MicroGrid Energy Balance Management for Emergency Operation

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***Abstract*— A distinctive characteristic of a Microgrid (MG) system is related to the ability of operating autonomously. However, the stability of the system relies in storage and generation availability, providing frequency and voltage regulation. Considering the deployment of distributed storage units in the Low Voltage network and of smart metering infrastructures, this paper presents an online tool for promoting an effective coordination of MG flexible resources in order ensure a secure autonomous operation and maximize the time that the MG is able to operate islanded from the main grid. The tool determines *a priori* an emergency operation plan for the next hours, based on load and microgeneration forecasting. The limited energy capacity of the distributed storage units participating in MG control is also considered.**

***Index Terms*—Electric Storage, Energy Balance, Islanded operation, Microgrid, State of Charge Control.**

I. Introduction

Reliability is considered one of the major benefits of a MG system due to its ability to operate both interconnected to the main grid or autonomously as a physical island – emergency operation. In fact, if a disturbance occurs in the main grid or in case of planned events (such as maintenance actions), the MG can be transferred to islanded operating conditions, supplying local loads with the MG generation capacity supported by fast acting storage units [1]-[3], assuming adequate control structure supported by an ICT infrastructure is available.

The organization of MG control structures typically follows a hierarchical arrangement comprising primary, secondary and tertiary control layers [3]. During islanded operation, the MG primary control layer is responsible for frequency and voltage regulation strategies that will assure the continuous power balancing with minimum dependence of communication system [2], [3]. Primary control is usually based on a droop strategy implemented as an external control loop of the storage unit coupling inverter, controlled as a Voltage Source Inverter (VSI). Then, the secondary control layer will be responsible to restore MG frequency and node voltages to reference set-points [1],[2], [3]. The MG secondary control is usually performed by the VSI and/or other controllable Microsources (MS), such as microturbines [1], [2], [3].

The effectiveness of the frequency and voltage regulation strategies will depend of the power disturbance severity and the availability of the resources to participate in frequency regulation. Primary control will only ensure power balance if there is sufficient storage capacity and if the inverters maximum power limits are not surpassed. Similarly, secondary regulation can be compromised if the MG lacks sufficient reserve capacity to compensate the power injected by the VSI and correct frequency deviation.

In addition to MS and flexible loads, the integration of grid distributed storage units owned either by the Distribution System Operator (DSO) or by the consumers (in a self-consumption model) can contribute to increase the global MG storage capacity, by exploiting their flexibility [4]. This is particularly interesting when the system is operating in islanding, since it increases the MG reserve capacity [4].

Local voltage and frequency control needs to be complemented by high level supervisory management functionalities specifically designed in order to ensure adequate MG controllability during islanding conditions. In [5] authors present an online tool which main objective is to define *a priori* an emergency load and MS control strategy which mitigates the impact resulting from the islanding transient or other disturbances occurring during the autonomous operation. However, the proposed algorithm was intended to support MG islanding operation during short periods of time. For longer time frames of operation in islanding conditions, alternative approaches need to be considered, involving the integration of information related to the forecasting of loads and renewable based microgeneration for the upcoming hours for which it is intended to maintain MG autonomous operation. In this context, several algorithms have been presented in the literature addressing longer time frames. A dynamic programming method is presented in [6],

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which determines the optimal dispatch of the MG controllable MS in order to reduce the operation costs. A day-ahead scheduling method for a planned MG islanding is also presented in [7]. The main objective of this algorithm is to determine the optimal battery charge/discharge schedule which maximizes the time the MG can operate islanding, based on PV generation and load forecasts. In [8], the authors present a centralized MG optimal scheduling model based on mixed linear programming, where different set of islanding constrains were tested, namely MG capacity to ensure a secure islanding, time of islanded operation, consumer convenience and model scalability and flexibility. However, the algorithms presented in [6]-[8] are not designed for the online manage the MG in islanded mode, ensuring only that the MG will have enough capacity if an islanding occurs during the next day.

