

Strategies of Power Management for a Grid-Connected Fed by Non-Conventional Energy Source

RAVI MYADARAM^(M-Tech), CH.SAMPATH KUMAR^{M-Tech,} DURGAM KUMARASWAMY^{M-Tech (Ph D)}
 Assoc.Prof. Assoc.Prof & HOD

Dept.of Electrical & Electronics Engineering,
 RAMAPPA ENGINEERING COLLEGE,
 WARANGAL.

Abstract: This paper presents a method to operate a grid connected hybrid system. The hybrid system composed of a Photovoltaic (PV) array and a Proton exchange membrane fuel cell (PEMFC) is considered. Two operation modes, the unit-power control (UPC) mode and the feeder-flow control (FFC) mode, can be applied to the hybrid system. 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. 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. 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 system can maximize the generated power when load is heavy and minimizes the load shedding area.

Index Terms—Fuel cell, hybrid system, micro grid, photovoltaic, power management.

NOMENCLATURE

D	Duty cycle
F	Switching frequency
F	Faraday constant (96487 coulombs per mol)
G_a	Irradiation (W/m)
G_{as}	Standard irradiation (1000 W/m)
I_{sc}	Short-circuit current
I_{ph}	Photo current
I_{sat}	Reverse saturation current
I_{limit}	Limitation current (in amperes)
K	Boltzmann constant
P_{pv}	Photovoltaic output power
P_{MPP}	PV maximum output power

P_{FC}	PEMFC output power
P_{FC}^{low}	PEMFC lower limit of high efficiency band
P_{FC}^{up}	PEMFC upper limit of high efficiency band
P_{FC}^{max}	PEMFC maximum output power
P_{Feeder}	Feeder power flow
P_{Feeder}^{ref}	Feeder reference power
P_{Feeder}^{max}	Feeder maximum power
P_{MS}^{ref}	Hybrid source reference power
P_{Load}	Load demand
q	Electronic charge
R	Gas constant, 8.3143 J/(mol.K)
R_s	Series resistance
T	Temperature (in Kelvin)
T_s	Standard temperature (298 K)
V_t	Thermal voltage
V_{op}	Open-circuit voltage
Z	Number of participating electrons
ΔI_{sc}	Temperature coefficient
$\Delta V/V_o$	Voltage ripples

1 INTRODUCTION

The conventional fossil fuel energy sources such as petroleum, natural gas, and coal which meet most of the world's energy demand today are being depleted rapidly. Also, their combustion products are causing global problems such as the greenhouse effect and pollution which are posing great danger for our environment and eventually for the entire life on our planet. The renewable energy sources (solar, wind, tidal, geothermal etc.) are attracting more attention as an alternative energy. 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 becomes 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 ways and even more popular for electricity generator where none was available before. With increasing penetration of solar photovoltaic devices, various anti-pollution apparatus can be operated by solar

PV power; for example, water purification by electrochemical processing or stopping desert expansion by PV water pumping with tree implantation.

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.

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. Its feasibility in co-ordination with a PV system has been successfully realized for both grid-connected and stand-alone power applications. Due to the fast responding capability of the fuel cell power system, a photovoltaic-fuel cell (PVFC) hybrid system may be able to solve the photovoltaic's 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. Moreover, their high efficiency results in low fossil fuel CO₂ emissions, which will help in reducing the rate of global warming. Therefore, the fuel cell power system has a great potential for being co-ordinated with the PV generator to smooth out the photovoltaic power's fluctuations.

2. POWER MANAGEMENT STRATEGIES FOR 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, environmental, geographical and geological factors. 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.

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.

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 produced from natural gas, or liquid fuels such as alcohols, or gasoline. Each unit ranges in size from 3 – 250 KW or larger MW size. 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 cell 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 Resource (DR) unit includes a Distributed Generation (DG) unit, a Distributed Storage (DS) unit, or a hybrid of DG and DS units. A micro-grid is a cluster of loads and distributed resource units serviced by a distribution grid and capable of

1. Operation in a grid-connected mode
2. Operation in an autonomous mode %
3. Ride-through between the above two modes

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.

A Power Management System (PMS) assigns references for real and reactive power components of DR units within a micro-grid to:

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

3. 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. In addition to PV generators, diesel generators, wind generators, small hydro plants, and others 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.

