Archived from the original (PDF) on 8 September 2014. Retrieved 8 September 2014.

[10] R. Myadraam, C.S. Kumarm, D. . Kumaraswamym (2013), "Strategies of Power Management for a Grid-Connected Fed by Non-Conventional Energy Source". International Journal of Engineering Research & Technology (IJERT), Vol. 2 Issue 8, A – 20

[11] www.NREL.gov Distributed Energy Resources Interconnection Systems: Technology Review and Research Needs, 2002

[12] www.smartgrid.gov Lexicon Distributed Energy Resource

[13] Endecon Engineering (2001), "A guide to photovoltaic (PV) system design and installation" 2001 by Endecon Engineering

[14] D. Sera, R. Teodorescu, and P. Rodriguez (2007), "PV panel model based on datasheet values," in Proc. IEEE Int. Symp. Industrial Electronics, Jun. 4–7, 2007, pp. 2392–2396.

[15] C. Hua and J. R. Lin (1996), "DSP-based controller application in battery storage of photovoltaic system," in Proc.22nd IEEE Int. Conf. Industrial Electronics, Control, and Instrumentation, Aug. 5–10, 1996, vol.3, pp. 1750–1810.

[16] W. Xiao, W. Dunford, and A. C apel, (2004) "A novel modeling method for photovoltaic cells," in Proc. IEEE 35th Annu. Power Electronics Specialists Conf., Jun. 2004, vol. 3, pp. 1950–1956.