Saritha Int. Journal of Engineering Research and Applications www.ijera.com
ISSN : 2248-9622, Vol. 4, Issue 8(Version 3), August 2014, pp.168-176

RESEARCH ARTICLE OPEN ACCESS

OPERATION & CONTROL OF SMART GRID CONNECTED PV- FC HYBRID POWER SYSTEMD.

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ABSTRACT
This paper presents a method to operate and control a grid connected hybrid power system. The hybrid system composed of a Photovoltaic (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, enhancing system stability, and decreasing the number of operating mode changes
Index Terms—Distributed generation, 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

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, works only at a high efficiency within a specific power (P_{FC}^{low} -P_{FC}^{up}) [1], [2].

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 P_{MS}^{ref} 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 P_{Feeder}^{ref} 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.

II. 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. 1. 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). 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 $\Delta V_{ref.}$

B. PV Array Model

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

$$I = Iph - Isat\left\{exp\left[\frac{q}{AKT}(V + IRs)\right] - 1\right\}. \quad (1)$$

Equation (1) 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

$$Iph(Ga) = Isc\frac{Ga}{Gas}. \quad (2)$$

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

$$Isc(T) = Iscs[1 + \Delta I_{sc}(T-T_s)]. \quad (3)$$

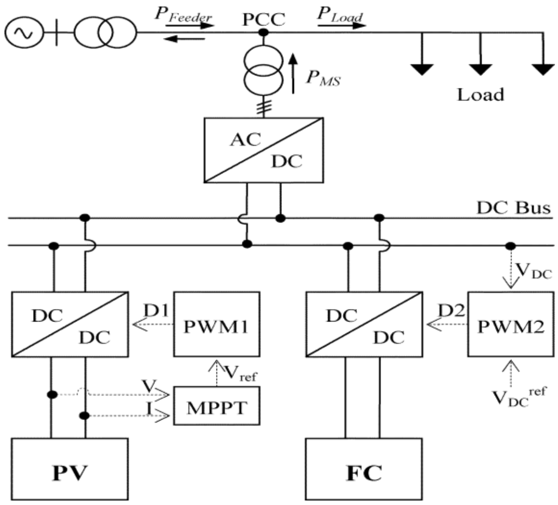

Fig. 1. Grid-connected PV-FC hybrid system.

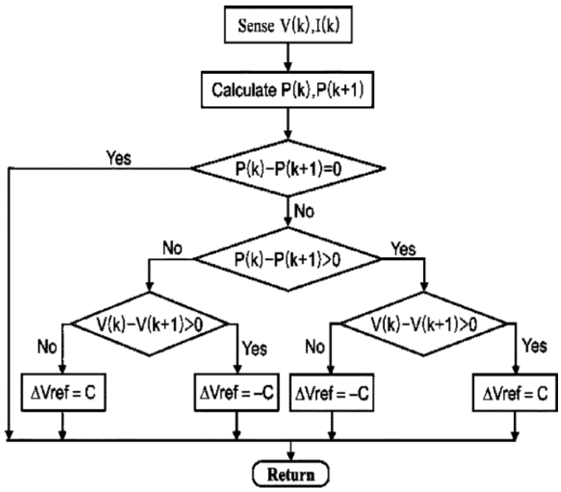

Fig. 2. P&O MPPT algorithm.

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

$$Iph(Ga, T) = I_{scs}\frac{Ga}{Gas}[1 + \Delta Isc\ (T - Ts)]. \quad (4)$$

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

$$Isat\ (Ga, T) = \frac{Iph(Ga,T)}{e^{\left(\frac{Voc(T)}{Vt(T)}\right)} - 1}. \quad (5)$$

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]:

$$V_{out} = E_{nerst} - V_{act} - V_{ohm} - V_{conc}. \quad (6)$$

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

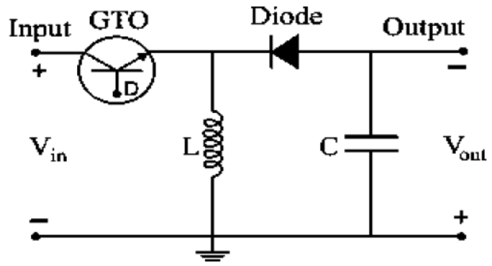

Fig. 3. Buck-Boost topology.