Therefore, energy planners must study the solar energy, wind, and other potential resources at the site, in addition to the energy demand. This will allow them to design the kind of hybrid power system that meets the

demands of the facility at best. In this chapter, 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 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. The advantages of this system are in general the same as for a Photovoltaic-Battery-Diesel hybrid system with regard to the PV generator size and batteries availability. Some principle differences exist between a diesel generator and a fuel cell which affect the design, sizing and the operating strategy of such a hybrid system.

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. 3.1

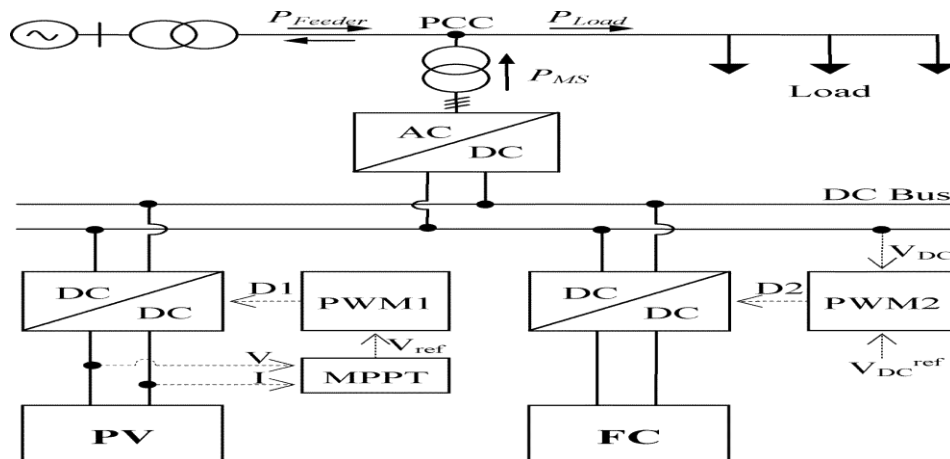


Fig. 3.1 Grid-connected PV-FC hybrid system

The system consists of photovoltaic cell and the 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 an 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 in this dissertation.

Photovoltaic (PV) is a method of generating electrical power by converting solar radiation into direct current electricity using semiconductors that exhibit the photovoltaic. 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, which is high purified silicon (Si), is obtained from sand or quartz. Materials presently used for photovoltaic include monocrystalline silicon, polycrystalline silicon, amorphous silicon, cadmium telluride, and copper indium selenide/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, the manufacturing of solar cells and photovoltaic arrays has advanced considerably in recent years.

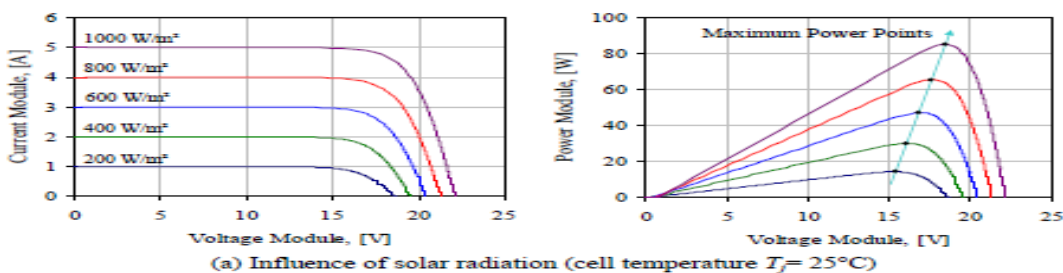
I-V Characteristics of a Photovoltaic Module

The performance characteristics of a photovoltaic module depend on its basic materials, manufacturing technology and operating conditions. Figure 3.5 shows typical current-voltage I-V and power-voltage P-V curves of a BP 585 High-Efficiency Monocrystalline 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 I_{sc}).
2. Maximum power point or MPP, where the product of current and voltage has its maximum (defined by $I_{mpp} * V_{mpp}$).
3. Open circuit point, where the current is zero and the voltage has its maximum (open circuit voltage V_{oc}).

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 V_{oc} . 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 I_{sc} at zero voltage. The series of all measured pairs (V, I) yields the characteristic I-V curve of the module.



