PREVENTIVE MANAGEMENT AND CONTROL OF A MICROGRID SYSTEM USING FLEXIBILITY OF DISTRIBUTED STORAGE

C. GOUVEIA, A. MADUREIRA, J. GOUVEIA, J. SUMAILI, D. RAHMAN, R. BESSA, C. MOREIRA, L. SECA,

INESC TEC Portugal
cstg@inesctec.pt, agm@inesctec.pt , jose.m.gouveia@inectec.pt, jean.sumaili@inesctec.pt,
dewan.f.rahman@inesctec.pt, rbessa@inesctec.pt, cmoreira@inesctec.pt, lseca@inesctec.pt

ABSTRACT

Distributed Electrical Energy Storage (EES) is a key element of the MicroGrid (MG). When associated with accurate load and generation forecasts, the management of EES can avoid potential technical problems and at the same time ensure adequate reserve capacity to ensure the autonomous operation of the MG. This paper presents a preventive management and control framework for the operation of the MG both interconnected and islanded from the main grid. The main results obtained in an experimental MG test setup at INESC TEC Smart Grid and Electric Vehicle Laboratory are also presented.

INTRODUCTION

When deployed as an extension of a Distributed Management System (DMS), the MicroGrid (MG) concept divides the distribution system into small controllable MV and LV clusters, which can be operated both grid-connected and islanded from the main grid [1]. This new distribution network operation philosophy can potentially increase the system reliability and resilience against not only component failures but also extreme events such as natural disasters.

One of the key elements of the MG is Distributed Electrical Energy Storage (EES). Its flexibility helps balancing renewable energy generation and load and enables the autonomous operation of the MG. However, in order to be effective, it requires an adequate management of its energy capacity as this is crucial to ensure the survival of the MG in islanded mode.

This paper presents a preventive management and control strategy for the operation of the MG in both interconnected and islanded operation modes. The main objective is to promote a coordinated management of both DSO controlled EES and flexibility services provided by the Low Voltage (LV) consumers for improving system efficiency, avoid technical limits violation and improve the system resilience in islanded operation.

MG ARCHITECTURE AS AN EXTENSION OF DMS/SCADA

The MG architecture adopted was defined in the context of SENSIBLE project [2] and is represented Figure 1. The observability of the LV network is ensured by the Automated Metering Infrastructure (AMI) consisting of two layers: the smart meter and the Distribution Transformer Controller – DTC) Together with the EES controller this system provides relevant information from the LV network, which is then used in the Analytics layer, where the MG tools are housed. Also, through a market platform, the DSO is able to subscribe flexibility services provided by LV clients. In this case, residential storage capacity is exploited for self-consumption purposes while the remaining capacity can be used by the DSO for voltage and congestion management through the Home Energy Management System (HEMS).

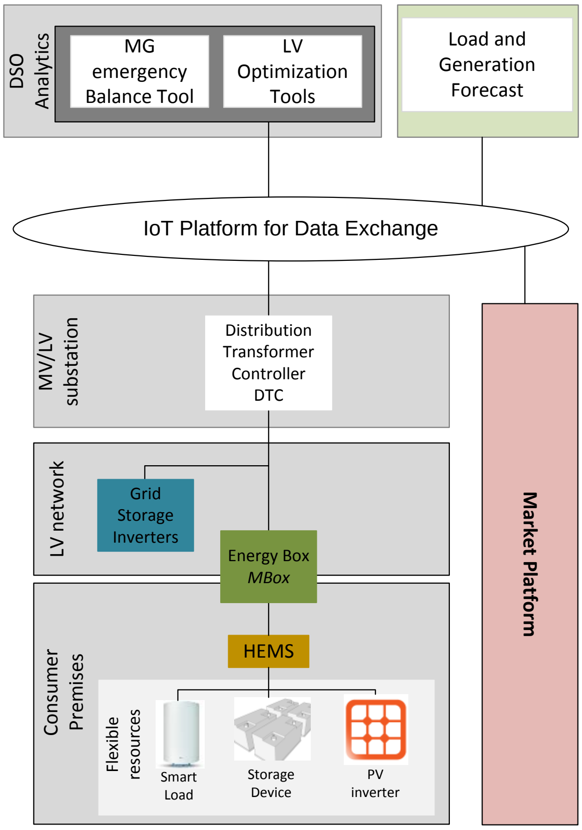

Figure 1. SENSIBLE Distribution Management and control architecture [2].

