OPERATION AND CONTROL STRATEGIES FOR A GRID INTEGRATERD PV-FC HYBRID POWER SYSTEM

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ABSTRACT

The main objective of this paper is to present a method to operate a grid connected hybrid system efficiently. 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. To make the system controllable, the Proton Exchange membrane fuel cell (PEMFC) is considered. This PEMFC compensates the load variations when the solar power was damping in nature.

Furthermore, it is not available during the night 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. When load is light, the UPC mode is selected and, thus, the hybrid source works more stably. The changes in operating mode only occur when the load demand is at the boundary of mode change; otherwise, the operating mode is either UPC mode or FFC mode. Besides, the variation of hybrid source reference power is eliminated by means of hysteresis. 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 in the MATLAB Simulink environment.

Key words: *unit-power control (UPC) mode, feeder-flow control (FFC) mode, maximum power point tracking (MPPT), Proton Exchange membrane fuel cell (PEMFC).*

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1. INTRODUTION

As conventional sources of energy are rapidly depleting and the cost of energy is rising, photovoltaic energy becomes a promising alternative source. Among its advantages are that it is: 1) abundant; 2) pollution free; 3) distributed throughout the earth; and 4) recyclable. The main drawbacks are that the initial installation cost is considerably high and the energy conversion efficiency is relatively low. To overcome these problems, the following two essential ways can be used: 1) increase the efficiency of conversion for the solar array and 2) maximize the output power from the solar array. The perturbation and observation method (P&O), which moves the operating point toward the maximum power point by periodically increasing or decreasing the array voltage, is often used in many photovoltaic systems. It has been shown that the P&O method works well when the insolation does not vary quickly with time; however, the P&O method fails to quickly track the maximum power points. 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.

From an operational point of view, a PV power generation experiences large variations in its output power due to intermittent weather conditions. One of the best method to overcome this type of problem is to integrate the photovoltaic plant with other power sources such as diesel, fuel cell (FC), or battery back-up [1-3 &5]. The hybrid system can either be connected to the main grid or work autonomously with respect to the grid-connected mode. When change in the load , the power from the main grid and hybrid system must be changed properly. To meet load demand the power delivered from the main grid, PV array as well as PEMFC must be coordinated. The two control modes of hybrid source are: 1) Unit-Power Control (UPC) mode and 2) Feeder-Flow Control (FFC) mode [8].

In the UPC mode, hybrid source output is regulated to reference power extra load demand is picked up by the main grid. Therefore, the reference value of the hybrid source output power 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. So the feeder reference power must be known [8-9].

2. SYSTEM DESCRIPTION

2.1 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.

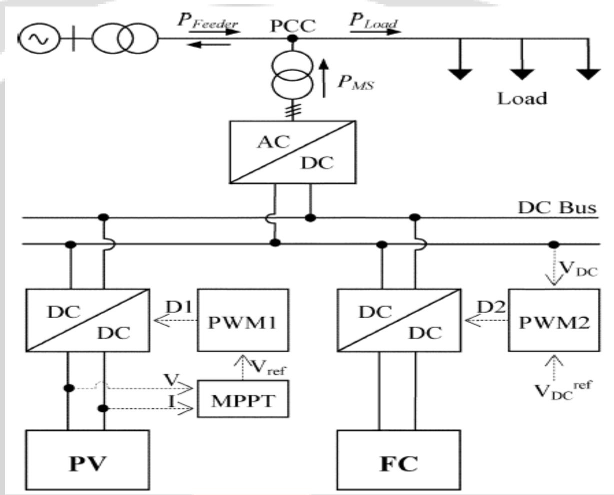

Fig -1: grid integrated PV-FC hybrid system

The photovoltaic [3], [4] and the PEMFC [5], [6] are modeled 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. The P&O MPPT method has been widely used because of its simple feedback structure and fewer measured parameters [7]. The P&O algorithm with power feedback control [1-3] &[6] is shown in Fig. 2. As PV voltage and current are determined, the power is calculated.

