

A hybrid agent-based secondary control for microgrids with increased fault-tolerance needs

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Keywords: multi-agent system; secondary control; reconfigurable architectures; microgrid; fault tolerant control

Abstract

This paper proposes a hybrid secondary control architecture for microgrids with AC-coupled droop-controlled units, based on both centralised and distributed control principles. The proposed secondary control is based on a multi-agent system (MAS), complemented by a microgrid centralised controller (MGCC). The system is able to adjust the droop curves dynamically in order to achieve voltage/frequency restoration as well as active/reactive power optimal allocation, based on the actual status of the controllable units, in particular, the state-of-charge of batteries and maximum power point of photovoltaics. The distributed nature of the agents is also fully exploited because the proposed framework retains operability even under fault on secondary MGCC. To evaluate the proposed framework, a scenario-based performance analysis has been tested over a simulated AC islanded microgrid, where communication from the MGCC is suddenly interrupted and the MAS is required to reconfigure in order to maintain the same control objectives. MATLAB/Simulink simulations have been realised using detailed physical form models for a small-scale microgrid, while the implementation of the MGCC and MAS is accomplished through Java Agent Development (JADE) framework.

1 Introduction

In the last two decades, considerable amount of research has been invested in microgrids (MGs) because of the prosperous solution they could offer to both the ever-growing penetration of distributed energy resources (DERs) and the need to develop stand-alone, isolated power systems for special applications. MG DERs are normally inverter-based, meaning that MGs become structures of parallel inverters, a fact that poses challenges to control systems design, especially in case of islanded operation [1]. Being a rather new field of research, highly diverse control system solutions have been proposed by both academia and industry, a tendency that can be seen even today. Depending on the centralised or non-centralised design and operating timeframe of the systems implementing the MG control objective, plethora of centralised, decentralised, distributed and hierarchical control approaches have been proposed throughout the years [2]. Despite the different design implementation, it can be observed that MG control systems follow a certain hierarchy, which most frequently is divided into two or three layers. The most usual secondary control

objectives are maintenance of high power quality level through voltage and frequency restoration to nominal values, voltage balancing and harmonic compensation [3] and optimised power sharing among DERs [4] especially during islanded operation. Centralised control, implemented often in one component called Microgrid Centralised Controller (MGCC) is regarded as the conventional approach with well-known drawbacks, the most significant of which are the single-point of failure of the component and of the necessary high-bandwidth communication, restricted plug-n-play capability and expandability and poor performance in case of contradicting interests among MG players [5]. Thus, efforts have been invested in order to implement the aforementioned control objectives in a non-centralised way, by employing distributed control systems based on Multi-Agent Systems (MAS). However, distributed MG control implies certain disadvantages such as increased complexity, inadequate transient performance compared to their respective centralised equivalents and limited proven good performance in real-site MGs. Efforts to combine the advantages of both centralised and decentralised/distributed control logics have been made,

however in the upper control levels, only one approach is followed: either MGCC or MAS. Consequently, the drawbacks of either approach still reside in such systems. In case the main design objective is to increase the fault-tolerance and thus the overall MG reliability, then a possible solution to this is to design a control system able to reconfigure in case of a failure. To the best knowledge of the authors, reconfiguration in upper level controllers has been very scarcely investigated in literature. In [6], such a controller is proposed, where in case of an MGCC failure, its responsibilities are transferred to another centralised auxiliary controller able to operate the MG in a suboptimal way. However, in this approach the overall system leads to a two-points-of-failure tolerance, which still does not solve the root of the problem of a centralised controller. In [7], the logic of combining MGCC and MAS is presented with the extra feature of designing a system that can withstand fault in the main container of the MAS. Nonetheless, that system is not tested under MGCC failure or during islanded operation.

To address these shortcomings and based on previous work of the authors [8], this paper presents a new hybrid MGCC/MAS-based secondary control scheme for a MG that includes PVs and storage units. The system performs voltage and frequency restoration and optimised power sharing by taking into consideration the available power from the PV and the state of the battery (SoC). The proposed control scheme is characterised by increased fault-tolerance since in case of an MGCC failure, the agents are able to take over the secondary control objectives. On top of that, even in case of a failure in the communication link, the MG operation will not be jeopardised because the DERs are controlled with droop control, thus the basic load sharing capability is still ensured. Performed simulations demonstrate both control modes (centralised/distributed) in islanded operation.