MG PREVENTIVE MANAGEMENT AND CONTROL TOOLS

A multi-temporal approach is proposed for an effective management strategy of DSO-owned electrical storage devices and for mobilizing flexibility services from the LV consumers. Based on load and generation forecasts, the algorithms are able to plan the operation of the MG and prevent probable technical problems.

As represented in Figure 1, two different tools were developed to plan the operation and control in real-time the microgrid resources in both interconnected and islanded modes, namely the LV optimization tool and the MG emergency balance tool respectively.

LV Optimization Tool

The LV optimization tool is responsible for planning and controlling the MG resources during interconnected operation. The algorithm that was developed is formulated as a multi-temporal Optimal Power Flow (OPF) with the objective of minimizing the power losses, while respecting the technical constraints of the network (namely in terms of voltage profiles) and considering the future states of the LV grid. The multi-temporal nature of the problem is due to the additional constraints that are taken into account in order to model the inter-temporal restrictions introduced by the storage devices [3].

The main innovation of this tool is its preventive nature by taking advantage of forecast data to anticipate technical problems that may arise during operation, namely in terms of voltage profiles. The final output consists of a set of set-points that represent the operating strategy of the storage devices and flexible loads for the next hours/day.

The tool is designed to run day-ahead (D-1) in order to define the LV optimal strategy for the storage units and other DER (namely demand flexibility of domestic clients via the HEMS) and provide to the MG operator a picture of the system for the next day regarding voltage magnitudes, energy losses, including potential technical restrictions that cannot be solved by the algorithm.

During the day (D), if updated forecast data is available, the tool updates the plan for the next hours, providing the same information as in the day before. In real-time, the set-points defined by the plan are validated considering the current state of the LV network. This avoids that in case there is a significant difference between forecasted and actual values, the operating conditions are not jeopardized.

MG Emergency Balance Tool

During islanded operation the balance between load and generation ensures the stability of the islanded MG. This balance is ensured mainly by the DSO's storage device with grid forming capabilities, which establishes the voltage and frequency reference of the system. The efficient management of the MG reserve capacity, namely through the dispatch of other EES and flexible loads, can increase the resilience and time that the MG can operate islanded from the main grid.

The MG emergency balance algorithm will evaluate the MG operating state for the next hours, based on load and microgeneration forecasting, and then dispatch the distributed storage units providing grid support. It comprises three different steps [4]: (1) characterize the MG operating state for estimating the available power and energy reserves for the next hours based on load and generation forecast; (2) emergency dispatch of MG controllable resources, to define 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: defines emergency demand response strategies to ensure power balance and thus avoid the system collapse.

The power dispatch is determined in order to ensure the power balance of the MG for each time step t, both the power and energy capacity of the DSO owned EES as well as the additional capacity of the flexible loads, controlled through the HEMS.

Behind-the-meter flexibility forecast

The multi-temporal approach for the LV grid management requires an innovative method to forecast the multi-temporal behind-the-meter flexibility, namely from flexible loads such as electric water heaters in combination with small-scale domestic storage and PV. In the proposed architecture, the HEMS makes available a forecast of a feasible flexibility envelope for a certain number of periods ahead. The method to forecast the domestic flexibility is as follows [5]: (i) generation of a set of feasible flexible trajectories; (ii) representation of the flexibility trajectories set by a Support Vector Data Description (SVDD) function. The following paragraphs present a summary description of the method.

