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Method for Load Sharing and Power Management in a Hybrid PV/Battery Source Islanded Microgrid

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***Abstract*—This paper presents a decentralized load sharing and power management method for an islanded microgrid composed of PV units, battery units and hybrid PV/battery units. The proposed method performs all the necessary tasks such as load sharing among the units, battery charging and discharging and PV power curtailment with no need to any communication among the units. The proposed method is validated experimentally.**

***Keywords*—islanded microgrid; decentralized power management; hybrid PV/battery; battery SOC.**

I. Introduction

Due to environmental concerns and continuous decrease in the price, utilization of photovoltaic (PV) generation systems has been increasing in the recent years. Because of the intermittent nature of the PV power output, storage batteries are integrated to PV systems and a set of PV sources, batteries and loads can form a microgrid. Battery storage can be connected through an inverter as a separate unit to the microgrid or can be combined with the PV unit forming a hybrid source unit [1], [2].

In islanded mode of operation, the control system objective is to share the load among different units and balance the power in the microgrid while considering power rating of the units and State of Charge (SOC) of the batteries. For eliminating communication among units, decentralized methods are used for controlling microgrids. In previous works, several decentralized control strategies are proposed. In [1-3] three power management methods are proposed based on frequency signaling but the application of these methods are limited to the microgrids composed of only one energy storage unit. In [4] a frequency based energy management strategy is proposed for a microgrid with distributed battery storage but it is only valid for systems with separate battery units not hybrid source units. Similarly the method proposed in [5] is only applicable to separate battery units. The strategy proposed in [6] considers a separate battery storage unit and a PV unit connected to a droop controlled microgrid while the decentralized power management strategy proposed by the same authors in [7] considers a single PV/battery hybrid unit connected to a droop controlled islanded microgrid. This strategy is very useful for a single hybrid unit connected to a microgrid that contains only droop controlled sources, however if there are multiple hybrid units or there are other battery storage units in the microgrid, this strategy will not be applicable.

This paper proposes a decentralized method for power management and load sharing in an islanded microgrid consisting of different PV units, battery storage units and hybrid PV/battery units. Unlike previous works, the proposed method is not limited to the systems with separate PV and battery units or systems with only one hybrid unit. A modified droop method is used in the proposed method that uses the frequency as trigger for different state changes in each unit. The main contributions of the proposed method are:

- When the microgrid load is more than total PV generation, all PV sources (in both separate and hybrid units) operate in Maximum Power Point (MPP) and all the batteries (in both separate and hybrid units) supply the surplus load power. The droop equations are chosen such that the surplus power is shared among the batteries such that batteries with higher SOC have higher discharging power.

- If some batteries have not reached to charge limiting mode and the total PV generation is more than microgrid load, the batteries are being charged with the excess PV power. The excess power is shared among the batteries such that batteries with lower SOC absorb more charging power.

- When the microgrid load is less than total PV generation and all batteries are in charge limiting mode, PV power curtailment is performed and the load is shared among the units that have PV source based on the inverter capacity and considering their available PV power.

It is worth noting that the proposed method is applicable to both single phase and three phase microgrids but for simplicity single phase microgrid is considered in this paper. Moreover, other sources other than PV can be used in the units.

The rest of the paper is organized as follows: in section II the general structure of the hybrid source single phase microgrid is presented. A microgrid with three hybrid units is considered in this study. In section III the proposed method is presented in detail and different operating modes of the whole microgrid and operating states of each unit in the microgrid are presented. The proposed method is validated experimentally in section IV. Section V concludes the paper.

II. Single Phase Microgrid Structure

A general single phase microgrid system consisting of PV units, battery units and hybrid source units is depicted in Fig. 1. For being comprehensive, a microgrid with three hybrid units is considered in the following analysis. The proposed method can be easily applied to separate PV and battery units with minor changes. All the microgrid loads are centralized in a single load.

By using an inductance in the output filter of each unit and by implementing virtual inductance [8], it is assumed that the output impedances of units are mainly inductive and a modified *P-f*, *Q-E* droop method is utilized in the proposed control method. The inner voltage and current loops are studied in other papers and they are not addressed in this paper.

