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Control of single-phase islanded PV/battery minigrids based on Power-Line Signaling

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Abstract—Power regulation of all converter units in a microgrid should not be only determined by load demand, but also by the available power of each unit, i.e. a converter fed by a battery. Energy management control is essential in order to handle the variety of prime movers which may include different types of renewable energy sources (RES) and energy storage systems (ESS). Specifically, the recharging process of secondary battery, the most prominent ESS, should be done in a specific manner to preserve its life-time, microgrid line voltage must be kept within the bounds and the energy offered by RES should be utilized as efficiently as possible. This paper proposes a coordinated control strategy based on power-line signaling (PLS), instead of common communications, for a single-phase minigrid in which each unit can operate in different operation modes taking into account the resource limitation. The whole system is explained ahead and finally, Hardware in the loop results obtained with a dSPACE are presented in order to validate the proposed control strategy.

Index Terms- Single-phase, minigrid, microgrid, PLS.

I. INTRODUCTION

Classical power systems make use of large power plants located far from the consumption points, at adequate places and transferring all the generated power through long, expensive transmission lines. This power system has to be continuously regulated by control centers to ensure the quality of the power, voltage and frequency. Nevertheless, nowadays this way of procedure is changing slowly but uninterruptedly due to the increasing number of dispersed distributed generation units (DG) and the integration of distributed storage systems (DS), including both renewable and non-renewable sources, like ESS [1]. The installation of small wind turbines and photovoltaic (PV) generators at user's home has become a new trend in many countries, so, in order to deal with them and also with the dispersed loads, intelligent microgrids appear to be a good solution. This will be a key point to cope with new functionalities, as well as to integrate RES into the grid. Those small grids should be able to generate and store energy near to the consumption points. This avoids large distribution lines coming from big power plants located far away from the consumption areas [2]. DG units are usually low cost, low voltage and low power (typically microturbines, PV and batteries). Power electronics provide the control and flexibility required by a microgrid [3], [4].

A microgrid can be operated either in island mode or grid-connected with similar configuration [5]. The main difference remains in the power balance in islanded microgrids, where

energy generation and power consumption must be in equilibrium and well coordinated [6]. Due to the intermittent nature of RES, added together with unpredictable load fluctuations, may cause instantaneous power unbalances that affect the operation of the microgrid. Hence, ESS are required to guarantee reliability, security and power stability [7]. A common mode of working is using RES to provide the maximum power they can to the loads and the ESS as a backup compensator, absorbing and injecting power when it is possible and/or necessary. If the batteries of the ESS are completely charged, the absorption of extra power from RES is not allowed, so they have to reduce the injection of power and work in another equilibrium point, lower than the maximum [2]. However, a practical islanded system may suffer from the lack of power generation or energy storage. These possible situations requires to work in a flexible way combining maximum power point tracker (MMPT) algorithms for RES with the state of charge (SoC) of the ESS. A good coordination between RES and ESS can make the difference between a reliable microgrid and a non-stable one.

For the coordination of RES and ESS in ac stand-alone systems, many techniques have been proposed. Some of them make use of central supervisory controllers with communication setups [8], [9]. However, since the control capability could be the best, the reliability is not suitable for a such sensitive and complex system. Moreover, with an increase in the number of units, their connectivity may require extensive hardware [7], [10].

In [11], a concept named distributed bus signaling (DBS) is proposed to avoid the use of a central controller for communications. This class of control methods are commonly used for industrial islanded systems in order to send messages to other points of the grid without the special need of a physical emitter and a demodulator. However, even though the need for supervisory controller is eliminated when DBS strategy is used, some other major issues are opened: for instance, fixed common voltage deviations are inherent to particular system operating mode, limiting the number of modes that can be reliably used [7]. In order to deal with this disadvantages, in [12] a method based on PLS for a three phase ac power system is proposed. The concept consists of using the power lines as carriers of sinusoidal logic signals only and the PLS has been proposed as a more flexible extension of DBS. The advantage over DBS is that instead of having fixed voltage deviation

throughout the particular operating mode, PLS signals are used as triggers for mode transitions where deviation can be optionally canceled by secondary control action without affecting proper operation [7]. Moreover, for typical small-scale stand-alone power systems, the use of this method is quite recommended, but it is not for big grids with resistive lines due to the fact that the signal can be lost during the process. In this paper, a similar methodology was used but using frequency signals instead of voltage ones. This means that depending on the value of the signal's frequency, the response of the slaves converters must be different.