Firstly, by means of sampling routines using domain knowledge, a sufficient number of feasible trajectories are created to define the flexibility (and feasible) space. These trajectories take into account the temporal evolution of the battery State Of Charge (SOC) or the water temperature range, and represent a feasible (i.e. respects technical and costumer's preferences constraints) load profile for a residential prosumer.

Having constructed a sufficient large number of feasible trajectories, the envelope for the flexibility provision can be defined. To do so, those trajectories are used as input in a SVDD function, namely a one-class machine learning function. The model that is created by this function is able of delimiting and learning the feasibility boundary (or flexibility set) based on the input data. This model is capable of classifying a new trajectory as "feasible" or "unfeasible" and represents the flexibility envelope by an equation that corresponds to the radius of a sphere.

This equation can be integrated in the formulation of the OPF problem for the LV grid, as a constraint that limits the multi-temporal vector of control set-points requested to a specific LV node. Moreover, it can be used to assess if the flexibility to be requested in MG islanding management is feasible and select an alternative load profile if necessary. Finally, it is important to underline that this representation keeps all behind-the-meter data private. An effort is being made to represent the flexibility set by a virtual battery, instead of the SVDD "black-box" representation.

VALIDATION OF THE PREVENTIVE MANAGEMENT CONCEPT

The preventive management tools developed have been implemented and validated in an experimental microgrid platform at the Smart Grid and Electric Vehicle Laboratory of INESC TEC. The MG set-up is shown in **Error! Reference source not found.** and consists of an LV three-phase-four-wire implementation with three electric nodes, Node 1, Node 2 and Node 3. Node 1 corresponds to the 400V bus of a secondary substation being monitored by the DTC. The three-phase four-wire cable emulators (LV100 and LV 50) are used to build the network feeder. The two controllable loads (CL2 and CL1) are connected to Node 2 and Node 3 respectively. CL1 is operated as a single-phase load connected to phase A.

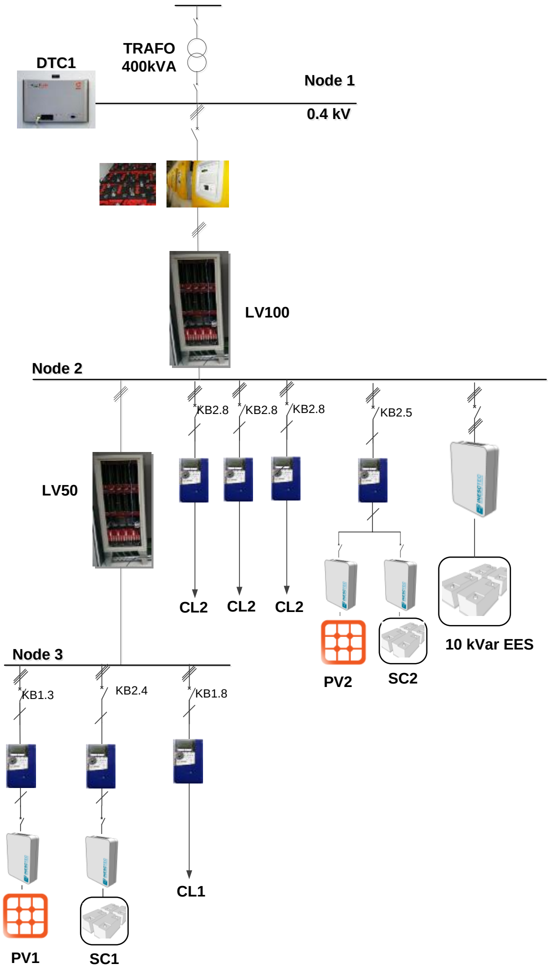

Figure 2. Microgrid experimental test system.