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

$$Vact = T[a + b\ln(I)]. \quad (7)$$

Where a,b are the constant terms in the Tafel equation (in volts per Kelvin)

The overall ohmic voltage drop V_{ohm} can be expressed as

$$Vohm = IRohm. \quad (8)$$

The ohmic resistance Rohm 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

$$Vconc = -\frac{RT}{zF}\ln(1 - \frac{I}{Ilim}) . \quad (9)$$

D. 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 a desired voltage. The drawback of the voltage-feedback control is its 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], [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]:

$$L > \frac{(1-D)^2}{2f}R; C > \frac{D}{Rf(\Delta V/Vout)} \quad (10)$$

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 sawtooth 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 inverter.

III. CONTROL OF THE HYBRID SYSTEM

control modes in the microgrid 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 microgrid, 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 $P_{Feeder.}$ With this control mode, extra load demands are picked up by the DGs, which maintain a constant load from the utility view point. 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.

IV. OPERATING STRATEGY OF THE HYBRID SYSTEM

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 are fulfilled. Once the constraints (P_{FC}^{low}, P_{FC}^{up} and P_{F}^{max}) are known, the control mode of the hybrid source (UPC mode and FFC mode) depends

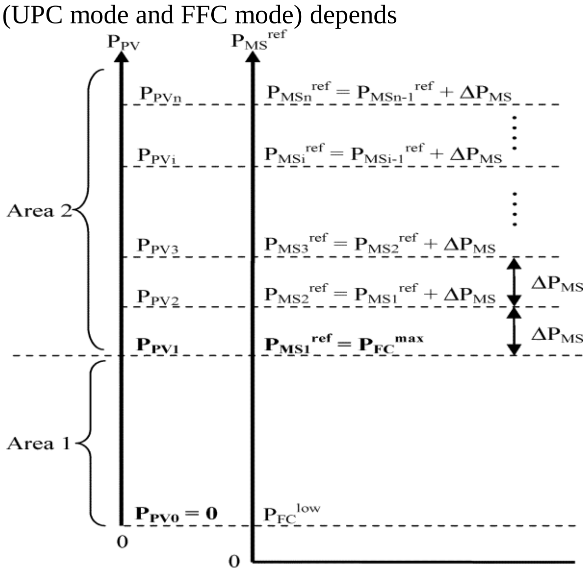

Fig. 4. Operation strategy of hybrid source in the UPC mode.

on load variations and the PV output. The control mode is decided by the algorithm shown in Fig. 7, Subsection B. In the UPC mode, the reference output power of the hybrid source P_{MS}^{ref} depends on the PV output and the constraints of the FC output. The algorithm determining P_{MS}^{ref} is presented in Subsection A and is depicted in Fig. 4.

A. Operating Strategy for the Hybrid System in the UPC Mode

In this subsection, the presented algorithm 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 regulates the output to the reference value. Then

$$P_{pv}+P_{fc}=P_{MS}^{ref} \quad (11)$$

Equation (11) 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 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

$$P_{pv} = P_{FC}^{up} - P_{FC}^{low}. \quad (12)$$

$$P_{MS1}^{ref} = P_{FC}^{up} \quad (13)$$

If PV output is zero, then (11) deduces P_{FC} to be equal to P_{FC}^{up}. If the PV output increases to P_{pv1}, then from (11) and (12), we obtain P_{FC} equal to P_{FC}^{low}. In other words, when the PV output varies from zero to P_{pv1}, the 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 limitP_{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. As depicted in Fig. 4, if PV output is larger than P_{pv1}, the reference power will be increased by the amount of ΔP_{MS}, and we obtain

$$P_{MS2}^{ref} = P_{MS1}^{ref} + \Delta P_{MS} \quad (14)$$

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

$$P_{pv2} = P_{pv1} + \Delta P_{MS} \quad (15)$$

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

$$\Delta P_{MS} \leq P_{FC}^{up} - P_{FC}^{low} \quad (16)$$

In general, if the PV output is between P_{pvi} and $P_{pv\,i-1}$(i = 1,2,3,4...), then we have

$$P_{MSi}^{ref} = P_{MSi-1}^{ref} + \Delta P_{MS} \quad (17)$$

$$P_{pvi} = P_{pvi-1} + \Delta P_{MS} \quad (18)$$

Equations (17) and (18) 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 (12), (13), and (18) in (17), and then

$$P_{MSi}^{ref} = P_{pvi} + P_{FC}^{min}, \; i = 2,3,4.. \quad (19)$$

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 is

$P_{pvi-1} \leq Ppv \leq Ppvi$, i = 2,3,4...

