An improved decentralised coordinated control scheme for microgrids with AC-coupled units

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***Abstract*—Microgrids composed of solemnly AC-coupled distributed energy resources can be found in many real-life applications while their control has not been researched nearly enough to address some fundamental challenges, the most important of which is overall system reliability and fault tolerance. This paper proposes a droop-based coordinated control scheme for microgrids with AC-coupled units, a method that enables distributed energy resources units to hot swap between current source and voltage source grid-supporting control modes for satisfying load demand and ensuring energy storage systems will constantly be able to form the grid during islanded operation. The proposed control scheme has been realised in MATLAB/Simulink simulation model of a small-scale microgrid of AC-coupled units that corresponds to a real testbed in Northern Greece. Preliminary simulation results, in islanded mode, demonstrate the effectiveness of the proposed control scheme regarding power-sharing accuracy among the resources and state-of-charge balancing among storage units.**

***Keywords*—microgrids, hybrid power systems, maximum power point tracking, energy storage, droop control**

I. Introduction

Microgrids (MG) are characterised by their need to cover many different control objectives and to perform according to well-established standards (e.g. EN 50160) regardless of their connection status to the main grid. Especially in case of Renewable Energy Sources (RES) inclusion, additional control designs must be explored in order to harvest the maximum energy that can be provided at particular weather conditions.

According to the nature of each Distributed Energy Resource (DER), different control schemes must be employed, with the most indicative being RES where extensive use of maximum power point (MPP) controllers is observed. Commonly, while connected to the grid, RES assets are operated in MPP and thus in P-Q mode behaving as grid-feeding units. However, when the MG is islanded, in order to ensure that the MG operation will not be jeopardized by potential excess of power, in many cases RES generation is curtailed [1]. On the other hand, regarding Energy Storage Systems (ESS), battery life expectancy is severely affected when during charging and discharging the recommended from the manufacturer C-rate is not respected [2]. Additionally, in case of multiple ESS in a MG, uneven stressing of units is observed, especially in cases where the typical decentralised control scheme, namely droop control, is employed. This is because conventional droop method takes into account the rated power of the ESS and not their remaining energy, a measurement of which is the State-of-Charge (SoC). For this reason, lately, several control schemes aim towards SoC balancing among ESS. For example, in [3] the SoC of all ESS is averaged and that averaged, through a simple PI, is added to the existing droop coefficient, however the collaboration between RES and ESS is not considered in the proposed controller. In a similar work [4], a droop coefficient adjusting method based on SoC calculation is proposed for both ESS and hybrid PV/ESS units, however there is no coordination between either units.

In order to design an integrated unit control coordination scheme, it is imperative to take into account individual control aspects and their in-between interaction. In such schemes, the most vital control objective is proper active and reactive power sharing, which is often accomplished via variants of droop controllers, master-slave techniques or hybrid combinations of those [5]. Such coordination highly depends on the MG architecture, namely whether the RES and ESS are DC- or AC-coupled, meaning coupling on a common DC bus between the unit's DC/DC converter and its respective inverter or directly on the AC bus. The majority of existing literature proposes coordinated control schemes for DC-coupled RES and ESS units [6]. Such a configuration, whilst convenient for tight regulation of the DC bus voltage, is not always applied in real site MGs. Nonetheless, AC-coupling unit configuration poses additional challenges in designing coordinated control for the MG units because extra care must be taken for the regulation of the voltage of each unit's DC bus, which affects the overall MG stability. Especially in cases of small-scale MGs, where the number of controllable units is limited and thus, there is no guarantee that at all time and regardless of the ESS state, a unit can act as voltage source. On the contrary, in the limited cases where coordinated control schemes for AC-coupled units have been proposed, there are still aspects that require extensive research for real-life applications. For example, in [6] each unit's DC bus is considered as a stiff voltage source and in [7] only one operational mode is being handled at a time without hot swap during transition from charging and discharging modes or grid-connected to islanded and vice versa.