This paper is structured as follows: Section II gives a brief description of centralised and decentralised upper control schemes. In Section III, the proposed control scheme is described in detail. Simulation results are given in Section IV. Finally, after a short discussion regarding future work in Section VI, the paper is concluded in Section VII.

2 Microgrid Secondary Controllers

2.1 Centralised Architectures based on MGCC

Regarding centralised control systems, control functionalities such as voltage/frequency regulation for power quality

improvement, active and reactive power sharing, harmonic compensation and transition from/to islanded operation are implemented by the MGCC, which coordinates accordingly the Local Controllers (LC) on each DER and potentially loads [3]. Often in literature, the MGCC is described as MG secondary control. In this paper, MGCC will signify a controller that includes also the control objectives of the second level of the ANSI/ISA-95 hierarchical control architecture that is voltage/frequency restoration [9]. These deviations are caused by the actions of the primary control that is responsible for load sharing, an objective most commonly achieved in a decentralised manner via droop control.

Preliminary MGCC approaches had as focus the economic optimisation of MG operation [10]. As islanded operation became a critical requirement, MGCC designs had to be performed equally well in both operating modes. For example, in [11] the MGCC is implemented using model-predictive control algorithms for the DER inverters in order to improve the accuracy of the calculated set points. However, heavy communication is required and the system will collapse in case of an MGCC failure. In [12], an event-driven communication protocol is used by an MGCC that directly takes, as an extra task, under its responsibilities load sharing, for which droop control is usually the most used implementation method. In a recent work [13], MGCC is further enriched with real-time optimal scheduling using mixed-integer nonlinear programming. In [14] additional MGCC functionalities based on linear quadratic regulator with prescribed degree of stability guarantee MG stability at all times. Despite the aforementioned examples that aim to either improve the MGCC accuracy or reduce the communication link usage, the problem of single-point failure remains mostly untackled. Overall, centralised approaches are to this day preferred by grid operators [13] since they have proven performance, plug-n-play capability is not yet critical and MG stability is ensured due to the global perception of the status of the MG [15].

2.2 Distributed Architectures based on MAS

Even though centralised approaches are still preferred, these systems have inherit single point of failure vulnerabilities which are augmented by requirements of high-bandwidth communication and finally, restricted plug-n-play capability and expandability [5]. Consequently, effort has been invested into the development of MAS-based distributed control strategies for the secondary and tertiary levels. MAS-based control schemes correspond to a distributed set of hardware or software agents able to act on their own and in collaboration

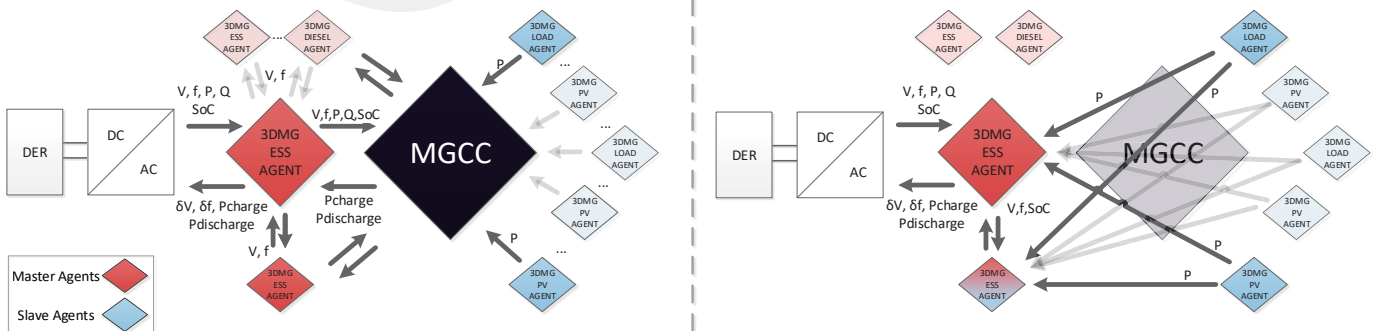


Fig. 1. MGCC and agent logic during centralised (left) and distributed modes (right)

with their neighbours in order to achieve global control objectives in consensus. In general, MAS control in MGs can be divided in the following categories: 1) distributed averaging, 2) average consensus, and 3) pinning-based distributed control [16]. Even though MAS have developed significantly over the last decade, they are still characterised by increased complexity and thus, they have not been applied in massive scale in the context of MGs.