This paper presents an islanded single-phase minigrid formed by one ESS which will be the master inverter that will generate the nominal voltage and frequency of 230 V rms and 50 Hz, and two RES. These RES consist of two independent groups of PV panels, that means both units are totally independent in terms of power generation. As the minigrid fulfill the previous premise of being a small-scale system, the use of a PLS is a good proposal in order to coordinate all the converters and control quite accurately the charge of the battery.

The paper is organized as follows. In Section II the physical configuration of the minigrid is presented and the primary control of each of the elements is revised: it will be explained how the decisions are taken in function of the SoC of the battery. Section III is dedicated to show the proposed PLS distributed energy management strategy, how the PLS frequency was chosen and also how to isolate this signal from the main voltage at 50 Hz, which is much bigger. In Section IV many issues related to the control of all the converters are presented: inner loops, calculation of frequencies and angles for synchronous transformations, SoC estimation algorithm or the MPPT method. Straightaway, some simulation results obtained with the dSPACE will be shown in Section V. Finally, it will be reached the part of Conclusions and Future developments.

II. MINIGRID STRUCTURE

In Fig. 1 an islanded single-phase minigrid which is made by a ESS unit and two RES ones is shown. In this configuration, ESS will work as a voltage source and RES, as they collaborate injecting power, will operate as current mode voltage sources inverters (CM-VSI). As it was explained in Section I, in general, in order to take the more possible advantage from renewables, RES units operate at the maximum power point. However, renewable power is usually kind of unpredictable, so a backup power is needed. Thus, the batteries have to be always available to compensate the likely variations in the power given by RES or demanded by the loads. Since in some cases, the power at the MPPT supplied by RES is bigger than the needed by the loads and hence there is a battery system, the best option is to charge the energy storage devices while it is possible. The SoC will increase while this injection of current continues, but when it reaches certain value, this extra power must be reduced in order to protect the batteries and avoid the destruction of the device. Hence, a coordinated control of

RES based on the SoC of the batteries is needed and it can be basically stated in three points:

- SoC is below 95%: keep RES at MPPT.
- SoC reaches 95%: begin to smoothly move the operating point of the PV panels, reducing in this way the power injected in the minigrid.
- At some moment, ESS needs to supply a load and SoC starts to decrease. PV panels begin to go back to the MPP.

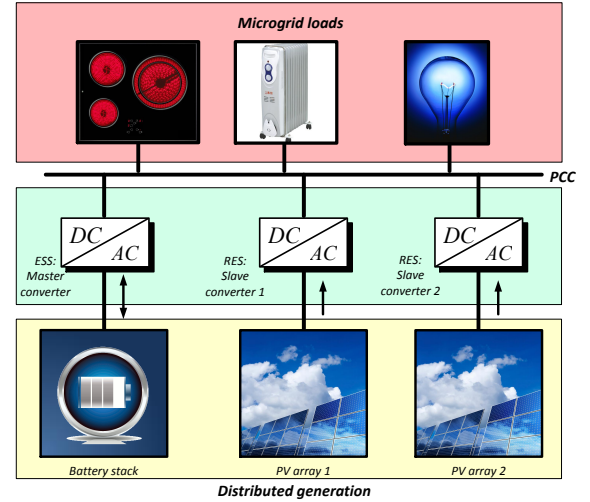


Fig. 1: Diagram of a small-scale minigrid.

III. PLS PRINCIPLE AND PROPOSED CONTROL TECHNIQUE

In order to control RES units without communications, in this paper is used a technique previously done in [12] but adapted to a single-phase minigrid needs. For decades, the power utilities have employed frequency droop to realize real power sharing among the generation facilities. Considering one facility, as power draw increases, the frequency is decreased. This reduces the phase angle of the voltage from that plant relative to the rest of the network [12]. Each plant has a droop coefficient associated with its output rating such that all the plants lower their frequency. Eventually, all the plants will have the same frequency and each will be putting out the same per-unit power. As the total load on the network increases, the frequency will decrease. The frequency of the network, therefore, indicates the per unit load on the system [12].

In the proposed technique, a small ac voltage signal is injected into the system as a control signal. When RES units detect it, they will start to decrease the injected power. When the SoC reaches the minimum level to activate the PLS, it will be injected by the master converter. Hence, this small signal will not be always in the minigrid, but only when it is necessary to control RES units. In order to detect this signal, the procedure will be:

- measure the capacitor voltage at the capacitor of the RES filter,
- filter the voltage and extract the desired frequency,

- use a phase-locked loop (PLL) to detect the value of this frequency,
- depending on this value, calculate the new operating point of the PV panel.