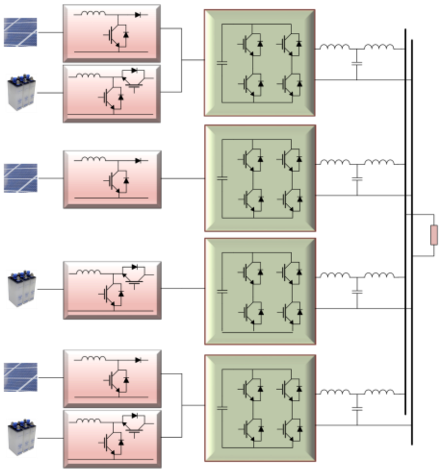

Fig. 1. Single phase microgrid system

III. PROPOSED METHOD

In this section, first, the general operating modes of the whole microgrid is described; then, the operating states of each hybrid unit and criteria for changing of states are described. It is worth mentioning that battery power, P_{Bat}, is positive in discharging mode and is negative in charging mode.

A. General Operating Modes of the Whole Microgrid

Depending on the total maximum available PV power, total charging capacity of the batteries and total load in the microgrid, it can operate in three main modes:

Mode I) Battery Discharging Mode

In this mode, the total microgrid load is more than total PV maximum power, i.e.

$$P_{LD} > \sum_{i=1}^{m} P_{PV-MP_i} \quad (1)$$

where P_{LD} is the load power, P_{PV-MP_i} is the maximum PV power of Unit_i and m is the number of units in the microgrid. P_{PV-MP_i} depends on the solar irradiance and temperature of the PV array.

In this mode, all PVs work at MP and the batteries supply the surplus load power, $P_{LD} - \sum_{i=1}^{m} P_{PV-MP_i}$. The dc-link voltage, V_{dc} is controlled by battery boost converter. In order to share the surplus load power among the units, load is shared such that the required total discharging power of the batteries is shared among units based on the State of Charge (SOC) of the unit's battery. The droop coefficient is selected to be inversely proportional to SOC of the battery similar to method proposed in [9, 10]for DC microgrids. To achieve this battery power sharing strategy, following droop equation is used:

$$f = f_0 + m_p (P_{PV-MP} - P_{out}), m_p \propto \frac{1}{SOC^n} \quad (2)$$

where n is selected as described in [9, 10]. In this strategy, considering that discharging power of the battery is

$$P_{Bat} = P_{out} - P_{PV}, \quad (3)$$

if m_p is same for all units, the battery discharging power of all units are equal regardless of their PV power (unless output power reaches inverter rating limit which is discussed in the next section.)

Mode II) Battery Charging Mode

In this mode, the total microgrid load is less than total PV maximum power and at least the battery of one unit has the capability to absorb the surplus power, i.e. one of the units has not reached to battery charge limiting mode. In this mode, all PVs work at MP. In units that are not in charge limiting mode, V_{dc} is controlled by battery boost converter, in addition, the inverter is controlled in Voltage Control Mode (VCM) and the *P-f* droop is selected similar to Mode I. The droop coefficient is selected to be proportional to SOC of the battery similar to method proposed in [10] for charging mode so that batteries with higher SOC absorb less power:

$$f = f_0 + m_p (P_{PV-MP} - P_{out}), m_p \propto SOC^n \quad (4)$$

In units that enter to charge limiting mode, V_{dc} is controlled by controlling output power, in addition, the inverter is controlled in Power Control Mode (PCM) and output power is controlled with following equations,

$$P_{ref} = (K_{V-P} + \frac{K_{V-I}}{s})(V_{dc} - V_{dc}^*) \quad (5)$$

$$f = f_0 + (K_{P-P} + \frac{K_{P-I}}{s})(P_{ref} - P_{out})$$

where P_{ref} is the reference value of output power, V_{dc}^* is reference value of dc-link voltage, K_{V-P} and K_{V-I} are proportional and integral gains of V_{dc} controller and K_{P-P} and K_{P-I} are proportional and integral gains of output power controller. Note that in steady state,

$$P_{ref} = P_{PV-MP} - |P_{Bat-ChLimit}| \quad (6)$$

where $P_{Bat-ChLimit}$<0 is battery charging power in charge limiting mode. $P_{Bat-ChLimit}$ is zero when battery reaches SOC_{max} and has varying value in constant current and constant voltage charging modes. This control strategy ensures charging power distribution between all batteries. It is worth mentioning that each battery can be charged with PV power of other units.