Several MAS that realise secondary control objectives, i.e. voltage and frequency restoration, can be found in literature. In [17], averaging communicated local measurements in order to calculate the new set points has been proposed, whereas improved methods that take into account the effect of line impedances can be found in [18]. MAS-based solutions propose variants of consensus-based distributed frequency and finite-time voltage controllers, as in [19]. Additional objectives such as optimised power sharing can also enhance MAS controllers [20]. One problem regarding these approaches is the necessity for extensive communication among the agents. To tackle this, [21] proposed the usage of an event-trigger logic, in order to decrease the communication needs.

3 Proposed Microgrid Control Architecture

The proposed scheme has been originally designed for MGs consisting of PVs operating at maximum power point (MPP), energy storage systems (ESS) and aggregated loads, each of which being considered as a ‘‘MG asset’’. Each asset is controlled by an agent specialised to the asset’s nature (Fig.1). Each agent is responsible for collecting specific measurements from its asset and communicating them to the MGCC (centralised mode) or the rest of the agents (distributed) according to the algorithmic logic that is described in the following paragraphs, in order to implement features such as data acquisition, V/f restoration and P/Q allocation.

3.1 Adaptive Droop-based Master & Slave Control during islanded operation

The basis of the proposed control logic is the assignment of specified roles to the DGs of a MG, which however may not be fixed. The logic derives from the established concept of master-slave control, which essentially describes the operating control mode of each DG (grid-forming, grid-feeding or current/voltage-controlled grid-supporting mode [22]). This architecture was presented in previous work of the authors [8]. *Master* role signifies voltage-controlled grid supporting operation and it consists of a SoC/C_{rate}-based adaptive droop control loop (1)-(2), a virtual impedance loop added in order to compensate for the resistive lines found in low-voltage MGs and the inner voltage and current loops. *Slave* role equals to current-controlled grid-supporting control which signifies for the ESS the reversed SoC-based droop curves of (1)-(6) and the PV the reversed MPP-based droop curves of (10)-(12) and the respective inner current loops. Both schemes are based on specific droop curves, depending on the nature of the DG. Units that are able to support their own DC bus (e.g. hybrid PV-ESS units, ESS etc.) can be either *master* or *slave* units, whereas units without stand-alone DC bus control, like many

PV installations found in real-site MGs, are assigned permanent *slave* role. Having these roles defined, the proposed MG control is applicable to MGs regardless of the coupling of the DGs (AC or DC-coupling).

During islanded operation, *master* ESS follow:

$$f = f_{nom} - \frac{f_{nom} - f_{min}}{P_{discharge}(SoC(t), C_{rate}(t))} P \quad (1)$$

$$V = V_{nom} - \frac{V_{max} - V_{min}}{2Q_{ESSmax}} Q \quad (2)$$

where

$$P_{discharge}(SoC(t), C_{rate}(t)) = \frac{SoC(t) - SoC_{MIN}}{C_{rate}(t)^{-1}} Cap_{nom} \quad (3)$$

$$Q_{ESSmax} = \sqrt{S_{nom}^2 - P_{discharge}^2(SoC(t), C_{rate}(t))} \quad (4)$$

Regarding the *slave* ESS that charge (P<0), the P-f reversed droop control is given by:

$$|P| = \begin{cases} \frac{P_{charge}(SoC(t))}{f_{min} - f_{nom}} (f - f_{nom}), & f \in [f_{min}, f_{nom}] \\ \frac{P_{charge}(SoC(t))}{f_{max} - f_{nom}} (f - f_{nom}), & f \in (f_{nom}, f_{max}] \end{cases} \quad (5)$$

where

$$P_{charge}(SoC(t)) = \frac{P_{chargeMAX}}{SoC_{MAX} - SoC_{MIN}} (SoC_{MAX} - SoC(t)) \quad (6)$$