A. Selection of the PLS frequency

In order to avoid any kind of conflict with key frequencies, like the harmonic ones for a 50 Hz grid, the selection of the signal's frequency has to be done wisely. In [12] is given a clue, taking into account possible sidebands around the selected frequency affected by the fundamental. As a first approach to this kind of solution in these ac systems, the selected frequency range has been chosen between 175 and 180 Hz. Thus, there is no objection with harmonics or any other consideration. In Fig. 2 it can be seen the distribution of the harmonic content and how the PLS does not have any special relevance. Typical loads can be roughly divided into passive and active ones, but all of them are usually designed for a specific main range of frequencies (50 to 60 Hz). The introduction of a small signal of 170 Hz does not affect its behavior.

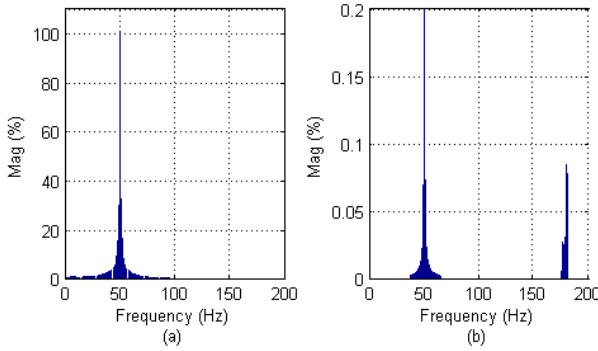


Fig. 2: Frequency analysis: (a) Before injecting PLS (b) After injecting PLS.

B. Detection of the PLS

As it can be seen in Fig. 2, this signal is very small in comparison with the line voltage, so high order filters are needed [12]. In this paper, a fourth-order bandpass filter in series with a bandstop was tuned in order to reduce to the minimum the 50 Hz component, which is much bigger (see Fig. 3).

After having the signal filtered, a PLL is able to detect the frequency and give a precise value.

C. Control of the PV panels with the PLS

As it was said, the injection of the PLS is used to control the power that the PV panels are giving to the minigrid. When the PLL detects it, the MPPT algorithm freezes and does not try to keep looking for the maximum power. In addition, an increment in the voltage reference for the PV panel related to the frequency of the PLS is added to the previous MPPT voltage, reducing this way the current supplied by the RES. Thus, the way of controlling the power the PV panels inject

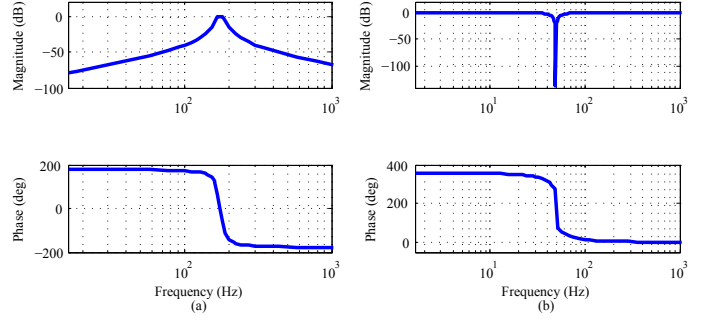


Fig. 3: Bode diagram: (a) Bandpass (b) Bandstop.

in the minigrid is by slightly modifying the operating point. In Fig. 4 is shown how the frequency of the injected signal to make the communications varies in function of the SoC of the battery. Until a 95%, the PLS is not injected, which means that the frequency is zero, but, nevertheless, beyond this SoC, this frequency begins to increase until a certain value, in this case, 180 Hz.

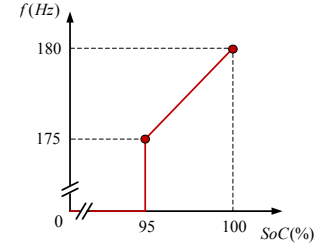


Fig. 4: PLS frequency selection depending on the SoC.

IV. CONTROL STRATEGY IMPLEMENTATION

In Fig. 5 a summary control scheme that represents the whole system is shown. ESS unit (the master converter) is controlled by two inner loops, as shown in Fig. 5: a voltage and a current loop. This inner loops are aiming at achieving good output capacitor voltage regulation. All the control was done in a synchronous reference frame (dq), hence, for this master inverter, the transformation from a single-phase signal to a dq one is done by calculating the synchronous angle in function of the frequency and then using Park transformation.