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This paper proposes a control scheme for MGs with AC-coupled units that is designed on a droop-based coordination logic. During grid-connected mode, PVs and ESS are operated as current source grid-supporting units. The PV injects constantly its MPP, while the ESS control is comprised by multi-segmented, adaptive reversed droop curves P-f, Q-V. The droop segments are defined by the operating mode (i.e. charging or discharging) and the segment inclinations are determined by the chosen C-rate and current SoC. On the other hand, during islanded mode, since the PV has no auxiliary means to support its DC bus and thus it is constantly controlled as a current source, the ESS are burdened with the grid formation responsibility. In order to increase the MG reliability, the proposed control scheme through its SoC balancing logic, ensures that there will always be more than one ESS able to act as a voltage source. In island mode, the PV follows a reversed MPP-adaptive droop, in order to limit output power in case of a frequency increase over the nominal, whereas discharging ESS are controlled as voltage source and charging ESS as current sources, both according to multi-segmented droop curves f-P. The proposed controller also includes virtual impedance loop in order to allow the usage of f-P/V-Q droop curves in the low voltage MGs.

This paper is structured as follows: in Section II a brief description of AC- and DC- coupled units along is presented, followed by the basic categories regarding the control of AC-coupled units in Section III. In Section IV, the proposed control scheme is analysed and the simulation results are given in Section V. The paper is concluded in Section VI with comments regarding future work.

II. AC-Coupled vs DC-Coupled Configurations

DERs can be integrated in a MG via various different architectures, depending on the type of buses selected for their coupling. The basic configurations are two: AC coupling and DC coupling. AC coupled units (Fig. 1) are a more mature architecture, with established know-how and lower MG development cost [8]. On the other hand, AC coupling demands more complex control algorithms. One demonstrative example is, in case of PVs, the control of the DC bus between the MPPT DC-DC converter and the DC-AC inverter, a fact that is often neglected in literature by assuming stiff voltage sources, a fact that implies some sort of storage at the DC bus, which however is not always the case in real applications.

Contrarily, DC coupling is a more intuitive solution due to the nature of commonly appearing DERs like PVs and batteries. Thus, the units can be controlled with simpler controllers that, depending on the unit, can either undertake the task of operating RES at their MPP or, in case of ESS, control the DC bus voltage. With a stiff voltage level at the DC bus, the inverter can easily change control modes and thus the overall MG operation is more versatile. Nevertheless, the multiple conversion points decrease the total system efficiency along with the reliability of the MG since the inverter presents a single point of failure and finally, increases the cost of MG deployment. To exploit benefits and address challenges from both configurations, various hybrid solutions have been proposed in literature, presenting promising results [8].