This paper presents an online algorithm for increasing the LV network resilience when operating autonomously, taking advantage of flexible resources such as storage devices and flexible loads [4]. The developed tool determines the MG emergency operation plan considering the occurrence of an unplanned islanding occurring during the next hours, based on load and microgeneration forecasting. In order to determine the MG operation plan for the next hours, a new emergency dispatch strategy is proposed for storage units distributed along the MG in order to preserve as much as possible the capacity of the storage unit(s) that is(are) responsible for frequency and voltage control in islanded mode. This is a new approach when compared to the secondary control strategies presented in literature [1], [2], [3], [5]. The proposed tool was developed and validated through simulation and experimentally in a MG laboratory setup [9].

II. MG Energy Balance Management Algorithm

Considering the additional storage capacity integrated at the LV level, a new algorithm is proposed for providing an effective management of the MG during autonomous operation. The main objective is to maximize the MG power and energy reserve capacity in order to maximize the time the LV system can operate autonomously.

The MG emergency balance algorithm can be set to plan the control for the next time-step or in a longer term (from minutes to a few hours), considering the time resolution of the real-time and forecasting data. The algorithm will evaluate the MG operating state and then dispatch the distributed storage units providing grid support. If the power and/or energy reserve capacity is insufficient, the algorithm will schedule additional control actions for mobilizing residential flexibility, managed through the Home Energy Management Systems (HEMS). The algorithm comprises three different steps:

1. Characterize the MG Operating State: The tool will collect the data relative to the MG storage devices, loads and microgeneration state and determines the available power and energy reserves.
2. Emergency dispatch of MG controllable resources: The algorithm identifies the operation plan for the defined timeframe, based on the current state of the network and in the load and microgeneration forecasts.
3. Schedule Emergency Control Actions: In case the MG does not have enough power and/or energy reserve capacity to guarantee the power balance, it is necessary to exploit emergency demand response strategies to ensure power balance and thus avoid the system collapse.

A. *Emergency dispatch of MG controllable resources*

The storage unit's active power set-points for the time horizon considered for the islanded operation will be calculated through an iterative approach as illustrated in Fig. 1. The algorithm will return a plan for the time horizon considered, t_n, consisting on a set of active power set-points for each time step, *t*.

In a first step, the algorithm will determine an initial solution for the power dispatch of the distributed storage units participating in the secondary control, considering their power reserve. Then, in the second stage the algorithm will redistribute the amount of power dispatched for the distributed storage unit(s) according to the State Of Charge (SOC) estimated at the end of the considered time horizon t_n.