On the other hand, both RES units work as CM-VSI. This means that there are only one inner loop, a current one, which assures the injection of the current precisely in the minigrid. Nevertheless, in this case, the transformation to a synchronous reference frame can not be achieved by using the same method as with the master inverter due to the lack of data transmission between all the stations. The way to do it is by means of a SOGI-PLL [13]. Measuring the voltage, a SOGI-PLL is able to track the frequency of the signal (and basically, the phase angle), thus doing the transformation to dq is now possible.

Because of the use of the synchronous reference frame, all the signals are not sinusoidal anymore, so PI regulators were

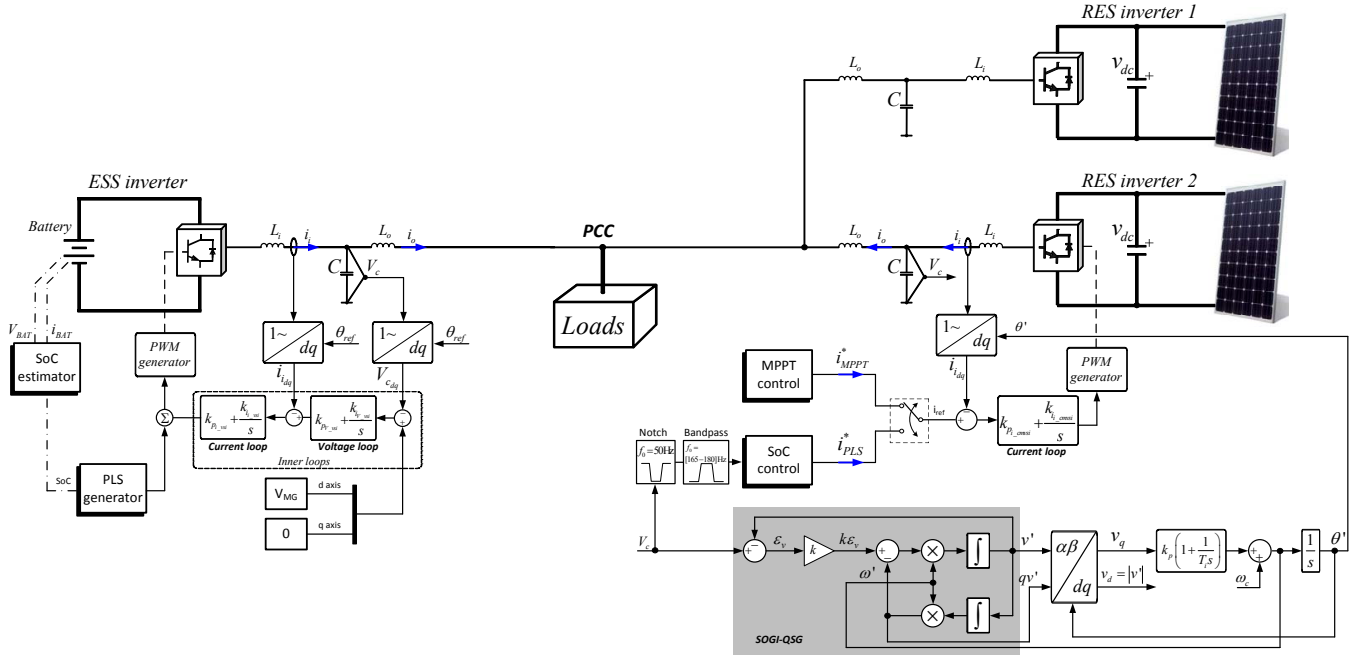


Fig. 5: Control scheme of the minigrd.

used to control all the variables. They are described as (1):

$$G_{in}(s) = k_p + \frac{k_i}{s} \quad (1)$$

A possible different solution would be by making use of proportional-resonant controllers after transforming into $\alpha\beta$ with an expression as (2):

$$G_{in}(s) = k_p + k_{res} \frac{s}{s^2 + \omega^2} \quad (2)$$

Both options are feasible and correct but in this paper, the decision was made in base to previous experiences.

A. SoC estimation

The SoC is estimated by ampere-hour (Ah) counting method expressed in (3).

$$SoC = SoC(0) - \int_0^t \frac{I_{bat}(t)}{C_{bat}} dt \quad (3)$$

where $SoC(0)$ represents the initial SoC, C_{bat} is the capacity of the battery and I_{bat} is the current of the battery [14].