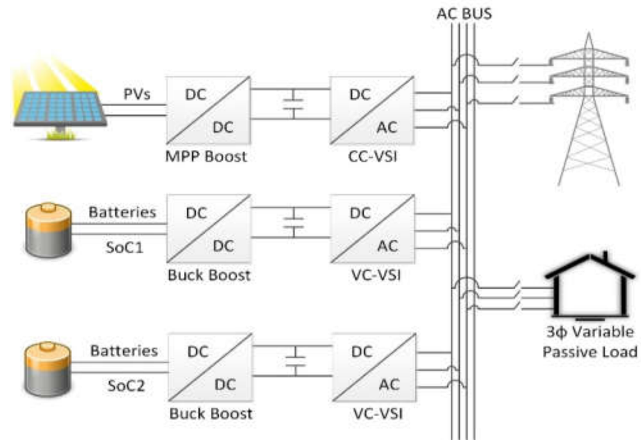

Fig. 1. Microgrid with AC-coupled units

III. Coordinated Control Schemes for AC-Coupled Configurations

Initially, MGs were developed as fully controllable structures of the distribution grid with the objective to increase the reliability of the grid and islanding operation was defined only for emergency or fault cases [9]. However, nowadays, islanding is pursued, as a necessary function during MG control design, during not only grid faults or maintenance requirements but also when economic MG operation dictates disconnection from the grid. It is evident that during islanded operation at least one DER must be operated as voltage source, whereas other units can be controlled as current sources. Voltage source operation can be by either grid-forming or voltage-source grid supporting controls, whereas current source behavior is exhibited by grid-feeding or current-sourced grid-supporting unit [10]. In general, MG control schemes can be separated in three extensive groups: master-slave, peer-to-peer/ multi-master and hybrid control schemes. A brief description of these schemes follows.

A. Conventional Methods: Master/Slave & Peer-to-Peer

In grid-connected operation, all DERs are operated as current sources, most usually as grid-feeding units, while set points are provided by a secondary control for regulating inverters' output power [11]. On the contrary, during islanded operation, one DER must operate as a as grid-forming unit (Master), in order to set the voltage and frequency, whereas the rest (Slaves) operate in grid feeding mode [12]. Set points regarding injecting/absorbing power are set by a MG central controller (MGCC). The aforementioned scheme has been the most common control method for independent PV-ESS systems. Using an MGCC allows the introduction of elaborate control objectives to be accomplished, however this is achieved at the expense of MG reliability due to the system susceptibility to single-point failures (e.g. malfunction of the master unit or the MGCC). For example, [13] introduces a coordinated SoC control strategy that achieves SoC balancing in islanded MGs through output power control of ESS as dictated by an MGCC. Such master-slave control requires fast communication between the slave units and the MGCC, a requirement that if not met, as for example in cases of large MGs, can jeopardize MG proper operation.

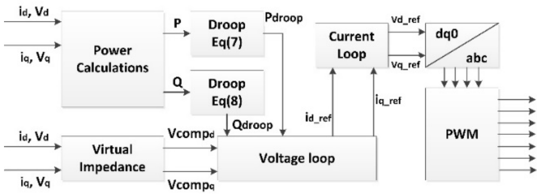

Fig. 2. Control Loops for a Master Unit

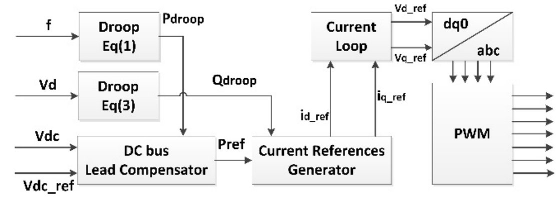

Fig. 3. Control Loops for a Slave Unit

On the other end, peer-to-peer or multi-master architectures have been proposed tackle the aforementioned issues by allowing all DERs to participate in voltage and frequency regulation, acting as voltage source grid-supporting units [9]. Power sharing is accomplished via the employment of droop control and its variants. The basis of droop control derives from the parallel operation of UPS. It dictates is the adjustment of active power injection by frequency and the manipulation of reactive power by the voltage. However, the line impedance seriously affects the accuracy in power sharing, especially regarding reactive power. Particularly in low voltage MGs that exhibit resistive behavior, droop curves must be altered and have voltage controlling active power and frequency adjusting reactive power. Another approach is to include the virtual impedance loop, which essentially alters the output impedance of each converter in order to emulate mainly inductive behavior systems [14]. Even if the well-known drawbacks of droop are tackled by such droop variants, the complete lack of coordination among the units, poses great challenges in order to achieve complex control objectives, such as SoC balancing, but even when they do, as in [15], the overall system complexity increases considerably.