Similarly, Q-V reversed droop is dictated by:

$$Q = \frac{2Q_{ESSmax}}{V_{min} - V_{max}} (V - V_{nom}) \quad (7)$$

$$Q_{ESSmax} = \sqrt{S_{nom}^2 - P_{charge}^2(SoC(t))} \quad (8)$$

Finally, PVs, assuming they have permanent *slave* role due to absence of independent DC bus regulation, are governed by:

$$P_{PV} = \begin{cases} P_{MPP}, & f \in [f_{min}, f_{nom}] \\ P_{MPP} - \frac{P_{MPP}}{f_{max} - f_{nom}} (f - f_{nom}), & f \in (f_{nom}, f_{max}] \end{cases} \quad (9)$$

$$Q_{PV} = \frac{2Q_{PVmax}}{V_{min} - V_{max}} (V - V_{nom}), \quad V \in [V_{min}, V_{max}] \quad (10)$$

where

$$Q_{PVmax} = \sqrt{S_{PVnom}^2 - P_{MPP}^2} \quad (11)$$

3.2 Proposed MAS Algorithmic Control Logic

Fig.2-3 present the flow charts regarding the algorithms followed by the MAS in order to perform voltage and frequency (V,f) restoration and also to adjust the droop and reversed droop coefficients of the ESS, after collecting information regarding the load consumption and power PV production. In the following paragraphs, detailed description of each function is given, with and without the MGCC operation.

3.2.1 *Distributed Voltage and Frequency Restoration*: The first function is implemented based on the work of Shafiee et.