2.2 PV Array Model

The one-diode, the two-diode, and the empirical model are the main three common models most commonly used by researchers to describe the behavior of the equivalent electrical circuit of a PV cell [9]. The mathematical model of the one diode equivalent circuit can be expressed as

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

Equation (5) shows that the output characteristic of a solar cell is nonlinear and vitally affected by solar radiation, temperature, and load condition. Photocurrent I_{ph} is directly proportional to solar radiation G_{a}

$$I_{ph}(G_{\mathrm{a}}) = I_{sc}\frac{G_{\mathrm{a}}}{G_{\mathrm{as}}} \qquad (2)$$

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

$$I_{sc}(\mathrm{T}) = I_{scs}[1 + \Delta I_{sc}(\mathrm{T} - \mathrm{T}_s] \qquad (3)$$

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

$$I_{ph}(G_{\mathrm{a}}, \mathrm{T}) = I_{scs}\frac{G_{\mathrm{a}}}{G_{\mathrm{as}}}[1 + \Delta I_{sc}(\mathrm{T} - \mathrm{T}_s] \qquad (4)$$

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

$$I_{sat}\,(\mathrm{G}_a, \mathrm{T}) = \frac{I_{\mathrm{ph}}\,(\mathrm{G}_a,\mathrm{T})}{e^{\frac{V_{oc}\,(\mathrm{T})}{V_t\,(\mathrm{T})}}} \quad (5)$$

The energy through the solar photovoltaic effect can be considered the most necessary and prerequisite sustainable resource because of the ubiquity, large quantity, and sustainability of solar energy. The output characteristics of PV module depends on the solar irradiance, cell temperature and output voltage of PV module. Since PV module has nonlinear characteristics, it is necessary to model it and simulate for Maximum Power Point Tracking (MPPT) of PV system applications. A PV module generates small power, so the task of a MPPT in a PV energy conversion system is to continuously tune the system so that it draws maximum power from the solar array regardless of weather or load conditions. The most commonly used MPPT algorithm is P&O method [6]. This algorithm uses simple feedback arrangement and little measured parameters shown in Fig. 2.

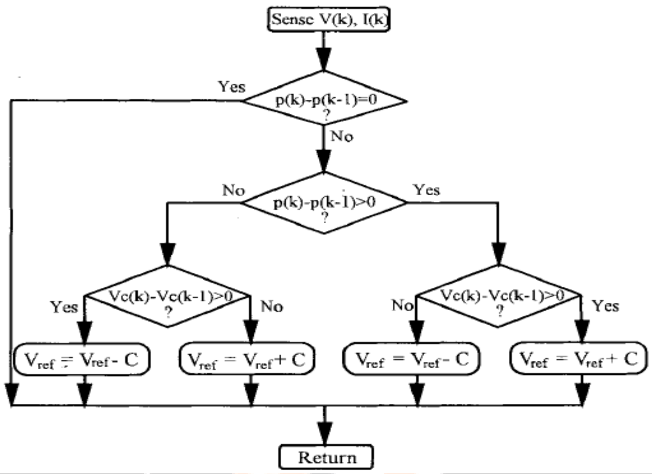

Fig -2: P&O Algorithm

In order to gain high efficiency power with the P&O MPPT algorithm, a buck-boost dc/dc converter is used as depicted in Fig. 3.

The parameters and in the buck-boost converter must satisfy the following conditions:

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

The buck-boost converter consists of one switching device (GTO) that enables it to turn on and off depending on the applied gate signal. The gate signal for the GTO can be obtained by comparing the sawtooth 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.