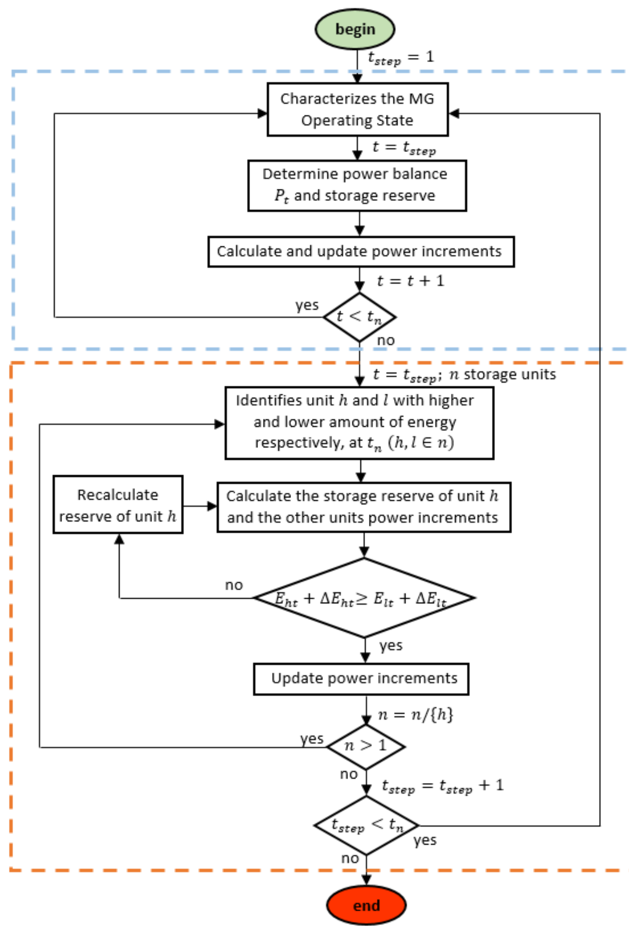

Figure 1.Emergency dispatch algorithm of MG distributed storage units providing grid support.

The power dispatch is determined in order to ensure the power balance of the MG for each time step t, as in (1).

$$\Delta P_t = P_{MS_t} - P_{L_t} + \sum_{i=1}^{m} P_{i_t} \qquad (1)$$

Where P_{i_t} corresponds to the active power set-point of storage unit, *i*, P_{MS_t} corresponds to the active power provided by the microgeneration units and P_{L_t} to the load consumption for time interval *t* respectively. ΔP_t will in fact correspond to the power that without control will be provided by the VSI.

The initial solution dispatches each storage unit based on its power reserve upward and downward. When the MG generation exceeds the load, the VSI will charge in order to balance the system. In this case, the algorithm will request a power consumption increase to the grid supporting storage units, considering the reserve up available. On the contrary, when the VSI is discharging in order to supply the remaining load, the dispatch will define new set-points either to reduce the power consumption from the storage units, or even to reverse its power output and inject power in the LV system.

The reserves upward and downward are determined as presented in (2).

$$\begin{cases} R_{up} = P_i^{charge} - P_{it} \\ R_{down} = P_i^{discharge} + P_{it} \end{cases} \qquad (2)$$

Where, R_{up} and R_{down} are the active power reserve up and down respectively. P_i^{charge} and $P_i^{discharge}$ correspond to the maximum power the storage unit *i* can provide when charging and discharging respectively. These values are updated each time step *t*, considering the SOC of the storage unit, as in (3).

$$\begin{cases} P_i^{charge} = \min\left(\dfrac{C_i - E_{it}}{\Delta t}; P_{i,\max}^{charge}\right) \\ P_i^{discharge} = \min\left(\dfrac{E_{it}}{\Delta t}; P_{i,\max}^{discharge}\right) \end{cases} \qquad (3)$$

The contribution of each storage unit will be defined for unit *i* by the ratio between its reserve (R_i) and the total storage reserve, according to (4),

$$P_{it} = \frac{R_i}{\sum Ri} \times \Delta P_t \qquad (4)$$

At the end of the first stage of the algorithm, the final SOC of the storage units are determined for the time horizon t_n.

Based on final SOC, the algorithm will then adjust the storage units' power set-points by increasing the power provided by the unit with the highest SOC in order to reduce the power provided by units with lower SOC. The power change for the other units will be determined as shown in (5).

$$\Delta P_{it} = \frac{(C_i - E_i)}{\sum (C_i - E_i)} \times \Delta R_{\max} \qquad (5)$$

Where, ΔP_{it} is the active power change for unit *i* at time step *t*, considering the additional reserve capacity provided by the unit with the maximum SOC, $\Delta R_{\max}$. The reserve is distributed by the other unit(s) considering the ratio between the energy capacity available at the end of the time horizon (E_i) and the total energy capacity available.

The balancing of the distributed storage dispatch is performed iteratively. A constraint was imposed in order to ensure that the SOC of the re-dispatched units does not get lower than the unit with the lowest SOC. This prevents the algorithm from getting a worst solution than the one determined initially.

B. Schedule Emergency Control Actions

For each time-step the algorithm will verify the VSI limits and the network technical limits (e.g. under and over voltages or congestion. However, in case a violation is detected, the algorithm will schedule other consumers load flexibility in order to support the MG islanded operation.