B. MPPT algorithm

The selected method in this paper for tracking the maximum power point of the PV panels was the classical Hill-climbing algorithm. There are many different options ([15], [16], [17]) to track this point but despite the fact that this method seems easy to implement, the model used in this paper has been well developed because it is able to find the operating point with changes in the temperature of the PV panel and oscillations in the irradiation due to possible shadows or other circumstances.

Fig. 6 shows a basic flowchart where it is described the main decisions taken by the control algorithm.

V. HARDWARE IN THE LOOP RESULTS

Results shown in this Section are called "Hardware in the loop" due to the fact that they were obtained by using a dSPACE 1006 and the software *ControlDesk*.

First of all, Table I summarizes the main parameters of the system.

TABLE I: Parameters of the minigrd

Parameter	Symbol	Value
Nominal output voltage	V_{ref}	230 V
Nominal output frequency	f_{ref}	50 Hz
Filter input inductor	L_i	1.8 mH
Line impedance	L_o	1.8 mH
Filter capacitor	C	27 μ F
Current integral Term (ESS)	$k_{pI_{vsi}}$	10
Current integral Term (RES)	$k_{pI_{cmvsi}}$	40
Voltage integral Term (ESS)	$k_{pV_{vsi}}$	2
Current proportional Term (ESS)	$k_{pI_{vsi}}$	1.8
Current proportional Term (RES)	$k_{pV_{cmvsi}}$	15
Voltage proportional Term (ESS)	$k_{pV_{vsi}}$	0.2
PLS frequency range	f_{PLS}	175-180 Hz

Fig. 7 shows the results which have been obtained and all the transitions will be detailed next. Initially, just the ESS is feeding the load, thus, the SoC of the battery decreases. In $t = 3s$, both RES units are started up and they begin to find the maximum operating point. It can be seen in Fig. 7b or in Fig. 7c how they increase continuously their power and at the same time how the power the battery is giving is reduced, even below 0, the point where it changes to charging mode, at $t = 10s$ (Fig. 7f).

It is shown how this process goes on without changes until $t = 27s$, when battery reaches 95% of the SoC and the power given by RES units starts to get reduced until a new operation

