Using Low Voltage MicroGrids for Service Restoration

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***Abstract*—Under normal operating conditions, a MicroGrid is interconnected with the medium voltage network; however, in order to deal with black start and islanded operation following a general blackout, an emergency operation mode must be envisaged. A sequence of actions and conditions to be checked during the restoration stage are identified and tested through numerical simulation. Voltage and frequency control approaches, inverter control modes, and the need of storage devices are addressed in this paper in order to ensure system stability, achieve robustness of operation, and not jeopardize power quality during service restoration in the low voltage area.**

***Index Terms*—Dynamic response, energy storage, frequency control, microgrid, power system dynamic stability, power system restoration.**

NOMENCLATURE

DG	Dispersed Generation.
MG	MicroGrid.
LV	Low Voltage.
MS	Microsource.
MV	Medium Voltage.
BS	Black Start.
MGCC	MicroGrid Central Controller.
DMS	Distribution Management System.
LC	Load Controller.
MC	Microsource Controller.
SSMT	Single-Shaft Microturbine.
PV	Photovoltaic.
VSI	Voltage Source Inverter.
SMO	Single Master Operation.
MMO	Multi Master Operation.
DT	Distribution Transformer.

I. INTRODUCTION

IN the last decades, electric power systems undertook several modifications toward a more decentralized energy system paradigm, allowing the increase of DG levels. DG technology has matured enough to present capability of providing ancillary services with reduced investment costs so that it can be seriously considered as a robust solution for the electricity consumption growing needs. Special attention should now be given to MG, a new paradigm for the development of electric power systems, which results from the connection of small and modular generation units, in the range of a few tens of kW or even less, to LV distribution networks [1]. Microgeneration can offer substantial environmental benefits through the integration of renewable forms of energy, such as wind or solar. Connection of MS can bring significant benefits to power system operation in terms of loss reduction and reliability improvement. Future grid reinforcements and expansion can also be deferred since branch congestion can be controlled. Furthermore, an MG can be an extremely flexible cell of the electrical power system if properly controlled through management and control systems. Two different modes of operation can be envisaged [1].

- Normal Interconnected Mode—the MG is connected to the MV grid, being either partially supplied from it or injecting some amount of power into it.
- Emergency Mode—the MG operates autonomously (as in physical islands) when the disconnection from the upstream MV network occurs.

Reduction of LV consumer's interruption time can be performed by allowing MG islanded operation, until MV network is available, and by exploiting MG generation and control capabilities to provide fast BS at the LV level. If a system disturbance provokes a general or local blackout, such that the MG was not able to successfully separate and continue to operate in islanded mode, and if the MV network is unable to restore operation within a predefined time, a first step in system recovery will be a local BS in the LV grid, which is a quite innovative approach. This first step will be afterward followed by the MG synchronization with MV grid. The feasibility of this operational concept was described by the authors in [2]. Preliminary experiments on real MG islanded operation were performed in a prototype system installed in the Laboratories of the National Technical University of Athens, which comprises a photovoltaic generator, battery energy storage, loads, and a controlled interconnection to an LV grid [3]. The feasibility of control strategies to be adopted for the operation of an MG when it becomes isolated, after a contingency in the MV network, is described in [1].

A. General Overview

If a blackout occurs, restoration times need to be reduced as much as possible to ensure a high level of reliability. Power system conventional restoration procedures are usually developed before any emergency situation occurs, adopting heuristic approaches, which reflect human operators' experience to deal

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with the problem. Furthermore, the size and specific characteristics of each of the actual power systems precludes the definition of a universal methodology [4]. The restoration plan is defined step by step, based on predefined guidelines and operating procedures, sometimes exploiting decision support tools, which are an extremely valuable resource to assist system operators [5], [6]. The restoration procedure is focused on the plant preparation for restart, network energization, and system rebuilding. Depending on system characteristics, a choice must be made between a strategy of energizing the bulk network before synchronizing most of the generators or a strategy of restoring islands that will be synchronized later [7]. With the dissemination of the MG concept, local self-healing techniques can be derived, since MG can be used for service restoration in their area of influence. The entire power system restoration procedure can then exploit a simultaneous bidirectional approach: 1) conventional top down, starting from large plant restart and transmission energization, 2) bottom-up, starting from the distribution side, exploiting DG units and microgeneration capabilities. Synchronization among these areas follows afterward. This approach helps to reduce restoration times and to reduce the unserved electric energy during major failures.

During conventional power system restoration, a set of critical issues should be addressed carefully: reactive power balance, switching transient voltages, load and generation balance and coordination, sequencing of generating units startup, and definition of the relays settings [8]. In case of an MG, the restoration procedure is much simpler due to the reduced number of controllable variables (switches, MS, and loads). On the other hand, it will not be expectable to find conventional synchronous machines in an MG, which are liable for voltage and frequency control in conventional power systems. Most of the MS currently available are not suitable for direct connection to the LV grid due to the characteristics of the energy produced. Therefore, power electronic interfaces (dc/ac or ac/dc/ac) are required. Another special issue related to MS operation concerns its slow response to the control signals in order to change the output power [1]. The absence of synchronous machines connected to the LV grid requires that power balance during transients should be provided by energy storage devices (batteries and flywheels). Furthermore, the controllability characteristics of the power electronic interfaces used in MS contributes to the definition of very specific restoration strategies.