B. Hybrid Methods: Coordinated Schemes

To overcome the shortcomings of the two aforementioned control types, research has recently shifted towards various hybrid control schemes. The basic principle followed is that a MG can have multiple master and slave units, with either pre-assigned roles or the ability to change dynamically their control modes depending on various factors (e.g. SoC). [16] presents a strategy for voltage source grid-supporting master units based on static conventional droop control and current source grid-supporting or grid-feeding slave DGs, however, the DC bus voltage regulation has not been considered. In [17] a coordinated control strategy for PV and battery systems is presented, in which both the RES available active power and the battery levels are taken into account. However, this control method is normally suitable in systems that the ESS is integrated on the DC link of the PV unit and needs additional improvements to succeed the coordination of different distributed energy sources connected on the AC bus. This approach is followed in [18], where a coordinated control strategy is designed for an AC islanded Microgrid to prevent over-charging / over-discharging of the ESS units. The control mode of the ESS units changes from voltage control mode to current control mode when the SoC overtakes an upper limit while the output power follows some reference value. That control method was experimentally tested only with two paralleled ESS inverters and no PV. In [6] a control architecture is proposed to coordinate RESs and ESS in islanded MGs manipulating smooth switching droop control. The aforementioned method does not consider actions for avoiding deep discharges of batteries, cooperative operation between ESS, while the experimental results show that the steady state frequency deviates severely from the nominal value. In a more recent work of the same laboratory [19] these shortcomings were addressed by employing distributed decision-making units for controlling the variable RES and distributed ESS in order to achieve SoC balancing and curtail the generated active power of RES. Nevertheless, in the experimental configuration the grid side converter of RES is connected to a stiff voltage source that emulates the intermediate dc-link, in order to achieve the grid-forming mode for the RES unit.

IV. Proposed Decentralised Coordinated Control Scheme for MG with AC-Coupled Units

In order to address the shortcomings or simplifications of other coordinated controls, this paper proposes a coordinated control scheme that enables all DER units to hot swap between current-source grid-supporting (Slave) and voltage-source grid-supporting (Master) control modes based on predefined scenarios. Unlike previous approaches [6][19], the proposed control scheme takes into account the lack of additional batteries at the DC bus of PV inverters, in other words there is no assumption of stiff DC voltage in any unit and proper DC voltage control loop is added in each DER inverter. DER units like PVs without additional battery module at their DC bus are

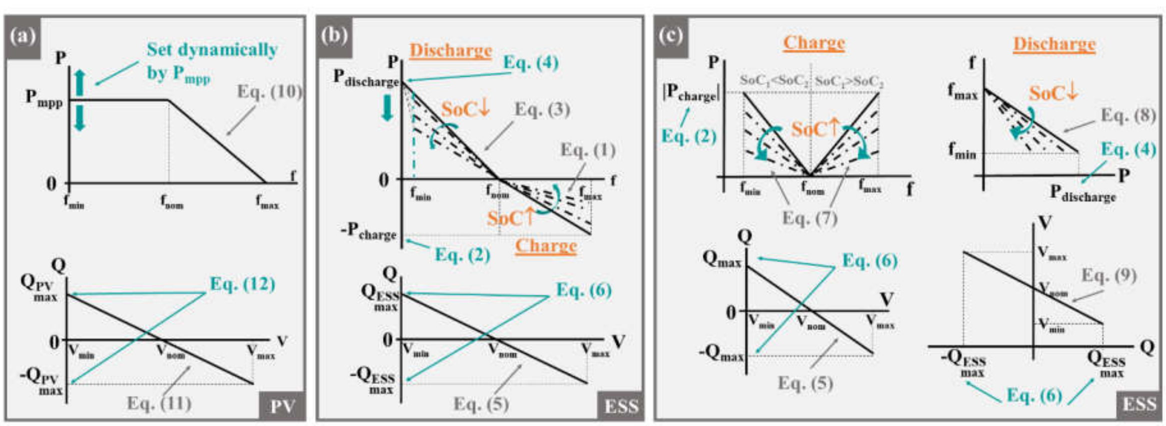

Fig. 4. Proposed droop-based coordinated control: (a) PV slave operation, (b) ESS operation during grid-connected mode and (c) ESS operation during islanded mode.

assigned permanent Slave character, whereas units that feature independent DC bus voltage regulation (e.g. ESS) can be controlled as either Master or Slave, depending on predefined scenarios. The suggested scheme has been designed and tested via simulations for a MG consisting of one PV and two Li-ion-based ESSs, all purely AC-coupled, however with slight modifications, its logic can be expanded to MGs with diesel generators, wind turbines, etc. Finally, the proposed control is decentralised since there is no centralised controller that dictates the mode of operation to the units.