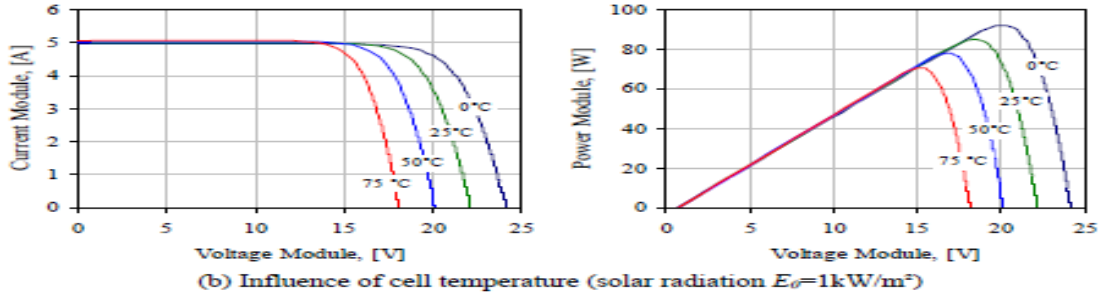


Fig. 3.2 I-V characteristics of Monocrystalline PV Module

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. 3.2. 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.

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.3.3.

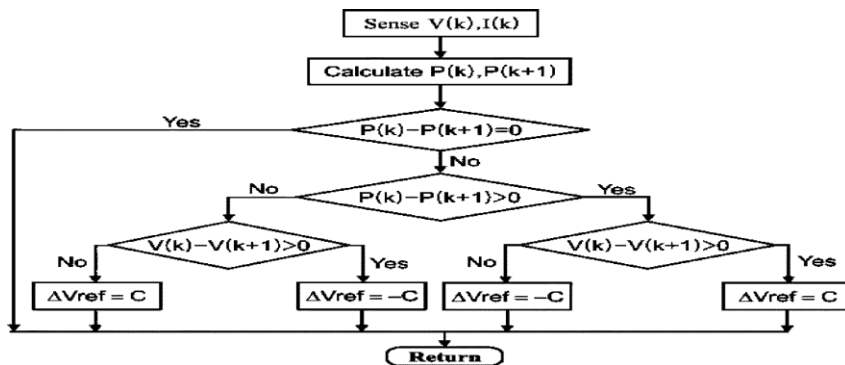
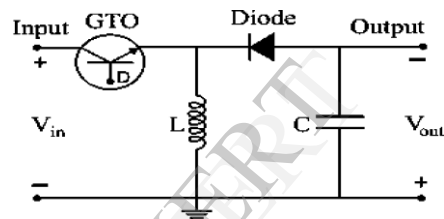


Fig. 3.3P&O MPPT flow chart

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 ($dP/dV < 0$) where as 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) where as the left side curve is for the higher duty cycle (nearer to unity).

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 is tracked and delivered to the ac side via a dc/ac inverter.

**Fig. 3.4 Buck-Boost converter**

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

$$L > \frac{(1-D)^2 R}{2f} \quad C > \frac{D}{Rf(\Delta V/V_{out})} \quad \dots\dots (3.1)$$

4. OPERATING STRATEGY OF 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. 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 (P_{FC}^{low} , P_{FC}^{up} and P_{Feeder}^{max}) 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.

OPERATING STRATEGY FOR THE HYBRID SYSTEM IN THE UPC MODE

In this subsection, determines the hybrid source works in the UPC mode. This algorithm allows the PV to work at its maximum power point, and the FC to work within its high efficiency band. In the UPC mode, the hybrid source P_{MS}^{ref} regulates the output to the reference value. Then $P_{PV} + P_{FC} = P_{MS}^{ref}$... (4.1)

Equation (4.1) shows that the variations of the PV output will be compensated for by the FC power and, thus, the total power will be regulated to the reference value. However, the FC output must satisfy its constraints and, hence, P_{MS}^{ref} must set at an appropriate value.

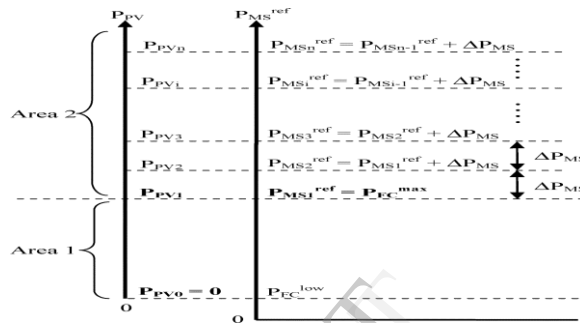


Fig 4.1 Operation strategy of hybrid source in the UPC mode

Fig. 4.1 shows the operation strategy of the hybrid source in UPC mode to determine P_{MS}^{ref} . The algorithm includes two areas: Area 1 and Area 2.