Fig. 2-a shows the P-f characteristics of a two hybrid unit microgrid system in Modes I and II. It is assumed that SOC_1>SOC_2; therefore, the discharging and charging powers of Unit1 battery are higher and less than that of Unit2 battery, respectively. In this figure, f_I and f_{II} are sample equilibrium

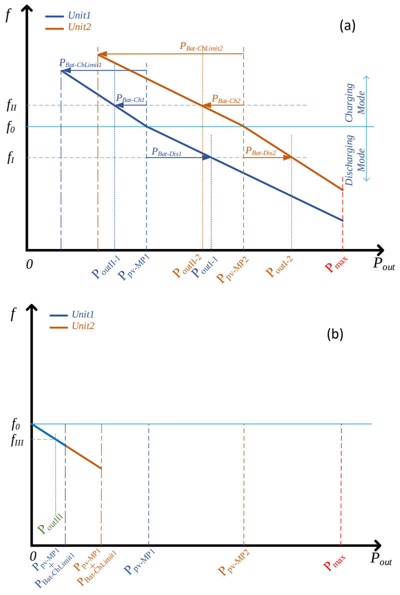

Fig. 2. P-f characteristics of a two hybrid unit microgrid system in a) Modes I and II assuming $SOC_1>SOC_2$ b) Mode III

frequencies in discharging and charging modes, P_{outI} and P_{outII} are corresponding output powers, and $P_{Bat\text{-}Dis}$ and $P_{Bat\text{-}Ch}$ are corresponding discharging and charging powers, respectively.

Mode III) PV Power Curtailment Mode

In this mode, the sum of total microgrid load and total charging capacity of the batteries is less than total PV maximum power, i.e.,

$$P_{LD} + \sum_{i=1}^{m} P_{Bat-ChLimit_i} < \sum_{i=1}^{m} P_{PV-MP_i} \tag{7}$$

therefore, PV power curtailment should be performed and some PVs must deviate out of their maximum power. In this mode all batteries are charged with maximum power, units with low PV maximum power work at MP and are controlled in PCM, units with high PV maximum power are controlled in VCM and PV boost converter controls the dc-link voltage. The simple *P-f* droop is used for VCM units in this mode:

$$f = f_0 - m_p P_{out}, m_p = \frac{\Delta f_{max}}{P_{max}} \tag{8}$$

Fig. 2-b shows the P-f characteristics of a two hybrid unit microgrid system in Mode III. It is assumed that m_p is equal for two units. In this figure, f_{III} is a sample equilibrium frequency and P_{outIII} is its corresponding output power for two units.

B. Operating States of Each Unit in the Microgrid

The general operating modes of the microgrid was described in previous section. In this section, the detailed operating states of a single unit in the microgrid and criteria for different state changes are presented. In the following, “this unit” refers to the single unit under control.

Each unit in the microgrid can be in five states:

State 1) VCM, battery charge/discharge, V_{dc} is controlled by battery boost converter

This state is associated with Mode I or VCM condition of Mode II of the described operating modes. In this state, PV works at MPP and battery boost converter controls V_{dc} by either charging or discharging of the battery. If total PV maximum power is less than load power and battery is in discharging mode, (2) is used for controlling output power; otherwise, (4) is used. Note that in (4), if $P_{PV\text{-}MP}$ is small or zero, P_{out} can be negative which means that battery is charged with power delivered by the microgrid.