then we have

$$P_{MSi}^{ref} = P_{pvi} + P_{FC}^{min}, \; i = 2,3,4... \quad (20)$$

$P_{pvi} = P_{pvi-1} + \Delta P_{MS}$, i = 2,3,4... (21)
it is noted that when i=1, P_{pv1} is given in (12), and
$P_{pvi-1}=P_{pv0}=0$ (22)

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.

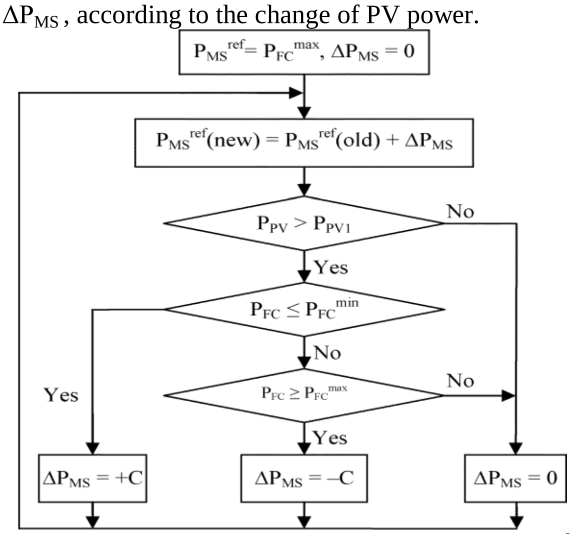

Fig. 5. Control algorithm in the UPC mode (P_{MS}^{ref} automatically changing)

The reference power of the hybrid source P_{MS}^{ref} in Area 1 and Area 2 is determined by (20) and (21). P_{pv0}, $P_{pv1,}$ and ΔP_{MS} are shown in (22), (12), and (16), respectively.

Fig. 5. shows the control algorithm diagram for determining the reference power automatically. The constant C must satisfy (16). 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 P_{MS}^{ref} is depicted in Fig. 6.

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_{MS}^{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 P_{MS}^{ref} 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 P_{Feeder}^{ref}

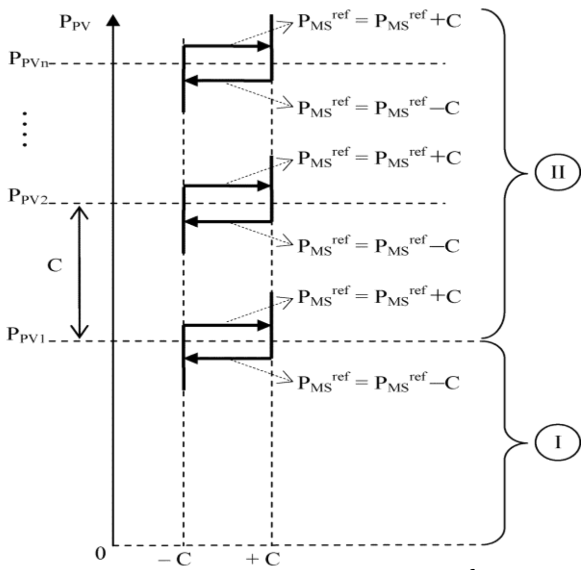

Fig. 6. Hysteresis control scheme for P_{MS}^{ref} control.

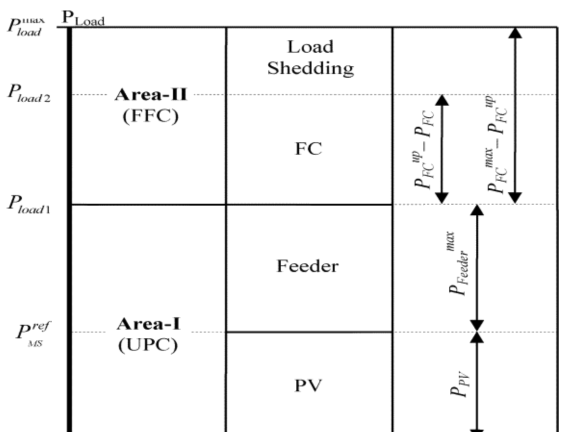

Fig. 7. overall operating strategies for the grid-connected hybrid system

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 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 P_{Load1} is