A. Battery Control

The inverters of the batteries are voltage-source converters (VSC) and they have been designed to operate as either Master (Fig.2) or Slave (Fig.3) depending on either the MG operating mode or the charging of discharging mode of the battery module. Master Control mode consists of the following control loops: a SoC/C-rate-based adaptive droop control loop, a virtual impedance loop and the inner voltage and current loops. Slave control consists of a reversed SoC-based droop loop and an inner current loop. For the VSC control, Park transformation of the three-phase quantities to the DC quantities of the dq0 plane in order to use simple PID controllers. A schematic of the described control is shown in Fig 4.

Grid-connected Mode: All ESSs are acting as Slaves and discharging or charging according to the grid demands (Fig. 4b). The droop coefficient changes dynamically according to the available energy that the batteries can inject, an indicator of which is the SoC. Regarding discharging, the C-rate is also included in order to protect the battery and not step over the allowed limitation by the manufacturer.

During charging (P<0) and $f > f_{nom}$, the reversed P-f droop curve is:

$$P = \frac{P_{charge}(SoC(t))}{f_{max} - f_{nom}} (f_{nom} - f) \tag{1}$$

where

$$P_{charge}(SoC(t)) = \frac{P_{charge_{MAX}}}{SoC_{MAX} - SoC_{MIN}} (SoC_{MAX} - SoC(t)) \tag{2}$$

During discharging (P>0) and $f \leq f_{nom}$, the P-f droop curve is:

$$P = \frac{P_{discharge}(SoC(t), C_{rate}(t))}{f_{nom} - f_{min}} (f_{nom} - f) \tag{3}$$

where

$$P_{discharge}\big(SoC(t), C_{rate}(t)\big) = \frac{SoC(t) - SoC_{MIN}}{C_{rate}(t)^{-1}} Cap_{nom} \tag{4}$$

Similarly, the reversed Q-V droop curve is dictated by:

$$Q = \frac{2Q_{ESS_{max}}}{V_{min} - V_{max}} (V - V_{nom}) \tag{5}$$

where

$$Q_{ESS_{max}} = \begin{cases} \sqrt{S_{nom}^2 - P_{discharge}^2\big(SoC(t), C_{rate}(t)\big)} \\ \sqrt{S_{nom}^2 - P_{charge}^2\big(SoC(t)\big)} \end{cases} \tag{6}$$

Islanded Mode: The ESSs that are charging are operated as Slave units and their operation is dictated by similar droop curves as in Eq. 1:

$$|P| = \begin{cases} \frac{P_{charge}(SoC(t))}{f_{min} - f_{nom}} (f - f_{nom}), & f \in [f_{min}, f_{nom}] \\ \frac{P_{charge}(SoC(t))}{f_{max} - f_{nom}} (f - f_{nom}), & f \in (f_{nom}, f_{max}] \end{cases} \tag{7}$$

where $P_{charge}(SoC(t))$ is given by Eq. 2.