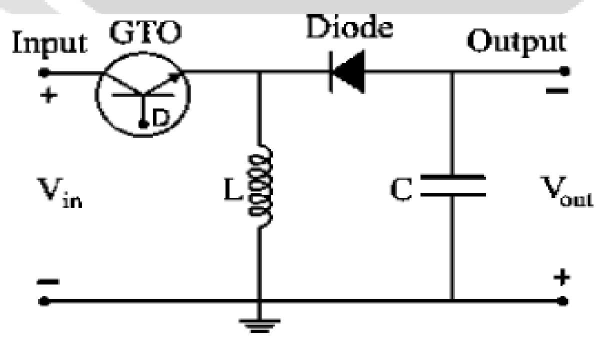

Fig -3: Buck-Boost converter

2.3 Proton Exchange Membrane Fuel Cell (PEMFC)

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:

$$\mathrm{V}_{out} = \mathrm{E}_{Nerst} - V_{act} - V_{ohm} - V_{conc} \quad (6)$$

Where E_{Nerst} is the "thermodynamic potential" of Nerst, which represents the reversible (or open-circuit) voltage of the fuel cell. Activation voltage drop V_{act} is given in the Tafel equation

$$V_{act} = T[a + b\ln(I)] \quad (7)$$

Where are the constant terms in the Tafel equation (in volts per Kelvin)
The overall ohmic voltage drop V_{ohm} can be expressed as

$$V_{ohm} = IR_{ohm} \quad (8)$$

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

$$V_{conc} = -\frac{RT}{zF}\ln\left(1 - \frac{I}{I_{limit}}\right) \quad (9)$$

3. CONTROL AND OPERATING STRATEGY OF THE HYBRID SYSTEM

The control modes in the microgrid include unit power control, feeder flow control, and mixed control mode [8 &9]. In UPC mode if a load increases anywhere in the microgrid, the extra power come from the grid, since every unit regulates to constant output power. In FFC mode extra load demands are picked up by the DG showing a constant load to the utility grid. In this case, the microgrid becomes a true dispatchable load as seen from the utility side, allowing for demand side management arrangements [8].

3.1 Operating Strategy for the Hybrid Power System in 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 P_{MS}^{ref} regulates the output to the reference value. Then

$$P_{PV} + P_{FC} = P_{MS}^{ref} \quad (11)$$

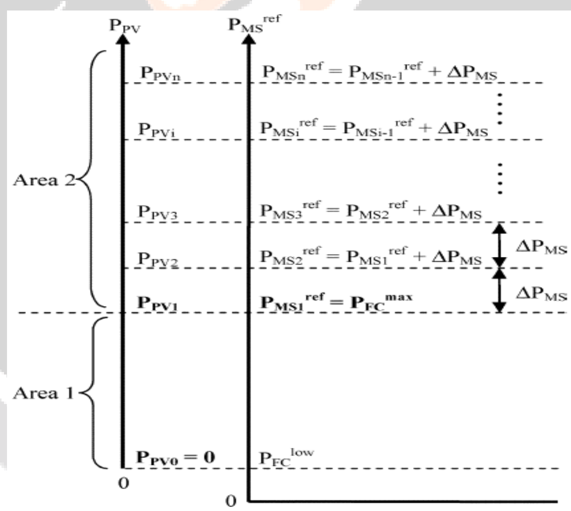

Fig -4: Operation strategy of hybrid source in the UPC mode.

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, 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

$$P_{PV1} = P_{FC}^{up} - P_{FC}^{low} \quad (12)$$

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

If PV output is zero, then (11) P_{FC} deduces 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}. 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

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

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 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_{PVi-1} and, 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

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

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

$$P_{PVi-1} \leq P_{PV} \leq P_{PVi}, \quad i = 1,2,3 \ldots \quad (20)$$

Then we have

$$P_{MSi}^{ref} = P_{PVi} + P_{FC}^{min}, \quad i = 1,2,3 \ldots \quad (21)$$

$$P_{PVi} = P_{PVi-1} + \Delta P_{MS}, \quad i = 2,3,4 \ldots \quad (22)$$

The reference power of the hybrid source in Area 1 and Area 2 is determined by (21) and (22), and are shown in (12), and (16), respectively.