$$P_{Load\ 1} = P_{Feeder}^{max} + P_{MS}^{ref} \tag{23}$$

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

$$P_{Feeder}^{ref} = P_{Feeder}^{max} \tag{24}$$

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

$$P_{Load\ 2} = P_{Feeder}^{max} + P_{FC}^{up} + P_{PV} \tag{25}$$

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

$$P_{Load\ 2}^{min} = P_{FC}^{up} + P_{Feeder}^{max} \tag{26}$$

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 $P_{Load\ 2}^{min}$ 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

$$P_{Load}^{max} = P_{FC}^{max} + P_{Feeder}^{max} \tag{27}$$

If FC power and load demand satisfy equation (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:

$$P_{Area\ -11} = P_{FC}^{max} - P_{FC}^{up} \tag{28}$$

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 is P_{Load1}, which is calculated in equation (23). Equation (23) 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. 4 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

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

ΔP_{MS} must satisfy equation (16) and, thus, the minimized number of mode change is reached when ΔP_{MS} is maximized

$$P_{MS}^{max} = P_{FC}^{up} - P_{FC}^{low} \tag{29}$$

In summary, in light-load condition, the hybrid source works in UPC mode, the hybrid source regulates output power to the reference value P_{MS}^{ref} and the main grid compensates for load variations. P_{MS}^{ref} is determined by the algorithm shown in Fig. 4 and, thus, the PV always works at its maximum power point and the PEMFC always works within the high efficiency band ($P_{FC}^{low} \div P_{FC}^{up}$). In heavy load conditions, the control mode changes to FFC, and the variation of load will be matched by the hybrid source. In this mode, PV still works with the MPPT control, and PEMFC operates within its efficiency band until load increases to a very high point. Hence, FC only works outside the high efficiency band ($P_{FC}^{up} \div P_{FC}^{max}$) in severe conditions. With an installed power of FC and load demand satisfying (27), load shedding will not occur. Besides, to reduce the number of mode changes must be increased and, hence, the number of mode changes is minimized when maximized, as shown in equation (29). In addition, in order for system operation to be seamless, the reference value of feeder flow must be set at P_{feeder}^{max}.

V. SIMULATION RESULT AND DISCUSSION

A. Simulation Results in the Case without Hysteresis

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 1.

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. 8 shows the simulation results of the system operating strategy. The changes of P_{PV} and P_{Load} are shown in Fig. 8(a) (red line) and Fig.8(b) (yellow line), respectively.

Based on and the constraints of shown in Table 1 the reference value of the hybrid source output P_{MS}^{ref} is determined as depicted in Fig. 8(a) (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 shown in Fig. 4 or 5. The PEMFC output P_{FC} as shown in Fig. 8(a) (pink 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.