As it can be observed, we demand charging operation for the whole span of $[f_{min}, f_{max}]$. The algorithmic logic aims to SoC balancing between the storage units (see Fig. 4c), even when the master ESS is discharging. The goal is to ensure that the MG will never be left with only one ESS able to set the grid. That way the single point of failure of the conventional master slave control schemes is lifted. This of course leads to an increase of losses, however this is considered acceptable in MG applications where increased reliability is a high priority feature. This logic clarified with the following example. Assume one ESS is at 20% SoC, the other is at 80% SoC, and there is slight excess of power generation. Then, based on the proposed control, the ESS with the higher SoC is assigned Master role and it sets the frequency at a lower value than the nominal value; however, the first battery would still need to be charged in order not to leave the MG with only one unit able to set the grid and thus risk the overall having a MG black out. By allowing the second battery to charge, even when the frequency is lower than the nominal, SoC balancing is achieved. The Q-V reversed droop curve during charging of batteries at islanded MG operation is given also by Eq. 5-6. It should be noted that in regards to the Slave operation of the charging batteries, the set point of the reversed P-f is used in the DC voltage control loop, as depicted in Fig 3. Discharging operation starts for $f < f_{nom}$ and the ESS is controlled as Master unit, following the f-P, V-Q droop curves:

$$f = f_{nom} - \frac{f_{nom} - f_{min}}{P_{discharge}\big(SoC(t), C_{rate}(t)\big)} P \tag{8}$$

$$V = V_{nom} - \frac{V_{max} - V_{min}}{2Q_{ESS_{max}}} Q \tag{9}$$

where Q_{ESSmax} is given by (6).

B. PV Control

In order to demonstrate the logic of the proposed coordinated control, a PV module without additional support at its DC bus is assumed. The PV will be controlled as Slave units regardless of grid-connected or islanded operation. During grid-connected mode, the PV will inject constantly its MPP, whereas during islanded mode its active power will be drooped in order to avoid surplus of power (Eq. 10-12, Fig. 4a).

$$P_{PV} = \begin{cases} P_{MPP}, & f \in [f_{min}, f_{nom}] \\ P_{MPP} - \frac{P_{MPP}}{f_{max} - f_{nom}} (f - f_{nom}) & f \in (f_{nom}, f_{max}] \end{cases} \tag{10}$$

$$Q_{PV} = \frac{2Q_{PV_{max}}}{V_{min} - V_{max}} (V - V_{nom}), \; V \in [V_{min}, V_{max}] \tag{11}$$

where

$$Q_{PV_{max}} = \sqrt{S_{PV_{nom}}^2 - P_{MPP}^2} \tag{12}$$

Note that in Eq. 1-12, positive power (either active or reactive) signifies injection, whereas negative power is associated to power absorption.

C. Coordination of control modes

The control mode selection is achieved via mathematical analysis of the bus frequency. More specifically, each ESS measures via a Phase Lock Loop (PLL) the frequency at its terminals, then passes the measurement via a low-pass filter and then subtracts it from the nominal frequency. In case the result is positive, then this indicates that there is a surplus in power. Then each ESS calculates its SoC. Through low-bandwidth communication, the ESSs communicate to each other their SoC and the ESSs that have the lower SoC value swap their operating mode to/from Master from/to Slave. The elaboration of the decision-making logic and the implementation of the communication system can be realised with a Multi-Agent System however, further elaboration on this is out of the scope of this paper and it will presented in future publications of the authors.

V. Simulation Results

In order to prove the concept of the proposed control scheme, the results of the simulation scenarios of charging and discharging during islanded operation are presented. This case study has been selected for demonstration due to the higher challenges it exhibits and its increased complexity over the scenarios corresponding to grid-connected operation. The discrete model was constructed in MATLAB/Simulink using the Simscape Power Systems toolbox and the detailed PV and Li-ion physical modules it provides. The examined MG, depicted in Fig 1, is a detailed model of a testbed MG in CERTH, Greece. It consists of one Slave PV unit and two Li-ion-based ESS units with hot swap capability between Master and Slave control modes. The parameters of the model are given in Table I. It should be noted that in order to demonstrate the effectiveness of the proposed control scheme, a secondary control that restores bus frequency and voltage to the nominal values has been omitted.