In Area 1, P_{pv} is less than P_{pv1} , and then the reference power P_{MS1}^{ref} is set at P_{FC}^{up} where

$$P_{PV1} = P_{FC}^{up} - P_{FC}^{low} \quad \dots (4.2)$$

$$P_{MS1}^{ref} = P_{FC}^{up} \quad \dots (4.3)$$

If PV output is zero, then equation (4.1) deduces P_{FC} to be equal to P_{FC}^{up} . If the PV output increases to P_{PV1} , then from equations (4.1) and (4.2), we obtain P_{FC} equal to P_{FC}^{low} . In other words, when the PV output varies from zero to P_{PV1} , then FC output will change from P_{FC}^{up} to P_{FC}^{low} . 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 mode is fixed at a constant P_{FC}^{up} .

Area 2 is for the case in which PV output power is greater than P_{PV1} . As examined earlier, when the PV output increases to P_{PV1} , the FC output will decrease to its lower limit P_{FC}^{low} . If PV output keeps increasing, the FC output will decrease below its limit P_{FC}^{low} . In this case, to operate the PV at its maximum power point and the FC within its limit, the reference power must be increased. If PV output is larger than P_{PV1} , the reference power will be increased by the amount of ΔP_{MS} , and we obtain

$$P_{MS2}^{ref} = P_{MS1}^{ref} + \Delta P_{MS} \quad \dots (4.4)$$

Similarly if P_{PV} is greater than P_{PV2} the FC output becomes less than its lower limit and the reference power will be thus increased by the amount of ΔP_{MS} . In other words, the reference power remains unchanged and equal to P_{MS2}^{ref} if P_{PV} is less than P_{PV2} and greater than P_{PV1} where

$$P_{PV2} = P_{PV1} + \Delta P_{MS} \quad \dots (4.5)$$

It is noted that ΔP_{MS} is limited so that with the new reference power, the FC output must be less than its upper limit P_{FC}^{up} .

Then, we have

$$\Delta P_{MS} \leq P_{FC}^{up} - P_{FC}^{low} \quad \dots (4.6)$$

In general, if the PV output is between P_{PVi} and P_{PVi-1} and, then we have

$$P_{MSi}^{ref} = P_{MSi-1}^{ref} + \Delta P_{MS} \quad \dots (4.7)$$

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

Equations (4.7) and (4.8) show the method of finding the reference power when the PV output is in Area 2. The relationship between P_{MSi}^{ref} and P_{PVi} is obtained by using (4.2), (4.3), and (4.8) in (4.7) and then

$$P_{MSi}^{ref} = P_{PVi} + P_{FC}^{min} \quad i=2, 3, 4, \dots \quad \dots (4.9)$$

The determination of P_{MS}^{ref} in Area 1 and Area 2 can be generalized by starting the index from 1. Therefore, if the PV output

$$P_{PVi-1} \leq P_{PV} \leq P_{PVi}, i=1, 2, 3, \dots$$

Then we have

$$P_{MSi}^{ref} = P_{PVi} + P_{FC}^{min}, i=1, 2, 3, \dots \quad \dots (4.10)$$

$$P_{PVi} = P_{PVi-1} + \Delta P_{MS}, i=2, 3, 4, \dots \quad \dots (4.11)$$

it is noted that when $i=1$, P_{PVi} is given in (5.2), and

$$P_{PVi-1} = P_{PV0} = 0 \quad \dots (4.12)$$

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 P_{FC}^{up} . Otherwise, the reference value will be changed by the amount of ΔP_{MS} according to the change of PV power.

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

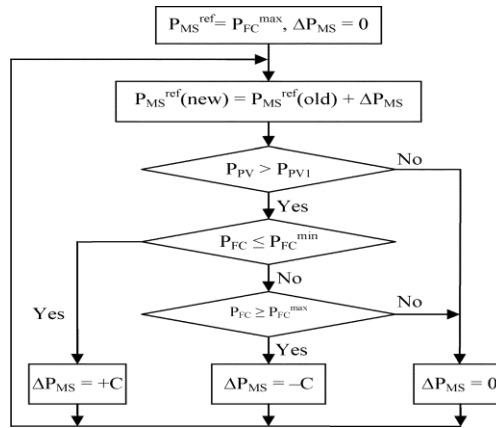


Fig. 4.2 Control algorithm in the UPC mode P_{MS}^{ref} automatically changing

The constant must satisfy equation (4.6). If C increases the number of change of P_{MS}^{ref} will decrease and thus the performance of system operation will be improved. However, C should be small enough so that the frequency does not change over its limits 5%.