Criteria for exiting from State 1:

- If *SOC* of the battery reaches to its minimum value, SOC_{min}, state is changed to State 4.
- If output power reaches inverter rating limit, $P_{out\text{-}max}$, state is changed to State 5.
- If battery is completely charged or battery reaches its maximum charging power due to decrease in load or increase in PV generation; in other words, when $SOC=SOC_{max}$ or $P_{Bat}=-P_{Bat\text{-}ChLimit}$ or $I_{Bat}=I_{Bat\text{-}max}$ or $V_{Bat} = V_{Bat\text{-}max}$, state is changed to State 2.

State 2) PCM, Battery charge limit, V_{dc} is controlled by output power

This state is associated with PCM condition of Mode II of the described operating modes. In this state, PV works at MPP, battery is in charge limiting mode and V_{dc} is controlled by (5).

Criteria for exiting from State 2:

- If because of decrease in load, increase in total PV generation or decrease in total battery charging power (as a result of reaching SOC_{max} or entering constant voltage charging mode) all units enter this state from State 1, due to using PI controller in (5) *f* increases in all units until it saturates to f_{max}. At this point all units change to State 3 to reduce PV power generation and keep the power balance.
- If at least one of other units is in State 1 in battery charging mode and the others—including this unit—are in State 2, (i.e. all batteries are in charging mode but some of them are in charge limiting mode) if load is increased or total PV generation is decreased, charging power of units in State 1 decreases and according to (4) *f* decreases. When charging power of units in State 1 multiplied by m_p of the units is less than a determined ratio of this unit’s corresponding value, unit must return to State 1. In other words, when

$$\left| m_{p-i} P_{Bat-S1-i} \right| < K_{ch} \left| m_p P_{Bat} \right|, \tag{9}$$

if state is returned to State 1 and the total charging power is shared again based on (4), this unit will no longer enter battery charge limit mode and return to State 2. $P_{Bat\text{-}S1\text{-}i}$ is charging power of i^{th} unit which is in State 1 and $K_{ch}<1$ is a margin used for preventing unwanted changing of state because of error in measuring power. Note that according to (4) $m_{p\text{-}i}P_{Bat\text{-}S1\text{-}i}$ are equal for all units in State 1. As P_{Bat} is negative in charging mode, (9) can be written as

$$m_{p-i} P_{Bat-S1-i} > K_{ch} m_p P_{Bat} \tag{10}$$

Since $m_{p\text{-}i}P_{Bat\text{-}S1\text{-}i}$ is not measurable directly, it can be determined according to f. As PI controller is used in (5), the unit's frequency follows the frequency of other units that are in State 1; therefore, after some manipulation using (3), (4) and (9) the criterion for returning from State 2 to State 1 is:

$$f < f_0 - K_{ch} m_p P_{Bat} \text{ and preState} = 1. \quad (11)$$

In the worst case that the unit is in SOC_{max} and P_{Bat} =0, if $f<f_0$ it means that other units are in discharging mode and this unit starts to discharge.

- If because of increase in load or decrease in total PV generation all units enter this state from State 3, due to using PI controller in (5) f decreases in all units until it saturates to f_{min}. At this point all units change to State 1 in order to reduce the battery charging power or enter battery discharging mode.

If at least one of other units is in State 3 and the others—including this unit—are in State 2, when load is decreased or output power of this unit is increased because of increase in the unit's PV generation, output power of units that are in State 3 decrease and according to (8) f increases. When output power of the units that are in State 3 multiplied by m_p of the units is less than a determined ratio of this unit's corresponding value, unit must return to State 3. In other words, when

$$m_{p-i} P_{out-S3-i} < K_{pc} m_p P_{out}, \quad (12)$$

if state is returned to State 3 and load is shared again based on (8), this unit will no longer return to State 2 because of insufficient PV power. $P_{out\text{-}S3\text{-}i}$ is output power of i^{th} unit which is in State 3 and K_{pc}<1 is a margin used for preventing unwanted changing of state because of error in measuring power. Note that in State 2, P_{out} is equal to P_{ref} determined by (6) in steady-state; furthermore, according to (8) $m_{p\text{-}i}P_{out\text{-}S3\text{-}i}$ are equal for all units in State 3. Since $m_{p\text{-}i}P_{out\text{-}S3\text{-}i}$ is not measurable directly, it can be determined according to f. As PI controller is used in (5), the unit's frequency follows the frequency of other units that are in State 3. Since P_{out}>0 for units that are in State 3, criterion (12) can be written as,