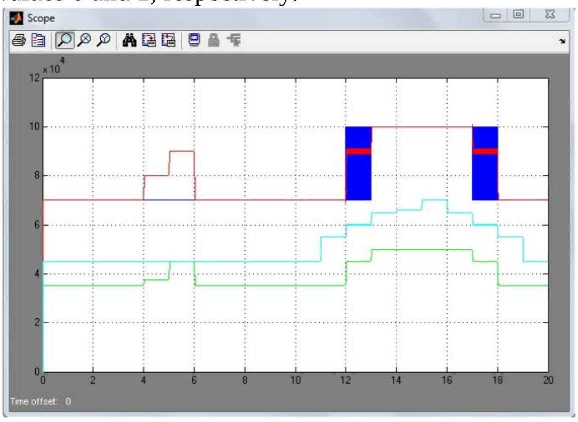

Fig 8(a): Operating strategy **of the hybrid source**

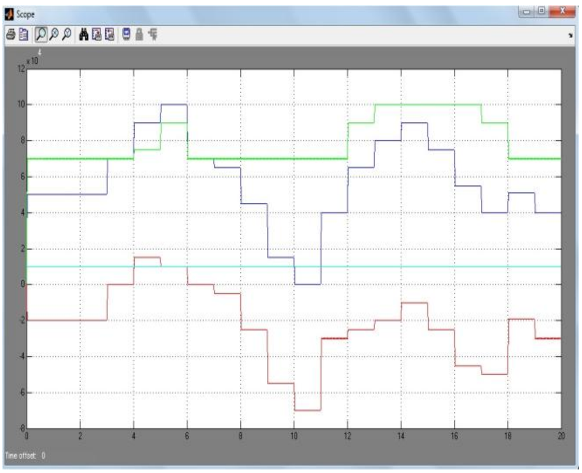

Fig 8(b): Operating strategy of the whole system

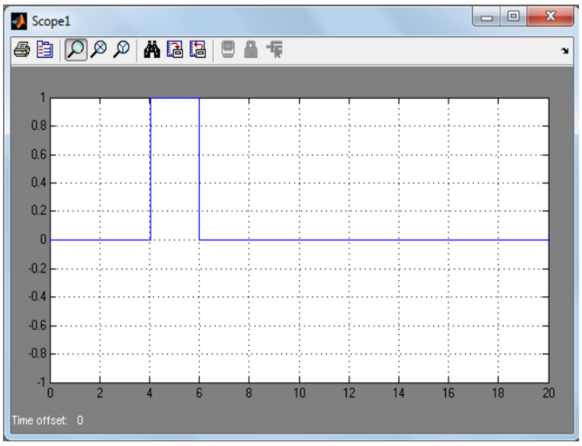

Fig 8(c): Change of operating modes

From 4 s to 6 s, the system works in FFC mode and, thus, P_{Feeder}^{max} becomes the feeder reference valueP_{Feeder}^{ref} . During FFC mode, the hybrid source output power changes with respect to the change of load demand, as in Fig. 8(b). On the contrary, in the UPC mode, P_{MS} changes following P_{MS}^{ref} as shown in Fig. 8(a).

It can be seen from Figures 8 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.

It can also be seen from Fig. 8(a) that at 12 s and 17 s, 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 ofP_{MS}^{ref}, as shown in Fig. 6. The simulation results of the system, including the hysteresis, are depicted in Fig. 9

B. Improving operation performance with hysteresis

Fig. 9 shows the simulation results when hysteresis was included with the control scheme shown in Fig. 6. From 12 s to 13 s and from 17 s to 18 s, the variations of hybrid source reference power, [Fig. 9(a), yellow line], FC output [Fig. 9(a), pink line], and feeder flow [Fig. 9(b), blue line] are eliminated and, thus, the system works more stably compared to a case without hysteresis (Fig. 8). Fig. 9(d) shows the frequency variations when load changes or when the hybrid source reference power P_{MS}^{ref} changes (at 12 s and 18 s).