In order to improve the performance of the algorithm, a hysteresis is included in the simulation model. The hysteresis is used to prevent oscillation of the setting value of the hybrid system reference power P_{MS}^{ref} . At the boundary of change in P_{MS}^{ref} the reference value will be changed continuously due to the oscillations in PV maximum power tracking. To avoid the oscillations around the boundary, a hysteresis is included and its control scheme to control is depicted in Fig.4.3

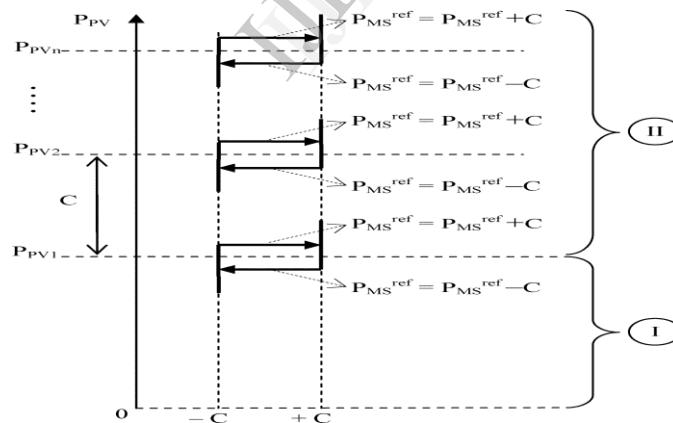


Fig. 4.3 Hysteresis control scheme for P_{MS}^{ref} control

OVERALL OPERATING STRATEGY FOR THE GRID-CONNECTED HYBRID SYSTEM

It is well known that in the micro grid, each DG as well as the hybrid source has two control modes: 1) the UPC mode and 2) the FFC mode. In the aforementioned section, a method to determine 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 in 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 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. 4.4

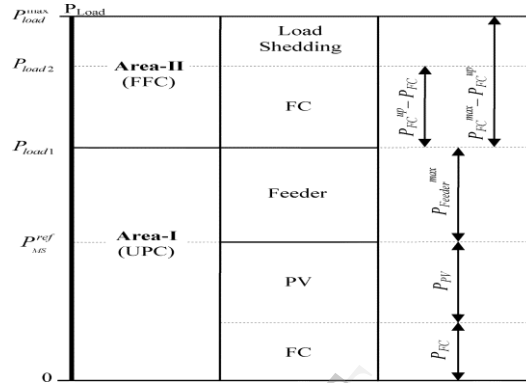


Fig. 4.4 Overall operating strategies for the grid-connected hybrid system

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. In the UPC area, the hybrid source output is P_{MS}^{ref} . If the load is lower than P_{MS}^{ref} , 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 P_{Feeder}^{max} , 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 II is

$$P_{Load1} = P_{Feeder}^{max} + P_{MS}^{ref} \quad \dots\dots (4.13)$$

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_{Feeder}^{max} , then we have

$$P_{Feeder}^{ref} = P_{Feeder}^{max} \quad \dots\dots (4.14)$$

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 is higher than the total generating power, then load shedding will occur. The limit that load shedding will be reached is

$$P_{Load2} = P_{Feeder}^{max} + P_{FC}^{up} + P_{PV} \quad \dots (4.15)$$

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

$$P_{Load2}^{min} = P_{FC}^{up} + P_{Feeder}^{max} \quad \dots (4.16)$$

Equation (4.16) means that if load demand is less than P_{Load2}^{min} , load shedding will never occur.