After identifying the problem, the algorithm will first select the phase and the MG feeder with the highest voltage deviation and mobilize the maximum flexibility available in each node to solve the balance or technical restriction. The solution will be determined iteratively and validated by running the unbalanced three-phase power flow. At the end of each cycle, it will be selected the solution which will cause more significant improvements on the MG voltage profiles. This process will end when the amount of active power to be injected/consumed by the HEMS will be reached, or when there is no more flexibility available at the MG.

For each node the algorithm can mobilize load flexibility for several time-steps. However, contrarily to load and generation forecasting, the availability of load flexibility for the next hours will be affected by the control actions defined for the different periods. In this sense, a multi-period load flexibility proposed by Pinto *et al* was adopted in order to validate the strategy defined [10]. The methodology constructs diverse and feasible flexibility availability trajectories (complying with technical constraints) by means of sampling routines. A sufficient number of feasible trajectories are then used as input in a Support Vector Data Description (SVDD) function which is capable of delimiting the HEMS flexibility provision search space. The model that is created by the SVDD function is capable of identifying new multi-temporal HEMS flexibility set-points as being feasible or not.

The control solution found to solve the reserve shortage or technical violation will have to always maintain MG power balance. For example, when mobilizing load flexibility to solve an under voltage problem, the algorithm will reduce the load in the affected phase. However, in order to maintain power balance, the load curtailed or power injection needs to be compensated in the other phases. This process will end when the MG voltage profiles be within their admissible range.

III. RESULTS ANALYSIS AND DISCUSSION

A test system consisting in a LV network endowed with four storage devices was considered for evaluating the effectiveness of the proposed solution. The storage unit consist in a 30 kW / 30 kWh battery connected through a VSI to the

LV side of the MV/LV substation. The remaining storage units have 10kW/10kWh capacity and are current controlled. They will provide support to the secondary frequency control strategy described in previous sections. It is also assumed that some LV clients have installed MS such as PV panels and distributed storage units (2 kW / 2 kWh battery) controlled under a self-consumption scheme. Through, the control of storage the consumers provide flexibility services to the grid. An initial SOC of 80% was considered.

An illustrative time horizon of one hour was considered as the maximum time the MG is able to operate autonomously. The time horizon was divided in four time steps of 15 minutes. Table I presents the load and microgeneration forecasting for the considered time horizon.

Table I. Forecasted data for the test system scenario.

Time interval	**1**	**2**	**3**	**4**
Load (kW):	32.69	43.45	37.47	46.43
Microgeneration (kW):	-19.2	-19.2	-19.2	-4.8
MG Power Balance (kW):	13.49	24.25	18.27	41.63

In order to demonstrate the effectiveness of the algorithm presented in section II, two distinct simulation scenarios were considered:

- Scenario 1: a conventional secondary frequency control strategy was considered, based only in the power reserve of the grid supporting storage.
- Scenario 2: Emergency dispatch of MG controllable resources: algorithm presented in section II.

The storage units participating in the dispatch are identified as PQ from this point forward. In the moment subsequent to the MG islanding the SOC of the MG storage devices are respectively: VSI=30%, PQ1=90%, PQ2=80% and PQ3=10%.

A. *Scenario 1*

In this scenario the storage active power set-points are determined based only on the PQ units power reserve determined for each time-step, as in [5]. Fig. 2 a) presents the resulting power set-points, while Fig. 2 b) presents the resulting SOC at the end of the hour. As shown, in order to compensate the power provided by the VSI, PQ 3 will fully discharge at the end of first period, having the MG only two PQ storage unit's participating in the remaining periods. Thus, the power unbalance in the MG will force the VSI storage unit to fully discharge after one hour (see Fig.4).

B. *Scenario 2*

Relative to scenario 2 two distinct cases were considered: 2-A and 2-B. The main difference is that in scenario 2-B load flexibility is mobilized when the VSI SOC reaches a minimum threshold value of 10%. As observed in Fig. 3, the algorithm will take advantage of the load and microgeneration forecasts, leading the unit PQ 3 to charge in the first two periods, allowing it to participate in periods three and four.