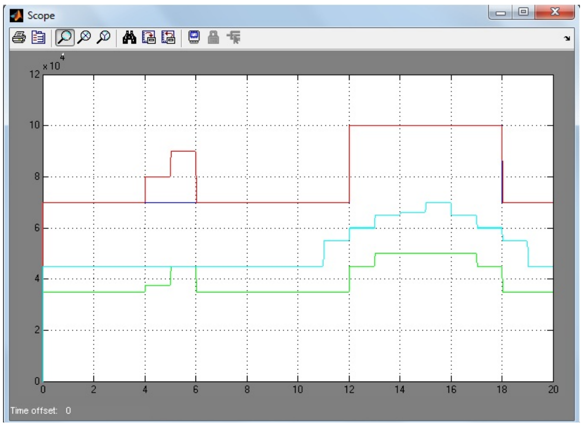

Fig. 9.(a) The operating strategy of the hybrid source

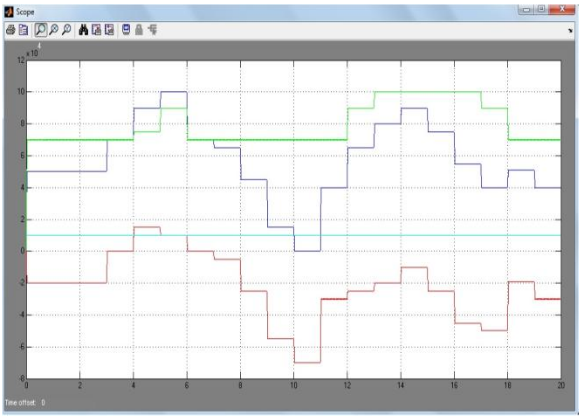

Fig. 9.(b) Operating strategy of the whole system

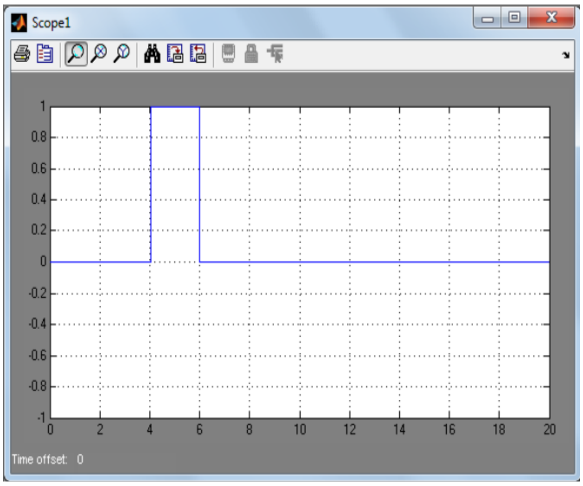

Fig. 9(c) Change of operating modes

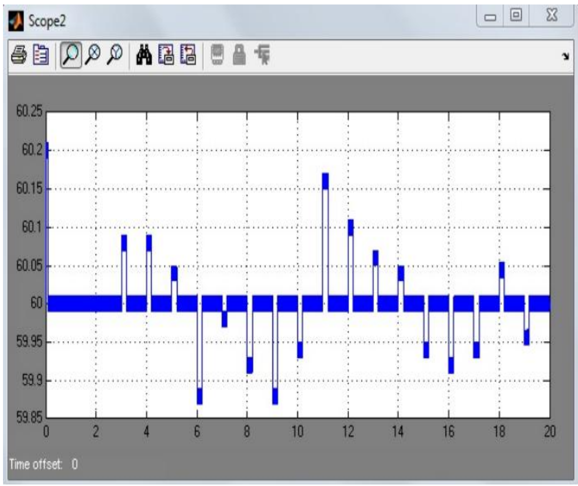

Fig. 9(d) Frequency variations occur in the system

C. Discussion

It can be seen from Fig. 9(b)that during the UPC mode, the feeder flow (blue line) changes due to the change of load (yellow line) and hybrid source output (pink line). This is because in the UPC mode, the feeder flow must change to match the load demand. However, in a real-world situation, the micro grid should be a constant load from the utility viewpoint. In reality, the micro grid includes some

DGs connected in parallel to the feeder. Therefore, in the UPC mode, the changes of load will be compensated for by other FFC mode DGs and the power from the main grid will be controlled to remain constant.

In the case in which there is only one hybrid source connected to the feeder, the hybrid source must work in the FFC mode to maintain the feeder flow at constant. Based on the proposed method, this can be accomplished by setting the maximum value of the feeder flow to a very low value and, thus, the hybrid source is forced to work in the FFC mode. Accordingly, the FC output power must be high enough to meet the load demand when load is heavy and/or at night without solar power. From the aforementioned discussions, it can be said that the proposed operating strategy is more applicable and meaningful to a real-world micro grid with multi DGs.

VI. CONCLUSION

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 powr point, and to operate the FC output in its high-efficiency performance band.

strateghown in Fig. 7 is to specify the control mode; the algorithm shown in Fig. 4 is to determine the reference power of hybrid system P_{MS}^{ref} 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, tus, 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 micro grid. It can improve the performance of the system's operation; the system works more stably while maximizing the PV output power.

VII. SCOPE FOR FUTURE WORK

To enhance the performance of hydrogen PVFC hybrid systems, the following recommendations for future work are proposed:

- The operating algorithm, taking the operation of the battery into account to enhance operation performance of the system, will be considered.
- By adding other renewable sources, such as a wind turbine to the system. A wind energy conversion would reduce the required PV generator area, and reduce the hydrogen storage volume. A trade-off between PV generator area and wind generator size is an interesting challenge for systems located at sites with high average wind speeds.
- The H2/O2 PEM fuel cell has a better performance than the Air/H2 PEM fuel cell which is used in this work, but requires a storage tank for oxygen and a purification system. Thus, it is recommended to study using H2/O2 PEM fuel cell with the PVFC hybrid system and evaluate the system according to the cost point of view.
- Moreover, the application of the operating algorithm to a micro grid with multiple feeders and DGs will also be studied in detail.

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