From the beginning, FC has always worked in the high efficiency band and FC output has been less than. If the load is less than P_{Load2}^{min} then load shedding is ensured not to occur. However, in severe conditions, FC should mobilize its availability, to supply the load. Thus, the load can be higher and the largest load is

$$P_{Load}^{max} = P_{FC}^{max} + P_{Feeder}^{max} \quad \dots (4.17)$$

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

$$P_{Area-II} = P_{FC}^{max} - P_{FC}^{up} \quad \dots (4.18)$$

In order for the system to work more stably, the number of mode changes should be decreased. The limit changing the mode from UPC to FFC is P_{Load1} , which is calculated in equation (4.13). Equation (4.13) shows that P_{Load1} depends on P_{Feeder}^{max} and P_{MS}^{ref} . P_{Feeder}^{max} is a constant, thus P_{Load1} depends on P_{MS}^{ref} . Fig. 5.1 shows that in Area 2 P_{MS}^{ref} depends on ΔP_{MS} . Therefore, to decrease the number of mode changes, P_{MS}^{ref} changes must be reduced. Thus, ΔP_{MS} must be increased. However ΔP_{MS} must satisfy equation (4.6) and, thus, the minimized number of mode change is reached when ΔP_{MS} is maximized

$$P_{MS}^{max} = P_{FC}^{up} - P_{FC}^{low} \quad \dots (4.19)$$

5. RESULT OF GRID CONNECTED PV-FC HYBRID SYSTEM

The system consists of a PV-FC hybrid source with the main grid connecting to loads at the PCC. The photovoltaic and the PEMFC 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.

RESULTS IN 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
P_{FC}^{low}	0.01	MW
P_{FC}^{up}	0.07	MW
P_{Feeder}^{max}	0.01	MW
ΔP_{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} , P_{Feeder}^{ref} , P_{MS}^{ref} and the operating mode were determined by the proposed operating algorithm. Fig. 5.1, Fig.5.2 shows the results of the system operating strategy.

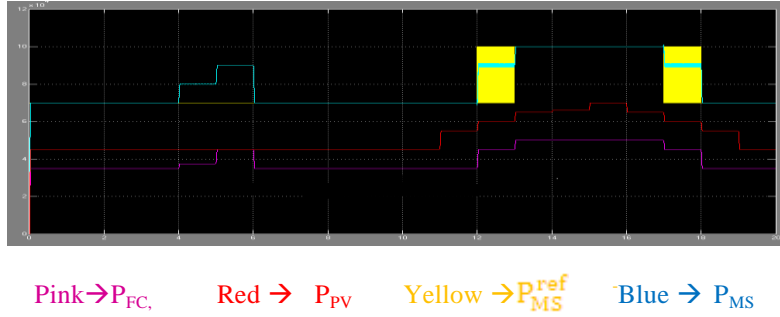


Fig. 5.2: Operating strategy of the hybrid source without hysteresis

The changes of P_{PV} and P_{Load} are shown in Fig. 5.1 (red line) and Fig. 5.2 (yellow line), respectively. Based on and the constraints of shown in Table 5.1 the reference value of the hybrid source output is determined as depicted in Fig. 5.2 (yellow line). From 0 s to 10 s, the PV operates at standard test conditions to generate constant power and, thus P_{MS}^{ref} constant. . From 10 s to 20 s, P_{PV} changes step by step and, thus, P_{MS}^{ref} is defined as the algorithm 4.2. The PEMFC output P_{FC} as shown in Fig. 5.2 (pink line) changes according to the change of P_{PV} and P_{MS} .

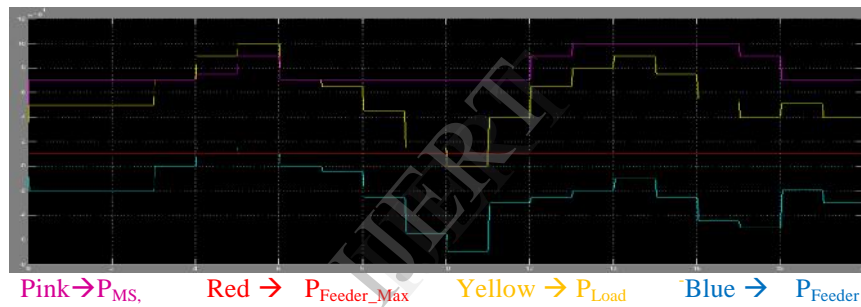


Fig. 5.3: Operating strategy of the whole system without hysteresis

Fig. 5.2 shows 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, P_{Feeder}^{max} becomes the feeder reference value P_{Feeder}^{ref} .