The impact of the proposed dispatch strategy in the VSI is presented in Fig. 4. Compared to scenario 1, in scenario 2 the VSI storage unit will not have such an extreme discharge due to the contribution of all PQ storage devices in the MG power balance. If the emergency control of flexible management is considered, the algorithm manages to maintain the VSI SOC above 10% by defining an active power injection of 1.64 kW at 45 minutes after the islanding.

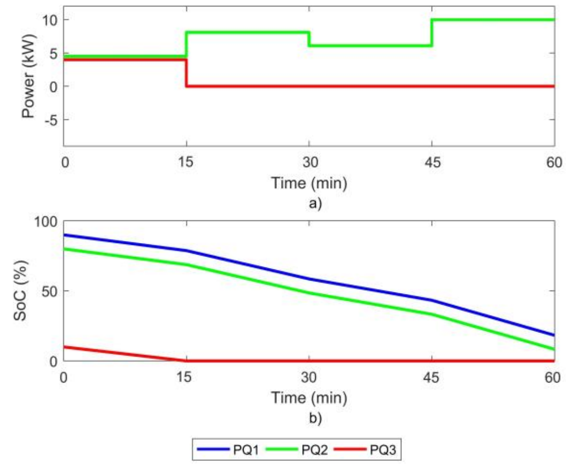

Figure 2. Scenario 1 - PQ Unit's Operational Strategy: a) Active Power Set-Points. b) State-of-Charge.

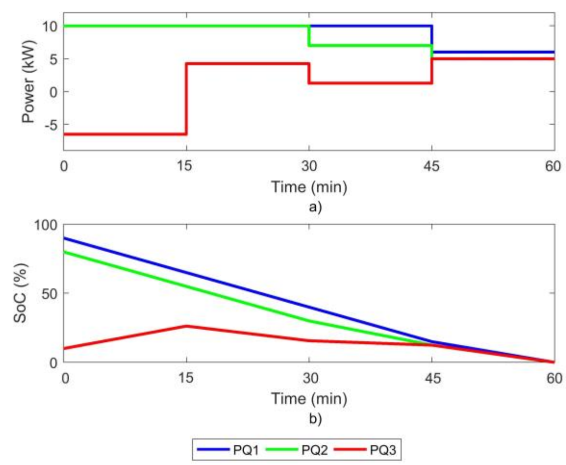

Figure 3. Scenario 2 - PQ Unit's Operational Strategy: a) Active Power Set-Points. b) State-of-Charge.

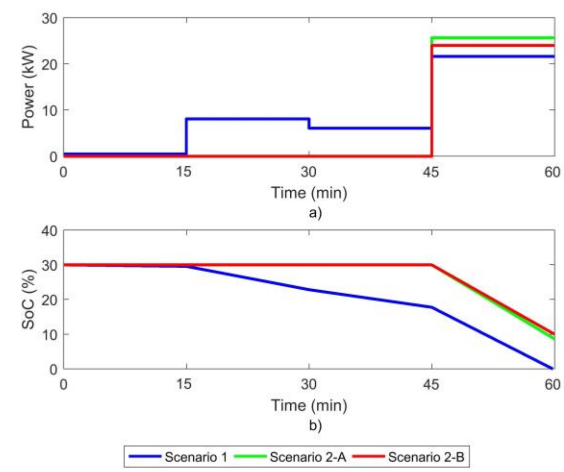

Figure 4. VSI Operational Strategy: a) Active Power Set-Points. b) State-of-Charge.

After calculating the operational plan, the power dispatch solution defined will be validated through an unbalance three-phase power flow. Fig. 5 shows the three-phase voltage magnitudes in the buses with highest voltage deviation, relatively to scenario 2.

As observed, in time step 4, the voltage magnitude exceeded the minimum limit (0.9 p.u.) in the three buses. In order to compensate the voltage deviation, the algorithm will schedule the available flexibility provided by the residential storage units. The residential flexibility connected to phase C of buses 97, 115 and 116 were mobilized to provide a total power of 1.64 kW. As represented in Fig. 6, the flexibility control strategy was able to restore voltages within admissible limits (approximately to 0.91 pu).