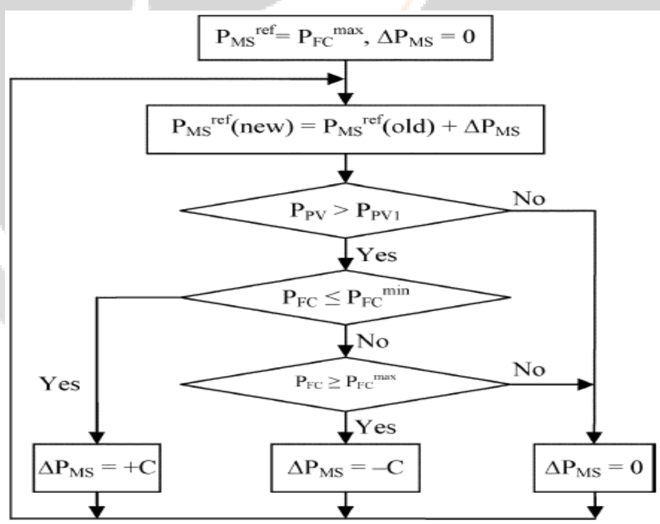

Fig -5: Control algorithm diagram in the UPC mode (P_{MS}^{ref} automatically changing).

Fig.5 shows the control algorithm diagram for determining the reference power automatically. The constant must satisfy (16).If increases the number of change of will decrease and thus the performance of system operation will be improved.

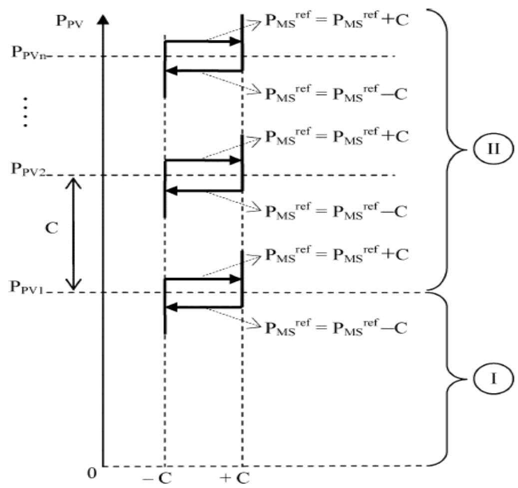

Fig -6: Hysteresis control scheme for P_{MS}^{ref} control.

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. To avoid the oscillations around the boundary, a hysteresis is included and its control scheme to control is depicted in Fig.6.

3.2 Overall Operating Strategy for the Grid-integrated Hybrid Power System

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.

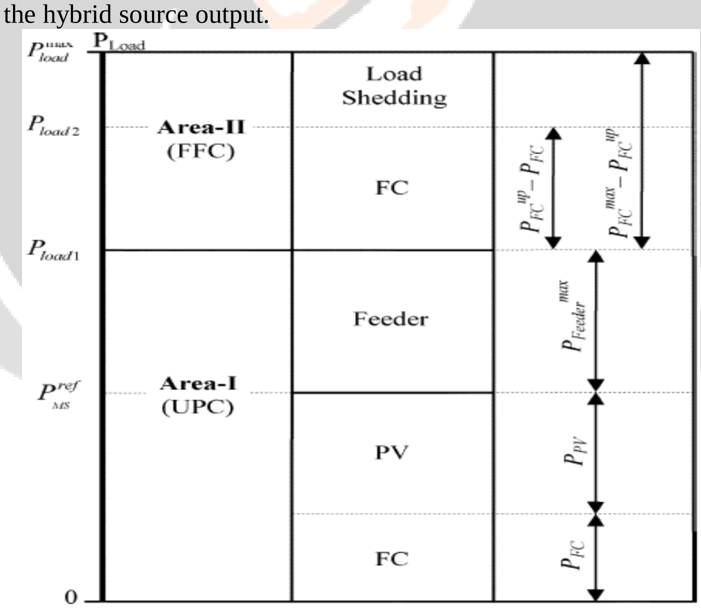

Fig -7: Overall operating strategy for the grid-integrated hybrid system.