Two types of distributed storage were considered: DSO owned and client owned. Regarding DSO owned storage a grid forming and a grid tied inverter were considered. The grid forming units consist in a three phase group of SMA Sunny Island inverters (15 kW, 400 V each) that interconnects the secondary side of the MV/LV substation (node 1) to the node where the VSI coupled to batteries is connected (node 2). A 10 kVA grid tied EES is also connected to Node 2 and is controlled by the DSO in order to provide power and voltage support at the LV feeder. Regarding residential storage, two households are represented, constituted by the two single-phase microgeneration inverter prototypes (PV1 and PV2) and the two 3.5 kW smart storage inverters (SC1 and SC2) connected to a small lead-acid battery bank. The two single-phase storage units are able to provide load flexibility services to solve technical restrictions. This means that, the tools can send a power control set-point for solving voltage limit violations or help in balancing the system in islanded mode.

MG interconnected operation

Based on the forecasting for the next day, the LV optimization tool defines the power dispatch of the 10 kW ESS as shown in **Figure *3***. The storage unit will only participate in the operation of the LV network during the night period, where the load is higher. In this case, the storage unit will discharge in order to reduce system losses and contribute to regulate node voltages. Besides the EES dispatch the LV multi-temporal OPF mobilized the participation of flexible resources, namely storage unit SC1 connected to Node 3. The flexibility is mobilized in two periods: first between 9:45 and 15:45 in order to solve an overvoltage problem and then between 19:00 and 23:00 to solve an undervoltage problem occurring due to an increase of load connected in phase A. The voltage magnitude with and without the preventive management plan is shown in Figure 4.

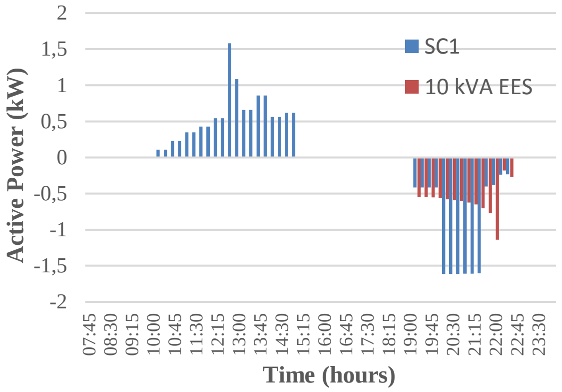

Figure 3. Active power set-point plan defined for the 10 kW ESS and for flexible client in Node 3 (SC1).

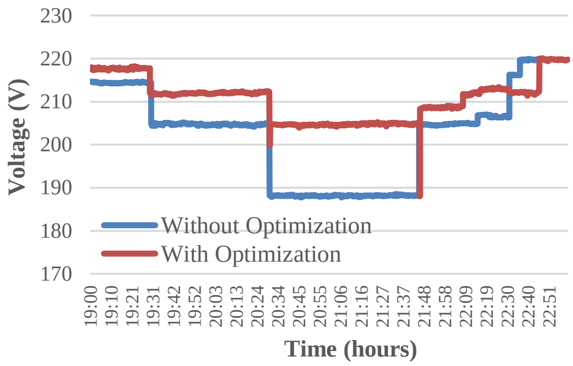

Figure 4. Comparison of voltage in phase A of Node 3 with and without considering the optimization strategy.

MG islanded operation

The MG emergency balance tool runs in parallel with the LV optimization tool, but will only send the set-points to the MG controllable resources in case of islanding. In order to test the MG emergency balance tool, an unplanned islanding was tested by opening the switch interconnecting the grid forming inverter to the main grid.

Considering the plan defined by the MG Emergency Balance Tool, after the islanding both the VSI and 10 kW ESS will discharge in order to supply the MG loads. As shown in **Figure 5** the 10 kW EES is dispatched to compensate the VSI power injection. As the load increases (at t=10min) so will the power provided by the 10 kW EES. However, the dispatch will also ensure that the minimum SOC limits of the EES are not surpassed. **Figure *6*** shows the system frequency, during the islanding transient and islanded operation. As shown, the dispatch strategy does not compromise the stability of the MG, causing small excursions when compared to the islanding transient.