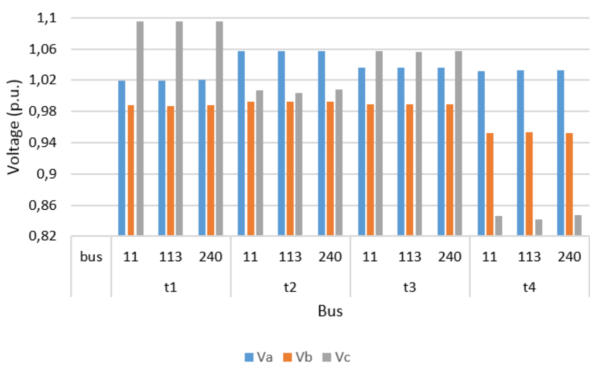

Figure 5. Voltage profiles of some critical buses – Scenario 2.

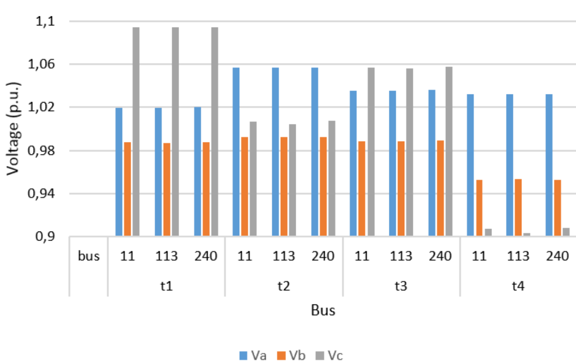

Figure 6. Voltage profiles of some critical buses – Scenario 2.

IV. LABORATORY SCALE MICROGRID

A. *Description*

The MG autonomous operation functionalities previously discussed were implemented and tested in the laboratory scale MG represented in Fig. 7. The laboratory MG set-up consists in a three-phase-four-wire implementation with three nodes. A three phase group of SMA Sunny Island inverters (15 kW, 400 V each) interconnects the secondary side of the MV/LV substation (node 1) to the node where the VSI coupled to batteries is connected (node 2). The inverters are connected to two Flooded Lead-Acid (FLA) battery banks (50 V, 20 kWh @ 10 h). These inverters operate in parallel with an existing grid and are able to operate autonomously in isolated systems. A LV cable emulator with a nominal resistance of 0.3 Ω is used to interconnect nodes 2 and 3. The PQ unit is represented by a 20 kW four quadrant back-to-back inverter, remotely controlled in terms of injected or absorbed active power is used to emulate an energy storage device [9].

Regarding loads, two 27 kW resistive load banks (controllable loads CL1 and CL2 respectively) are also connected to node 3. CL1 and CL2 are resistive load banks divided in 4 stages, and operate as a three phase constant power load. For providing flexibility, two 3 kW single-phase storage inverter prototypes developed in-house were considered, representing two single-phase consumers adopting a self-consumption scheme.

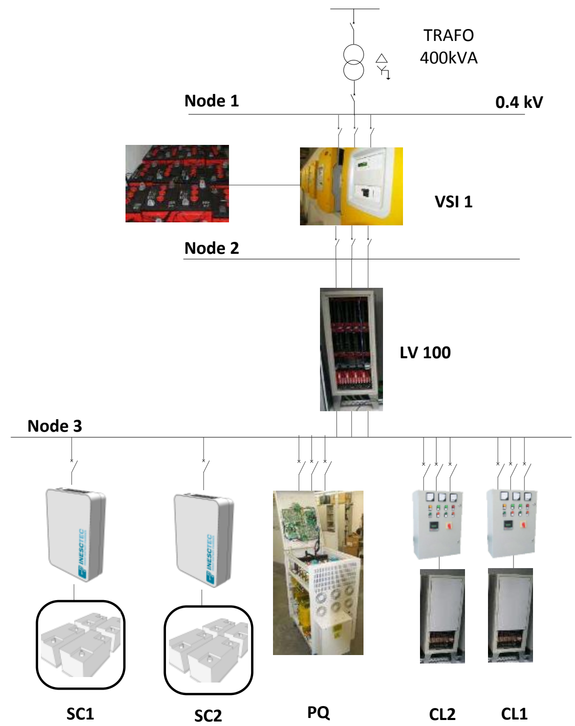

Figure 7. Microgrid experimental test system.