If the load is lower than, the redundant power will be transmitted to the main grid. Otherwise, the main grid will send power to the load side to match load demand. When load increases, the feeder flow will increase correspondingly. If feeder flow increases to its maximum, then the feeder flow cannot meet load demand if the load keeps increasing. In order to compensate for the load demand, the control mode must be changed to FFC with respect to Area II. Thus, the boundary between Area I and Area II is

$$P_{load\,1} = P_{Feeder}^{max} + P_{MS}^{ref} \quad (23)$$

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

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

4. RESULTS

Case 1: Simulation results without hysteresis

During FFC mode, the hybrid source output power changes with respect to the change of load demand, as in Fig. 11, On the contrary, in the UPC mode, Pms changes following as shown in Fig.10. It can be seen from Figs. 10, 11 & 12 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. 10 that at 12sec to 13sec and 17sec to 18 sec, P_{MS}^{ref} changes continuously. This is caused by variations of Ppv in the MPPT process. As a result, Pfc and Pms oscillate and are unstable. When the solar power is not maximum (low irradiation) and at that time load is heavier then the fuel cell will gives the required power to meet the load demand as in figure 10 from 4sec to 6sec.

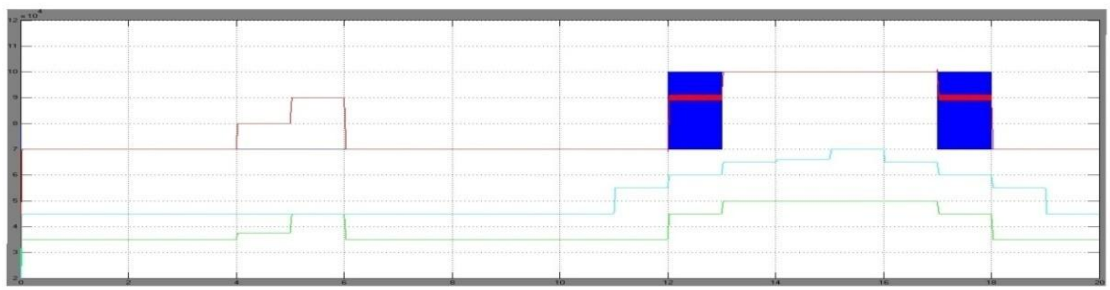

Fig -8: operating strategy of the hybrid source.

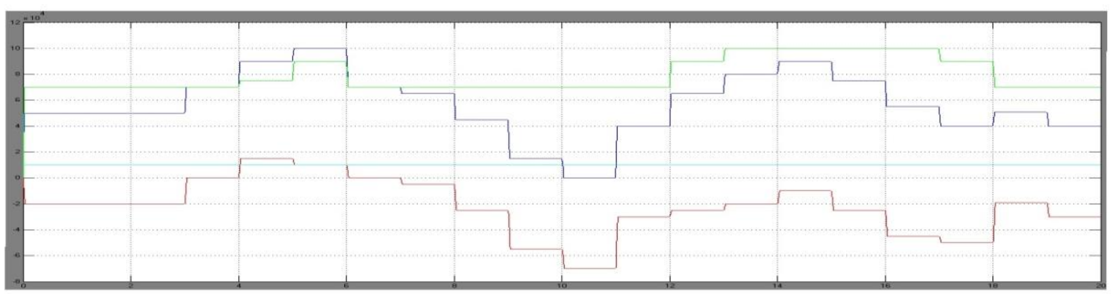

Fig -9: operating strategy of the whole system.

Fig -10: change of operating modes.

Case 2: Simulation results including hysteresis control

Figures 11& 12 are the simulation results of the grid integrated hybrid power system with including hysteresis control scheme. 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. So the system with using hysteresis control scheme will improve the performance of operation, obtains system stability and minimizes the number of mode changing operations. Figure.13 simulation result for the systems frequency response. Here with the presented operating algorithms the frequency of system did not reach over its limit. The frequency limit was ±5%.

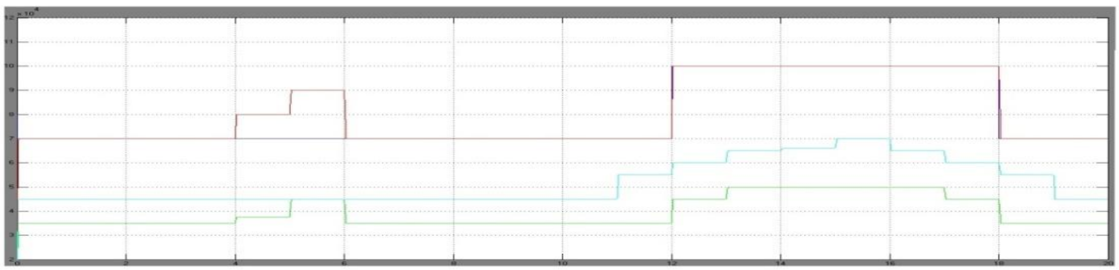

Fig -11: operating strategy of the hybrid source using hysteresis.