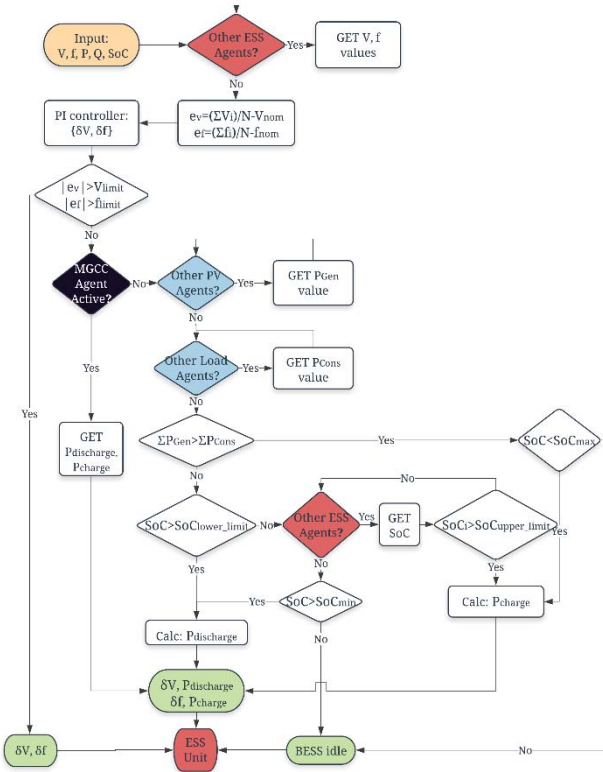


Fig. 2. Logical flow chart of the MGCC agent

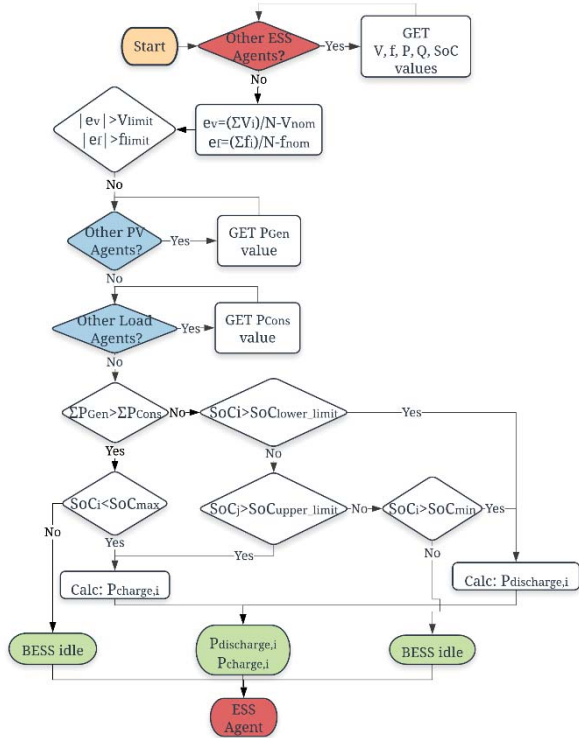


Fig. 3. Logical flow chart of the ESS agent

al. [17]. The restoration is always performed by the agents, regardless of the status of the MGCC, leading thus to a system that ensures proper power quality at all times. Essentially, the averaged measurements of V, f are passed through a PI controller. The resulting value $\Delta f, \Delta V$ is used by the embedded in the VSCs droop controllers in order to shift the droop

curves: vertically for *master* units and horizontally for *slave* units.

3.2.2 SoC-/MPP-based Optimal Power Allocation: The basis of algorithm logic aims to balance the energy between the storage units and to allocate optimally the requested power among units based on the actual available power/energy they can allocate. As each ESS agent has calculated the diversity of the average voltage and average frequency from their nominal values, they start the *Hybrid Optimal Power Allocation (HOPA)*, following the formulas presented in the previous paragraph. In case the MGCC agent is operational, it is responsible to coordinate the communication with all agents in order to retrieve all their current measurements, then calculate the optimal charge and discharge power according to (6) and (3) respectively for each ESS unit. If the MGCC has malfunctioned, the ESS agents take over the coordination of communication with the rest of the agents of DERs and loads, in the case study presented namely PV and Load agents. If generation is less than consumption, the ESS agents calculate the discharge power that can be provided based on the remaining stored energy as in (3). Regarding ESS that have reached a low threshold SoC (which can be arbitrarily defined by the user, for example $SoC_{average} \approx 20\%$), in order to ensure that these ESS will not be put into idle mode, their agents initiate search for the existence of an ESS agent with very high SoC. If found, then the final step is to change the operating mode of the low SoC ESS to charging and the high SoC ESS to discharging. Finally, based on (5), the MAS can allow the low SoC ESS to charge, even if the bus frequency is lower than the nominal. That way, SoC balancing can be achieved while the existence of at least two potentially *master* ESS is ensured, thus increasing the MG overall reliability.

4 Performance Analysis via Simulations

In order to demonstrate the main features of the proposed secondary controller that is performed by both the MGCC and in case of failure, by the rest of the agents- an islanded MG with AC-coupled units is simulated on MATLAB/Simulink. The respective agent-based communication has been implemented in Java using the FIPA protocol JADE framework. The examined MG, was based on a detailed model of a testbed MG in CERTH, Greece and it consists of one PV, two Li-ion ESS and passive aggregated loads, all connected on a common AC bus. The simulated MG is constructed a discrete model (resolution equal to $T_s=50\mu\text{sec}$) built in MATLAB/Simulink using the Simscape Power Systems toolbox and the detailed PV and Li-ion physical modules it provides, whereas all power electronic modules are modelled in detail using power IGBT and tailored LCL filters. For more details on the model parameters readers are invited to refer to previous work of the authors [8]. In the scenario selected for demonstration, the MG operates in islanded mode, the weather conditions are optimal (ambient temperature at 25°C and solar irradiance at $1000\text{W}/\text{m}^2$) and the MG performs black start. The first battery (ESS1) has an initial SoC equal to 80%, whereas the second one (ESS2) is at 20%. The MAS has stored knowledge of the status of the batteries prior to an assumed MG shut down and thus, based on the algorithmic logic presented in the previous section, ESS1 is assigned master role

and ESS2 operates as a slave. Since the MG units are all AC-coupled and there is no additional support on the DC bus of the PV, the PV is also controlled as a slave. From $t_0=0\text{sec}$ to $t_1=4\text{sec}$, the total passive load equals to 10kW, 0kVAr, from t_1 to $t_2=7\text{sec}$ a load increase takes place and the load is 10.5kW, 0.6kVAr and finally from t_2 to $t_3=10\text{sec}$, the load increases to 11kW, 1kVAr. From t_0 till $t'=1\text{sec}$, secondary control is disabled in order to allow the MG to perform the black start and at $t'=5\text{sec}$, the MG operates under the instructions of MGCC and at t'' all communications with MGCC are lost and the MAS takes up the optimal P-Q allocation.