$$f_0 - m_{p-i} P_{out-S3-i} > f_0 - K_{pc} m_p P_{out} \quad (13)$$

and based on (8) the criterion for returning from State 2 to State 3 is:

$$f > f_0 - K_{pc} m_p P_{out} \text{ and preState} = 3. \quad (14)$$

State 3) VCM, PV power curtailment, V_{dc} is controlled by PV boost converter

This state is associated with Mode III of the described operating modes in which total PV maximum power is more than total power required by load and charging of the batteries. In this state, the unit's battery is charged with maximum power, output power is controlled by (8) and PV boost converter controls V_{dc}.

Criterion for exiting from State 3:

- If the PV maximum power is less than sum of output power determined by (8) and battery charging power, state is changed to State 2. This criterion happens when the unit is in State 3 and either load is increased or PV generation is decreased, or when all units enter to State 3 from State 2 but PV power is not sufficient for this unit.

State 4) PCM, Battery disconnection, V_{dc} is controlled by output power

When SOC of the battery reaches to SOC_{min} the unit enters this state. In this state, battery is disconnected to prevent damage due to its deep discharging, PV works at MPP and V_{dc} is controlled by (5). Since P_{Bat}=0, in the steady-state

$$P_{out} = P_{PV-MP}. \quad (15)$$

Criterion for exiting from State 4:

- If all units enter this state and load power is more than total PV maximum power, f decreases until it reaches the critical minimum frequency. At this point load shedding is inevitable and some non-critical loads must be disconnected. Load shedding is out of scope of this paper.
- According to (2) and (4), if $f>f_0$ it means that P_{Bat}<0 in units that are in State 1 and they are in battery charging mode. Therefore, this unit can return to State 1 to charge the battery.

State 5) PCM, Output power limiting, V_{dc} is controlled by battery boost converter

When output power of the unit reaches $P_{out\text{-}max}$, the unit enters this state to limit its output power. In this state, PV works at MPP and V_{dc} is controlled by battery boost converter by discharging. Output power is controlled by (5) with P_{ref}= $P_{out\text{-}max}$.

Criteria for exiting from State 5:

- If all units enter this state and load power is more than total ratings of the units, f decreases until it reaches the critical minimum frequency. At this point load shedding is inevitable and some non-critical loads must be disconnected.
- If the unit is in output power limiting and load is decreased such that battery discharging power of other units in State 1 multiplied by m_p of the units is less than a determined ratio of this unit's corresponding value, unit must return to State 1. In other words, when

$$m_{p-i} P_{Bat-S1-i} < K_{pl} m_p P_{Bat} \quad (16)$$

if state is returned to State 1 and the load is shared again based on (2), this unit will no longer enter output power limiting. K_{pl}<1 is a margin used for preventing unwanted changing of state because of error in measuring power. Similar to previous discussions, this criterion can be determined indirectly by f and after some manipulation the criterion can be written as,

$$f > f_0 - K_{pl} m_p P_{Bat}. \quad (17)$$

Different states of each unit have been summarized in Table I. In addition, criteria for changing the states have been depicted in Fig. 3.