The simulated scenario takes place while the MG operates in islanded mode and the total duration is 10 seconds. The simulation resolution is T_s=50μsec. The weather conditions are optimal (i.e. ambient temperature at 25°C and solar irradiance at 1000W/m^2) and the PV injects 8.85kW and 0.28kVAr, the first battery (ESS1) starts its operation from an initial SoC of 59%, and the second battery (ESS2) has an initial SoC value of 22.45%. From t=0s until t=3sec, the total passive load equals to 18.2kW and 0.95kVAr. ESS1 operates as Master, injects almost its maximum allowed power and sets the bus frequency at 49Hz, whereas ESS2 is controlled as Slave. Due to the low SoC value of ESS2, the unit neither absorbs nor injects power. However, at t=3sec a slight load reduction takes place and the total load equals to 17.6kW and 0.95kVAr. The load reduction is detected by both ESS units and the SoC values of each are communicated to each other. Since $SoC_2 < SoC_1$, the ESS1 remains as the master module and ESS2 now, still controlled as slave, absorbs power equal to -1.25kW and starts charging. In Fig. 5a-f the simulation results regarding the active power (Fig. 5a), the reactive power (Fig. 5b) injected/absorbed by the units, the controlled DC bus voltages of the PV, ESS1, ESS2 (Fig. 5c), the bus frequency (Fig. 5d) and RMS voltage (Fig. 5e) and the SoC values of ESS1 and ESS2 (Fig. 5f) are presented. The results indicate that the coordinated control managed to detect the load change and consequently achieved effective power sharing and SoC balancing between the batteries.