In Fig. 4, the simulation results of the physical quantities demonstrating the operation of the MG are presented. Fig. 5 includes two screenshots of the messages exchanged between the agents with and without MGCC. During the centralised operation, the MGCC is active (red marked), it manages all messages traffic, whereas after the MGCC failure (yellow marked) the communication with other agents is managed by

ESS agents. As it can be observed, throughout the whole simulation the MG remains stable, even though the MG was forced to black start and handle fast (every 4 seconds) load step increases. Additionally, the distributed V, f restoration managed to perform adequately fast enough, resulting to a restoration time approximately equal to 2 seconds for both frequency and voltage amplitude. Finally, all master and slave DERs followed loyally the reference points as dictated by their respective droop and reversed droop curves. That said, PV and ESS shared the combined load of the actual passive load and the charging ESS according to their real-time capabilities and not a fixed rated value that does not correspond to the available energy from the sun and the remaining available energy stored to ESS1. Regarding the MGCC disappearance at $t'=5\text{sec}$, no apparent effect is observed on the physical quantities defining the MG performance, however as it can be observed (Fig.5), that without MGCC the exchanged messages number between the agents increases significantly. Finally, thanks to the MAS algorithmic logic for SoC balancing, the MG reliability is also

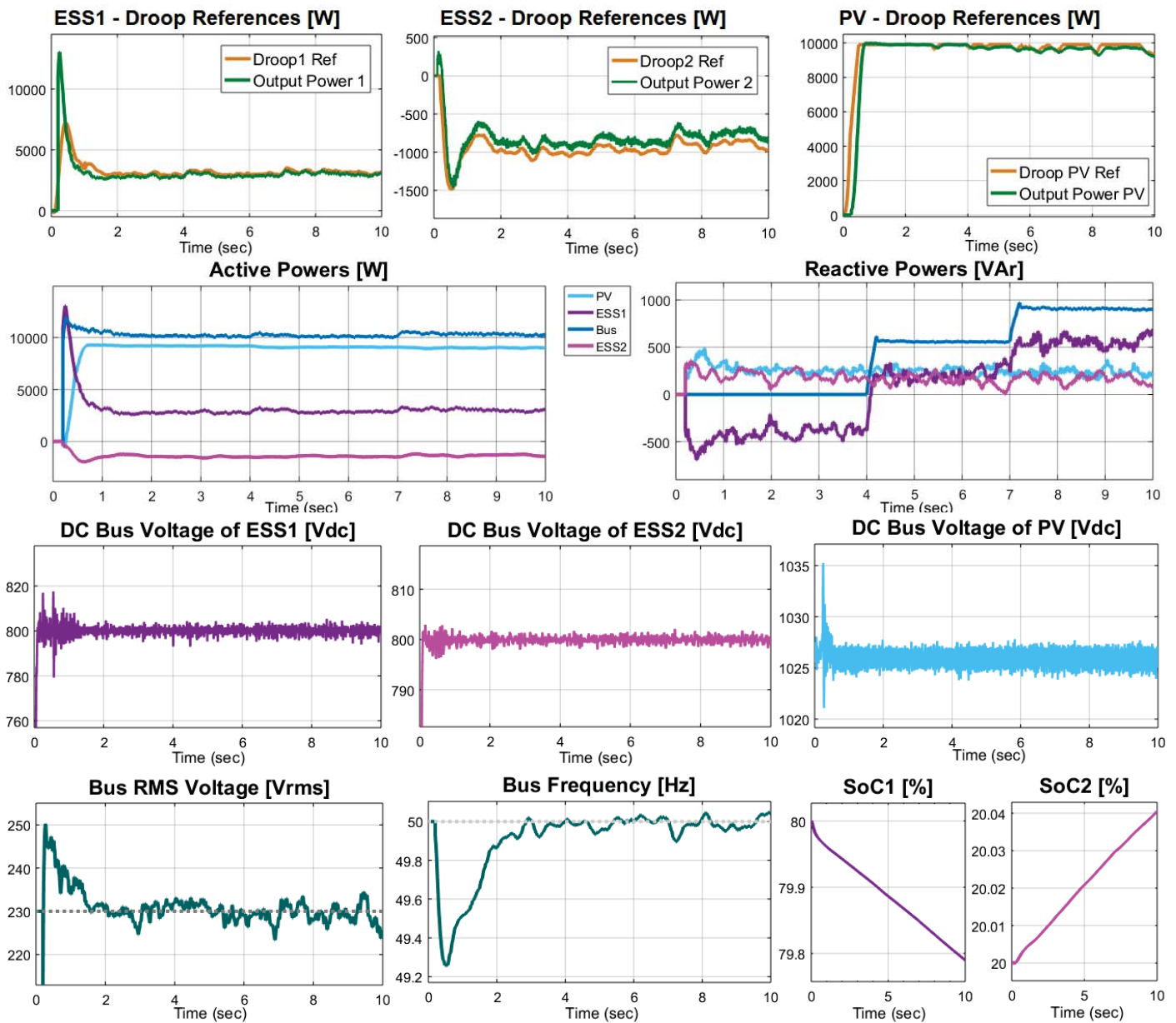


Fig. 4. Simulation results

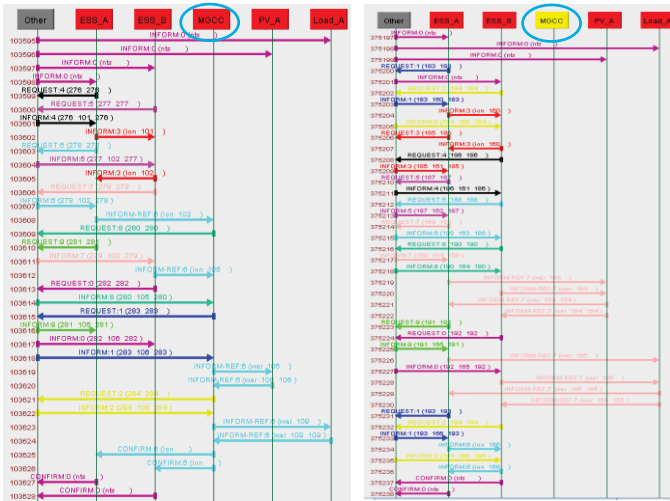


Fig. 5. MAS operation in JADE with (left) and without MGCC (right)

increased since in case of failure of ESS1, ESS2 is less close to drained and thus, is able to switch its role to master.

5 Discussion & Future Work