Table I Summary of states of each unit

State	1 Battery Charge/ Discharge	2 Battery Charge Limit	3 PV Power Curtailment	4 Battery Disconnect	5 Output Power Limit
Control mode	VCM	PCM	VCM	PCM	PCM
V_{dc} Control	Battery	Pref	PV	Pref	Battery
PV Power	MPP	MPP	<MPP	MPP	MPP

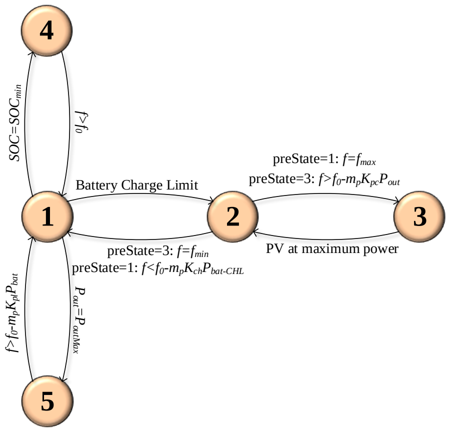

Fig. 3. Criteria for changing the states of each single unit in the microgrid

Fig. 4. Experimental setup

IV. Experimental Results

The proposed method has been evaluated experimentally using the experimental setup shown in Fig. 4. It consists of three Danfoss three phase inverters used as single phase inverters, a real-time dSPACE1006 platform, LCL filters and load. Batteries and PVs are emulated as Hardware In the Loop (HIL).

Fig. 5. shows the state, output power, PV power, battery power and output frequency of each unit in different load and PV generation conditions. In this experiment m_p is considered equal for all units for clarity of the results. The maximum PV powers of Units 1, 2 and 3 are considered 300W, 500W and 600W, respectively and the maximum charging powers of Units 1, 2 and 3 are considered 400W, 300W and 150W, respectively.

At start all units are in State 1 and load power which is 1700W is shared between units such that the battery discharging power of all units are equal. All PVs work at MP in this state.

At t=20s, load is decreased to 1400W, therefore discharging power of all batteries decrease to 5W.

At t=40s, load is decreased to 1100W and since total PV generation is more than load, all batteries enter to charging mode with equal charging power.

At t=60s, load is decreased to 800W, as a result, charging power of all units increase. Since Unit3 reaches its maximum charging power, it changes to State 2 with constant output power equal to $P_{pv\text{-}MP}+P_{Bat\text{-}ChLimit}$ in steady state. The remaining charging power is shared between Units 1 and 2 equally based on (4).

At t=80s, load is decreased to 500W, as a result, charging power of Units 1 and 2 increase. First Unit 2 reaches its maximum charging power and changes to State 2 and in a short time, Unit 1 also reaches maximum charging power and changes to State 2. Since all units are in State 2, frequency increases until it saturates to f_{max}. At this point all units change to State 3; however, since PV power is not sufficient for supplying both battery charging power and output power determined by (8) in Units 1 and 2, they return to State 2. Note that output power of Unit1 is negative at State 2 which means it is absorbing power from the microgrid to charge its battery.

At t=100s, load is decreased to 200W, since Units 1 and 2 are controlled in constant power, output power of Unit3 decreases and consequently f increases based on (8). After 3s criterion (14) is validated in Unit2 and it changes to State3 and decreases its PV generation.

At t=120s, irradiance of unit1 PV is increased and therefore unit1 PV maximum power increases from 300W to 600W; consequently output power of Unit1 increases to 600W. Since load power is constant it results in decreasing output power of Unit3 and increasing in f based on (8). After 3s criterion (14) is validated in Unit1 and it also changes to State3. At this point all units are in State 3 having same output power, battery charging with maximum power and deviating out of their maximum PV power.

At t=140s, load is increased to 500W and output power of all units increase equally. Since none of them reach maximum PV power, they remain at State3.

At t=160s, load is increased to 800W. Output power of all units increase but Units 1 and 2 reach their maximum PV power and change to State 2.

At t=180s, load is increased to 1100 W. Unit3 reaches its maximum power and it also changes to State 2. Since all units are in State 2, frequency decreases until it saturates to f_{min}. At this point all units change to State 1; however, since Unit3 battery charging power determined by (4) is more than its maximum value, it returns to State 2.