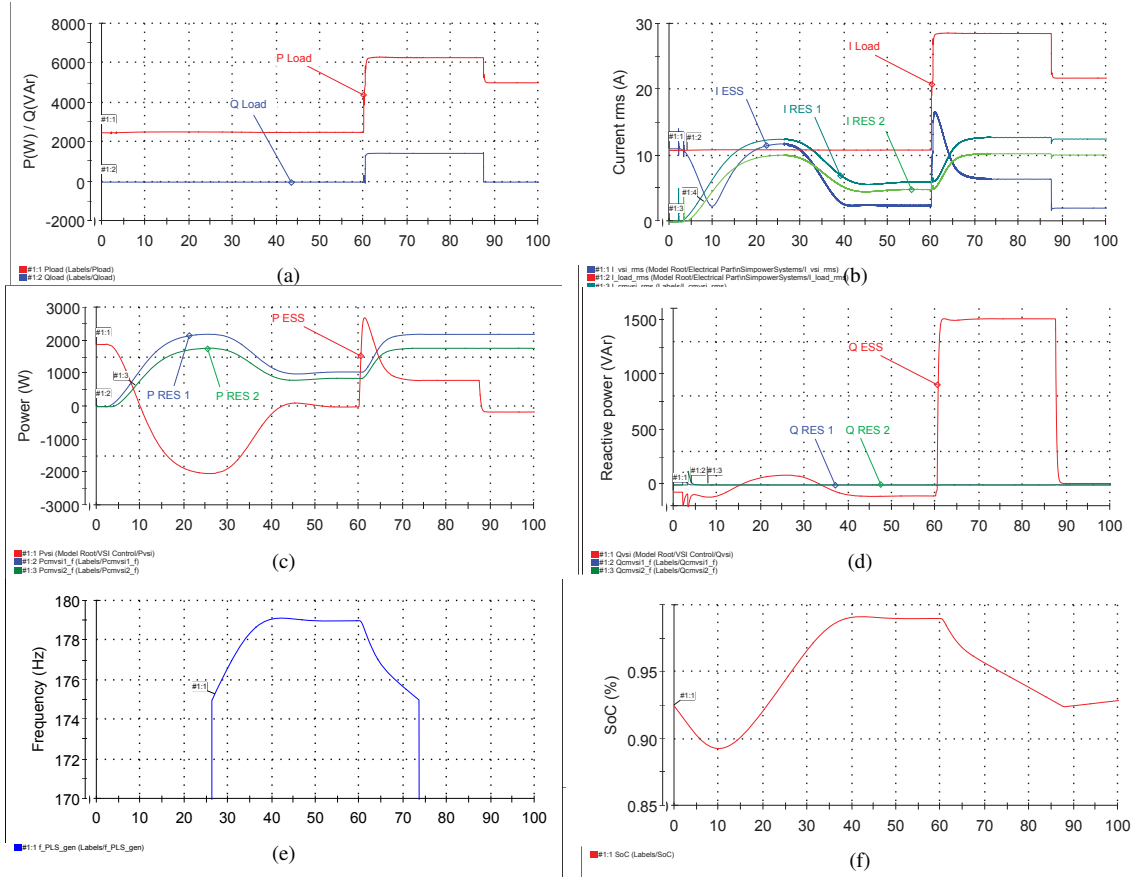


Fig. 7: Hardware in the loop results: (a) Load active and reactive power (b) RMS currents (c) Active power of the converters (d) Reactive power of the converters (e) PLS frequency detected with the PLL (f) SoC of the battery.

point is found. This operating point is the one where the load is fed just with renewable energies and ESS unit waits as a backup. Until $t = 60s$, this behavior is kept. In Fig. 7e can be seen how the PLS stays at the same frequency, but a change in the load (active and reactive power) makes the operating point of the whole minigrid changes, and the very first and fastest response to this load change is done by the ESS (red line in Fig. 7c). Then, the control system looks for the new operating point, that is the one between $t = 60s$ and $t = 87s$. During this time only ESS unit is able to inject reactive power in order to compensate the reactive power demanded by the load. That is the reason why the battery starts to discharge.

Suddenly, this previous load is disconnected, and everything goes to a new stable state.

VI. CONCLUSION

In this paper, a coordinated control strategy for islanded single-phase minigrids based on PLS communications has been presented. The aim is to coordinate ESS and RES unit to deal with the situation of source limitation. This PLS has been used in order to coordinate all the units without any communication link or a wireless one. Then, "Hardware in the loop" results obtained with the dSPACE has been shown and also how all the units work together to find an operating

point that minimizes the power given by the battery. Having a look to the results, it has sense to say that the expandability of proposed method to more units is possible, always taking into account that a PLS is possible for small-scale stand-alone power systems but it is not for big grids with resistive lines due to the fact that the signal can be lost during the process.

VII. FUTURE DEVELOPMENTS

Although in this paper, the voltage and the frequency references are given directly to the master converter, there is another possibility that is using a droop control for this unit. If this droop control is activated, a secondary control can be implemented to restore the voltage and the frequency to the nominal values. This issue was done and it will be implemented and improved in future works.

It has to be said that as a first approach, only maximum charging points of the battery have been taking into account. In future works, also a protection of the battery against depth of discharge will be treated.

Another improvement will be to help ESS unit with reactive power, if it would be necessary, with RES units. By doing this, the battery could remain completely charged during more time through the day and all its capacity could be used at night.

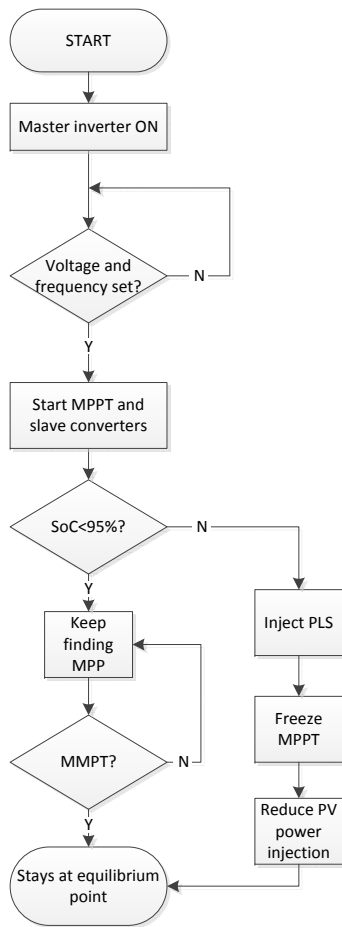


Fig. 6: General flowchart for the whole system.

Finally, install more than one ESS unit would be an important issue, but, nevertheless, synchronization between two or more master inverters needs a different strategy and a very precise control in order to keep a good power sharing.

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