The proposed architecture for secondary control demonstrates some interesting features, namely: the capability to ensure the global optimised operation implemented by a centralised controller and the repeal of dependence to this thanks to the reconfigurability to distributed secondary control. The inspiration for the presented design was to create an optimised combination of accurate secondary control and increased MG reliability. On top of that, the efforts of the research team focused on keeping the overall system as simple as possible in order to be able to install the MAS on existing MGCC-based MGs. The next steps include small-signal analysis in order to define in detail the factors of the MGCC, the maximum rates of change in the droop and reversed droop coefficients and finally, the deployment of the overall control system to a testbed MG in CERTH premises in Greece.

6 Conclusion

A hybrid MGCC/MAS-based secondary controller for MGs with AC-coupled droop controlled DERs has been presented. The main feature of the proposed controller relies on its inherent ability to reconfigure from a semi-centralised system to a fully distributed system. This fact lifts the single-point of failure that characterises all centralised configurations. Additionally, the control system ensures optimal power sharing for MGs that include PVs and ESS thanks to the MPP/ SoC adaptive droop control logic under which it operates. Preliminary simulation results during islanded operation demonstrate the fast reconfiguration of the system, during which the overall MG stability is ensured at all times. On top of that, power quality is not deteriorated even though the MGCC has ceased to function. Since the proof of concept has been established, next steps will be taken in the near future in order to deploy the control system on an actual real-site MG in Greece.

7 Acknowledgement

This work has been partially supported by the EC FP7 ERANETMED project named “3DMicroGrid” with project number: ERANETMED_ENERG-11-286.

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