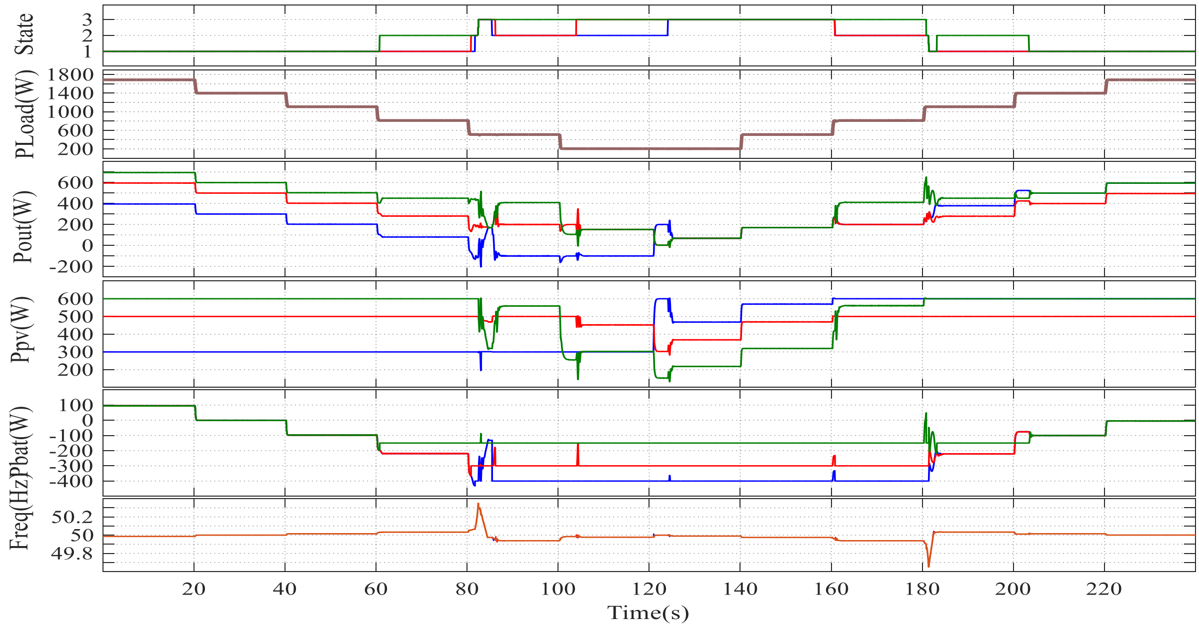

Fig. 5. Experimental results of a three unit single phase microgrid in different load and PV generation conditions. Blue: Unit1 Red: Unit2, Green: Unit3

At t=200s, load is increased to 1400W. Output power of Units 1 and 2 increase resulting in decrease in *f* based on (4). After 3s, criterion (11) is validated in Unit3 and it also changes to State 1. At this point all units are in State 1 having same battery charging power and PVs at their maximum power.

At t=220s, load is increased to 1700W and the charging power of all units decrease equally to -4W.

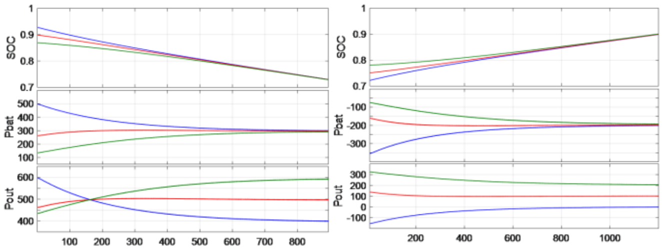

Fig. 6. SOC balancing in a) discharging mode b) charging mode

Fig. 6-a. shows SOC balancing of the batteries in discharging mode. All the units are in State 1 and the discharging power of the batteries are determined by (2) with n=15. Load power is 1500W, PV_1=100W, PV2=200W, PV3=300W. Fig. 6-b. shows SOC balancing of the batteries in charging mode. The charging power of the batteries are determined by (4) with n=15.

V. Conclusion

A decentralized method was proposed in this paper for load sharing and power management in an islanded microgrid with PV units, battery units and hybrid PV/battery units. The proposed method uses frequency as trigger for different state changes in each unit. The proposed method was validated experimentally with a three unit setup.

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