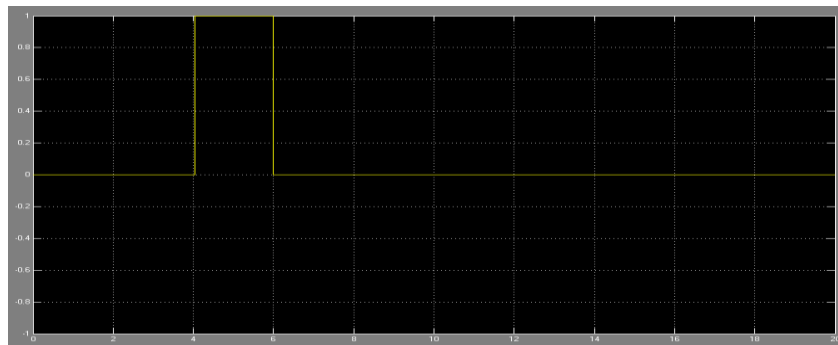


Fig. 5.4: Change of operating modes without hysteresis

During FFC mode, the hybrid source output power changes with respect to the change of load demand, as in Fig. 5.2. On the contrary, in the UPC mode, P_{MS} changes following P_{MS}^{ref} as shown in Fig. 5.1. It can be seen from Figures 5.1, 5.2, 5.3 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. P_{MS}^{ref} 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 P_{MS}^{ref} .

IMPROVING OPERATION PERFORMANCE WITH HYSTERESIS

Figures 5.4, 5.5 results when hysteresis was included with the control scheme shown in Fig. 5.2.

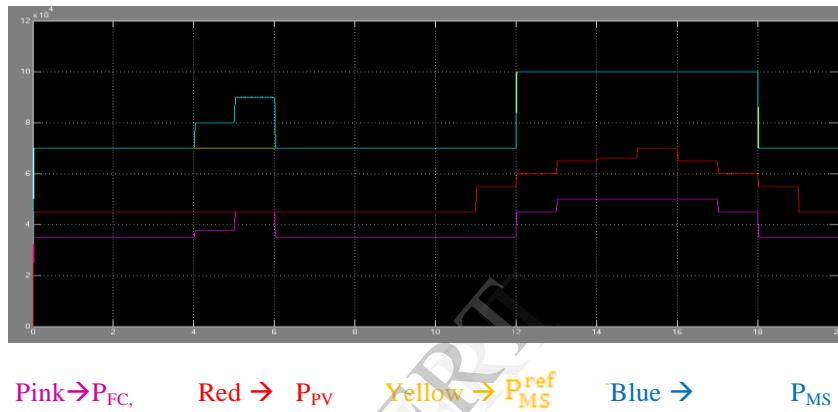


Fig. 5.5 Operating strategy of the hybrid source with hysteresis

From 12 s to 13 s and from 17 s to 18 s, the variations of hybrid source reference power, [Fig. 5.4, yellow line], FC output [Fig. 5.3, pink line], and feeder flow [Fig. 5.5, blue line] are eliminated and, thus, the system works more stably compared to a case without hysteresis.

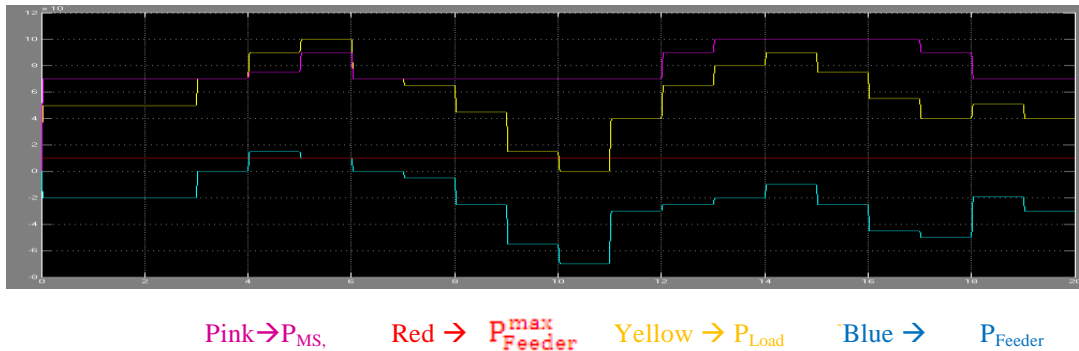


Fig. 5.6: Operating strategy of the whole system with hysteresis

6. CONCLUSIONS

The overall goal of this thesis is to investigate the operation of a grid connected PVFC hybrid system. The hybrid system, composed of a PV array and PEMFC, was considered. This project has presented 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 studied. The main conclusions and recommendations drawn from this work are summarized next.

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 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.

In brief, 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 maximizing the PV output power.

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