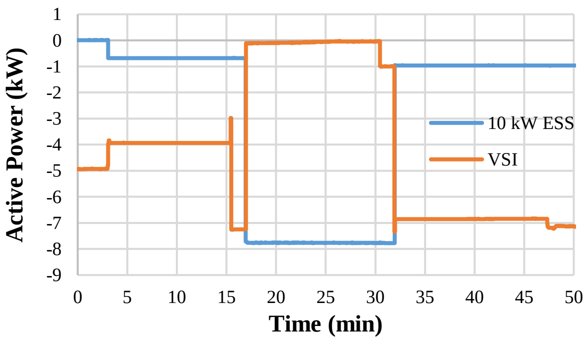

Figure 5. Grid storage active power set-points during the experiment.

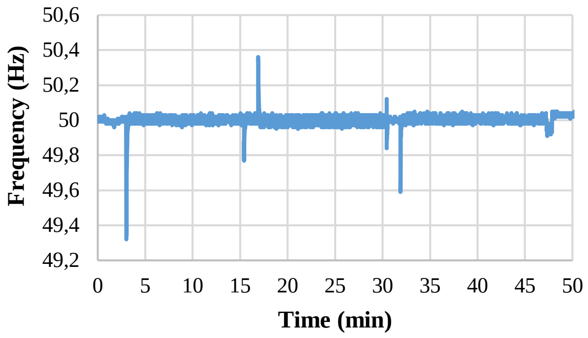

Figure 6. MG frequency during the experiment.

CONCLUSIONS

This paper presents a new framework for MG operation based on a preventive management control strategy that ensures the integrated planning of charging and discharging of DSO owned EES while also enabling the provision of grid support by residential storage devices. The tools that were developed - one for interconnected operation and the other for supporting islanded operation – are formulated as multi-temporal problems in order to effectively manage the storage capacity of the EES. The algorithms developed have been tested in a MG experimental platform, consisting of a typical LV rural feeder with a large integration of renewable energy based generation. The results have shown that in interconnected mode the multi-temporal OPF is able to improve the voltage profiles. However, in long feeders with high load unbalance having single-phase flexibility is especially relevant in order to solve possible technical restrictions. Also, the implementation of a dedicated tool to plan the islanded operation makes it possible to improve resiliency through a more stable autonomous operation, ensuring the necessary power and energy reserve capacity to maintain power balance. The tools will now be tested in a real MG pilot in Évora, Portugal in the context of H2020 SENSIBLE project.

ACKNOWLEDGEMENTS

The authors would like to thank the partners of the SENSIBLE project for the valuable discussions and, in particular, EDP NEW R&D and EDP Distribuição for providing the network data for testing the developed algorithm. This work is funded by SENSIBLE project (Storage ENabled SustaInable energy for BuiLdings and communitiEs - www.h2020-projectsensible.eu) that has received funding from the European Union’s Horizon 2020 - The EU Framework Programme for Research and Innovation 2014-2020, under grant agreement No. [645963].

REFERENCES

[1] J. Peças Lopes, A. G. Madureira, C. Moreira, "A View of Microgrids", *Wiley Interdisciplinary Reviews: Energy and Environment*, vol.2, no.1, pp.86-103, Janeiro, 2013.

[2] European project SENSIBLE - Storage ENabled SustaInable Energy for BuiLdings and communitiEs. Project Website: http://www.h2020-project-sensible.eu/

[3] H. M. Costa, J. Sumaili, A. G. Madureira, and C. Gouveia, "A multi-temporal optimal power flow for managing storage and demand flexibility in LV networks," in *2017 IEEE Manchester PowerTech*, 2017, pp. 1-6.

[4] J. Gouveia, C. Gouveia, J. Rodrigues, R. Bessa, A.G. Madureira, R. Pinto, C. L. Moreira, J. A. Peças Lopes, "MicroGrid energy balance management for emergency operation," *2017 IEEE Manchester PowerTech*, Manchester, 2017, pp. 1-6., 2017, pp. 1-6.

[5] R. Pinto, M.A. Matos, R.J. Bessa, J. Gouveia, C. Gouveia, 2017, “Multi-period modeling of behind-the-meter flexibility”, *Proc. of the IEEE PowerTech 2017*, Manchester, U.K.