B. *Result Analysis and Discussion*

In the beginning of the experiment the MG was supplying a total load of 14 kW (7 kW in CL1 and CL2). The PQ unit, as well as SC1 and SC2, were not injecting or absorbing active power. In the moment subsequent to the MG islanding the following SOC for the PQ and VSI was considered 50% and 80% respectively. So, the algorithm will define the operational strategy for the PQ, SC1 and SC2 units based in the load forecasts presented in Table Table **II**. A time range of one hour was considered, in time steps corresponding to the real forecast time resolution (15 min). Since the laboratory tests have as purpose the MG stability validation, in the experiences made the 15 min periods were scaled into 30 seconds periods.

Table II. Load forecasts for the laboratory test scenario

Time interval	**1**	**2**	**3**	**4**
Load (kW):	14	17.5	21	17.5

In Fig. 8 and 9 are represented the MG power balancing for the defined period. As shown in Fig. 9 before the islanding VSI AC1 is providing approximately 25 kW, 11 kW for charging the batteries and the remaining 14 kW to supply MG loads. As observed in Fig. 8, the PQ unit will fully discharge at the end of the first 30 minutes, forcing the VSI to increase its active power injection. To guarantee the system security, in time steps 3 and 4 the flexible resources (SC1 and SC2) were dispatched in order to prevent the VSI of surpassing its maximum power limit (a maximum of 14 kW was considered). The MG frequency measured is represented in Fig. 10, showing that the islanding operation the system stability is maintained. The frequency was measured with power quality analyser Fluke 1760TR® (in continuous recording mode, with an average sampling time of 10ms).

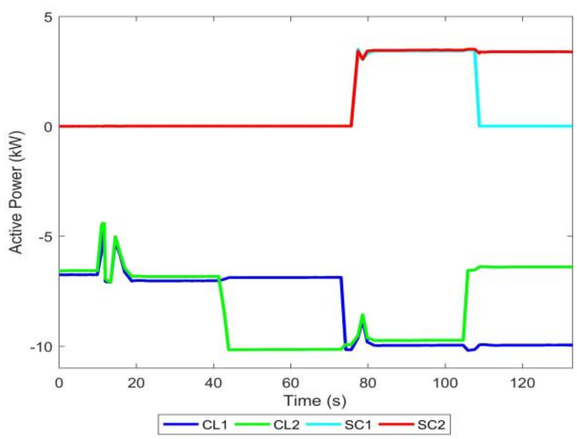

Figure 8. Load and flexible units power set-points.

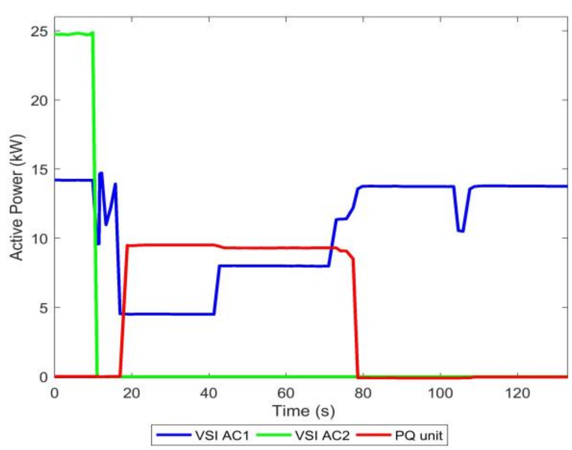

Figure 9. VSI and PQ active power set-points.