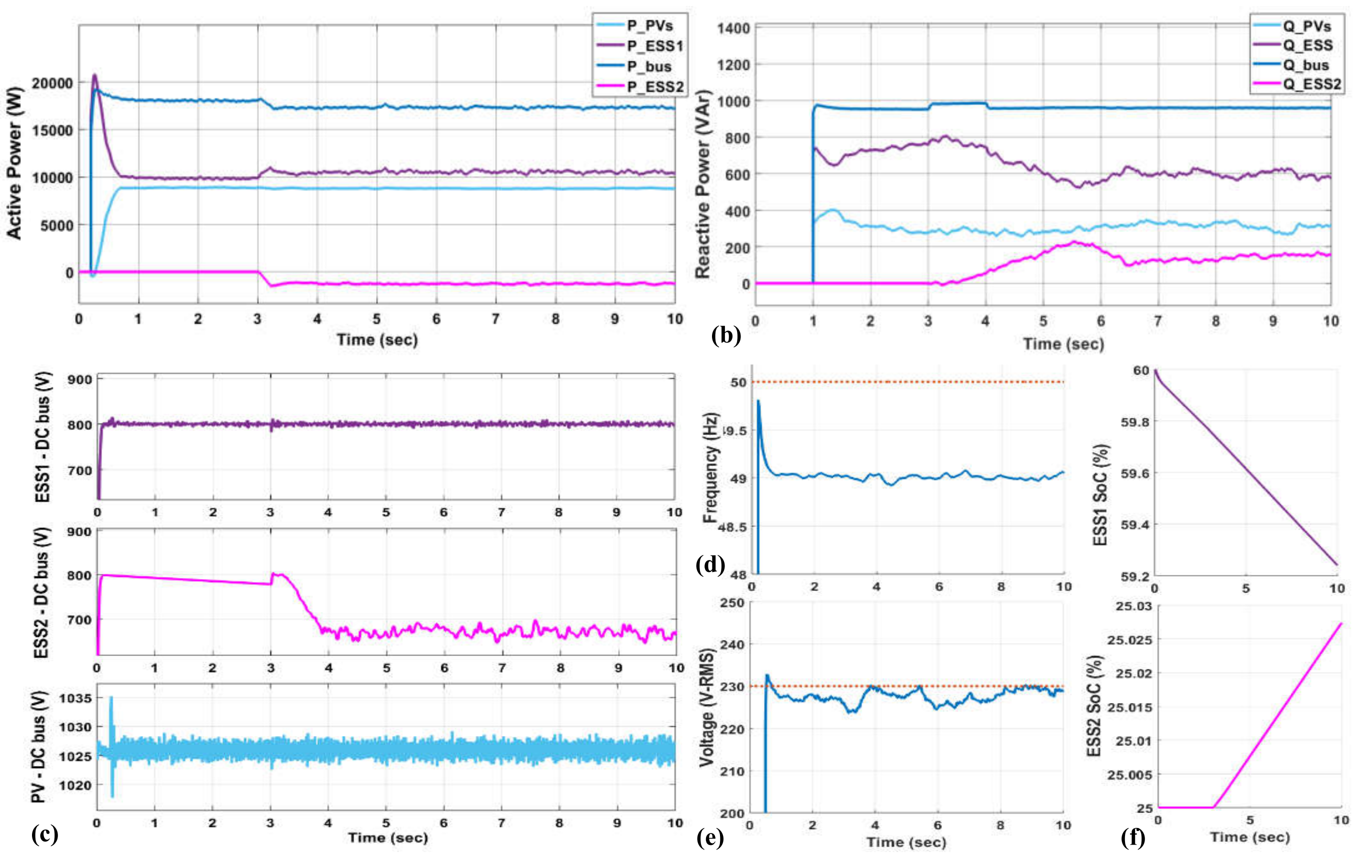

Fig. 5. Simulation results of the proposed control scheme during islanded mode

VI. Conclusion & Future Work

Regarding MGs with AC-coupled DERs, a precise coordinated control architecture that takes into account real-life restrictions that manages both the remaining energy of ESSs and the available output power of RESs is necessary. This paper presented a scalable and flexible decentralised droop-based coordinated control for such MGs. The simulation results for a small-scale MG in islanded mode indicate that the proposed control is successful at protecting the batteries from overcharging or overdischarging, balancing SoC between multiple storage units, while RES production is minimally curtailed. Additionally, due to the lack of centralised controller along with the multi-master logic of the architecture, the MG becomes single fault-tolerant and thus, the resilience of the system is increased. Simulations also demonstrated a successful change of control modes. The next steps regarding the improvement of the proposed control include stability analysis in order to specify the maximum change rates of the droop coefficient and the development of a Multi-Agent System in order to realise the necessary communication platform for the ESS that enables the hot swap between the control modes.

TABLE I. Model Parameters

Asset	Variable	Value
AC Bus	Frequency	50Hz ± 2%
	Phase Voltage (RMS)	230V ± 10%
	Line Impedance (R/L)	0.642Ω/ 0.264mH
PV	Maximum Power at 25ºC/1000W/m^2	9kW
	Inverter Nominal Apparent Power	10kW
	Filter Inductance	12mH
	Filter Capacity	5μF
	Switching Frequency	9.5kHz
	Current Loop gain k_p	10.3
	Current Loop gain k_i	401
	DC Loop Lead Compensator	$\frac{153\,s\,+\,12070}{s^2\,+\,506.8\,s}$
ESS	Nominal Capacity	4320Wh
	Max Discharge C-rate	2C/ 30sec
	Nominal Charge C-rate	0.167C/ 6h
	Inverter Nominal Apparent Power	10kW
	Filter Inductance	10.3mH
	Filter Capacity	5μF
	Switching Frequency	9.5kHz
	Current Loop gain k_p	10.3
	Current Loop gain k_i	401
	Voltage Loop gain k_p	0.003
	Current Loop gain k_i	1.17
	DC Loop Lead Compensator	$\frac{66.24\,s\,+\,4079}{s^2\,+\,649.6\,s}$
	Virtual Resistance	-0.642
	Virtual Inductance	-0.25mH

Acknowledgment

This work has been partially supported by the EC FP7 ERANETMED project named "3DMicroGrid" (www.3dmicrogrid.com) with project number: ERANETMED _ENERG–11–286.

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