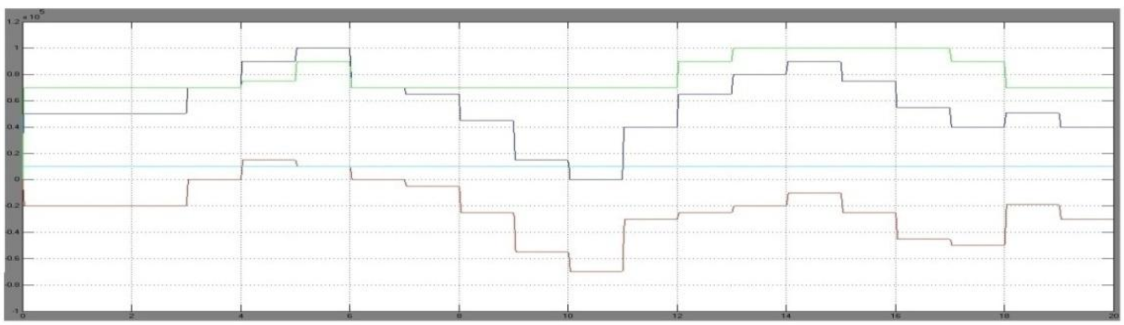

Fig -12: operating strategy of the whole system using hysteresis

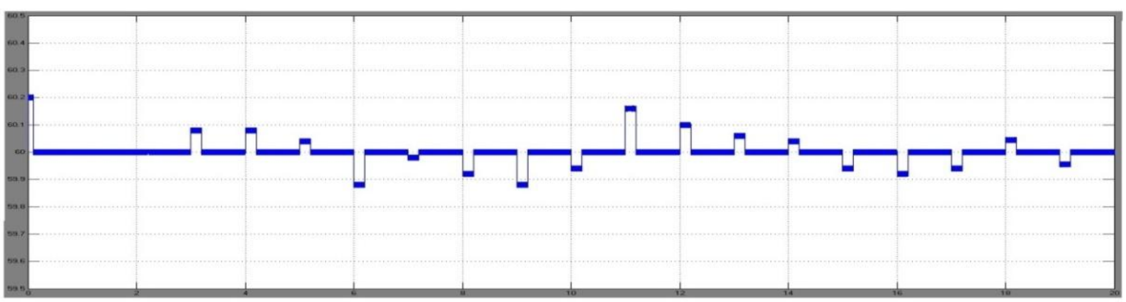

Fig -13: frequency variations occurs in the system

5. CONCLUSION

The overall goal of this paper is to investigate the operation of a grid integrated PV-FC hybrid system. The hybrid system, composed of a PV array and PEMFC, was considered. A comparison between different system operating strategies such as UPC mode and FFC mode are studied. The purposes of the proposed operating strategy presented in this thesis is to determine the control mode, to minimize the number of mode changes, to operate PV at the maximum power point, and to operate the FC output in its high-efficiency performance band.

The main operating strategy, shown in Fig.7 is to specify the control mode; the algorithm shown in Fig.4 is to determine 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.

The system can maximize the generated power when load is heavy and minimizes the load shedding area. When load is light, the UPC mode is selected and, thus, the hybrid source works more stably. The changes in operating mode only occur when the load demand is at the boundary of mode change otherwise; the operating mode is either UPC mode or FFC mode. Besides, the variation of hybrid source reference power is eliminated by means of hysteresis. In addition, the number of mode changes is reduced. As a consequence, the system works more stably due to the minimization of mode changes and reference value variation. In brief, the presented 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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