V. CONCLUSION

This paper presented a new emergency control tool for the MG islanded operation. The main objective of the tool is to ensure a secure islanding operation for a predefined time period, avoiding the need for flexible load mobilization. The proposed strategy determines the MG reserve capacity based on the available energy capacity of the distributed storage units providing grid support. The results show that the algorithm adopted is able to increase the MG reserve capacity for a longer term, increasing the resilience of the MG system. The results obtained experimentally in a laboratory scale MG demonstrate that the MG system stability is guarantee during the MG autonomous operation.

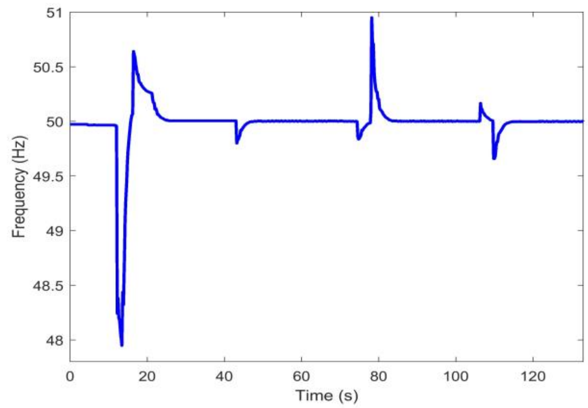

Figure 10. MG frequency.

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REFERENCES

[1] R.H. Lasseter, "Smart Distribution: Coupled Microgrids," Proceedings of the IEEE, vol.99, no.6, pp.1074-1082, June 2011.

[2] J.A. Peças Lopes, C.L. Moreira, A.G. Madureira, “Defining control strategies for MicroGrids islanded operation,” IEEE Transactions on Power Systems, vol.21, no.2, pp. 916- 924, May 2006.

[3] J.M. Guerrero, J.C. Vasquez, J. Matas, L.G. de Vicuna, M. Castilla, "Hierarchical Control of Droop-Controlled AC and DC Microgrids—A General Approach Toward Standardization," IEEE Transactions on Industrial Electronics, vol.58, no.1, pp.158-172, Jan. 2011.

[4] Commission Staff Working Document, " Best practices on Renewable Energy Self-consumption", July the 15th 2015. [Online]. Available: http://ec.europa.eu/energy/sites/ener/files/documents/1_EN_autre_document_travail_service_part1_v6.pdf

[5] Gouveia, J. Moreira, C. L. Moreira, J. A. Peças Lopes, "Coordinating Storage and Demand Response for Microgrid Emergency Operation," IEEE Transactions on Smart Grids, vol.4, no.4, pp.1898-1908, Dec. 2013.

[6] N. A. Luu, Q. T. Tran and S. Bacha, "Optimal energy management for an island microgrid by using dynamic programming method," *PowerTech, 2015 IEEE Eindhoven*, Eindhoven, 2015, pp. 1-6.

[7] M. Jin, X. Wang and X. Yu, "Security constrained day-ahead microgrid island scheduling with battery storage control," *2014 IEEE PES General Meeting | Conference & Exposition*, National Harbor, MD, 2014, pp. 1-5.

[8] A. Khodaei, "Microgrid Optimal Scheduling With Multi-Period Islanding Constraints," in *IEEE Transactions on Power Systems*, vol. 29, no. 3, pp. 1383-1392, May 2014.

[9] C. Gouveia, D. Rua, F. Ribeiro, L. Miranda, J.M. Rodrigues, C.L. Moreira, J.A. Peças Lopes, “Experimental validation of smart distribution grids: Development of a microgrid and electric mobility laboratory”, International Journal of Electrical Power & Energy Systems, Volume 78, pp. 765-775, June 2016.

[10] R. Pinto, R. J. Bessa, M. A. Matos, J. Gouveia, C. Gouveia, “Multi-temporal Modeling of Behind-the-Meter Flexibility,” *in 2017 IEEE PES Powertech Manchester*, pp. 1-6, June 2017.