A variety of technical and economical barriers hinder MG dissemination, and more work and adaptation on conventional power systems control centers is required in order to fully profit from MG potentialities. Equipment failures after a general blackout in a conventional power system may create difficulties to system restoration. MG black start is thus being developed as an emergency resource to be used in case of faults outside the MG not affecting seriously its equipments.

This paper tackles with black-start restoration sequences to be used for MG after a blackout. Based on the control strategies proposed in [1] and [2] and making use of the MG communication infrastructures, special issues for MG service restoration are identified in order to totally automate MG restoration procedure. Inverter control techniques are described and combined to find a suitable approach for LV distribution system restoration and ensure stable and robust operation. This restoration procedure was analyzed through numerical simulation. In order to study and evaluate the feasibility of the restoration sequences, two simulation platforms were exploited to deal with an LV study case network: an *EMTP-RV* tool used to analyze the fast transients associated with the initial stages of the restoration procedure and a *MatLab Simulink* simulation platform used to evaluate the longer term dynamic behavior of the islanded MG [1].

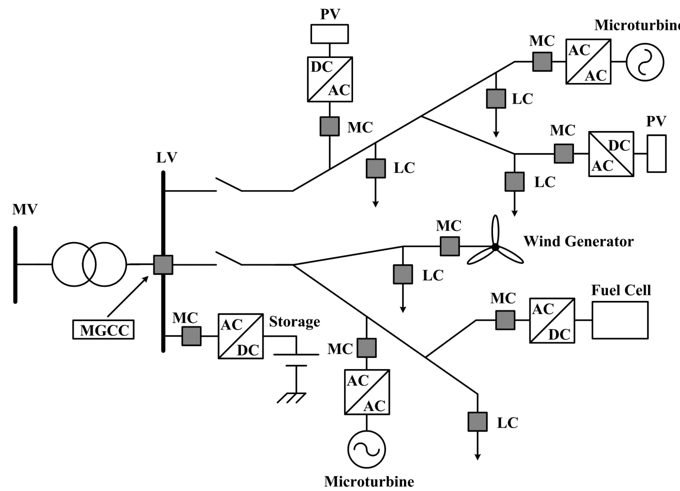

Fig. 1. MG architecture, comprising MS, loads, and control devices.

II. MicroGrid Architecture

The MG operational architecture was developed within the European Union R&D Microgrids project and is presented in Fig. 1. It comprises an LV network, loads (some of them interruptible), both controllable and noncontrollable MS, storage devices, and a hierarchical-type management and control scheme supported by a communication infrastructure used to monitor and control MS and loads.

The MG is controlled and managed by a MGCC installed at the MV/LV substation, which possesses several key functions and heads the hierarchical control system. The MGCC should also exchange information with the local DMS, which needs to be enhanced with new features related to the MG operation. Communication between MGCC and DMS includes information related to MV system status and economic issues for an efficient management of the MG. At a second hierarchical control level, controllers located at loads or at groups of loads (LC) and controllers located at MS (MC) exchange information with the MGCC and control local devices [1], [9]. During the initial stages of the LV restoration procedure, some MS overloads may occur if uncontrolled loads are connected to the system. Thus, it should be possible to remotely control all MG loads or, at least, groups of loads, in order to efficiently manage load switching and avoid large voltage and frequency excursions that could compromise the success of the restoration procedure. This is the assumption used in this paper. However, depending on the available MG storage capacity, it would be possible to consider the possibility of having different amounts of uncontrolled loads.

The information to exchange between the MGCC and local controls during the BS procedure involves mainly orders for switching management to rebuild the LV network and to connect MS and loads, information related to LV grid status, voltage and power levels, and set-points to local controllers. Conditions for specific tasks, such as synchronizations among MS, are to be checked locally by each MC. Thus, the amount of data to be exchanged among MG controllers does not require a large bandwidth.

III. Dynamic Modeling of Components

In this section, we briefly described the dynamic models used for simulating MS response during the restoration procedure.

A. Microsource Modeling

As mentioned previously, if an MG is operated in islanded mode, the power balance during transients must be provided by energy storage devices: MG main storage installed in the LV bus of the MV/LV transformer and frequently batteries connected to the dc bus of several MS. Flywheels are very promising units to be used as the MG main storage unit. In contrast to what happens with batteries, flywheels' life is almost independent of the depth of discharge and can operate equally well on frequently shallow discharges or on very deep discharges [10]. Storage devices play a key role in MG operation as they are the elements that provide energy in order to ensure system stability during islanded operation [1] and particularly in the service restoration procedure.

Regarding service restoration at the LV level, SSMT play a key role, due to their potential to autonomously restart within a few minutes after a complete shutdown and without the presence of the external grid, since they can be equipped with batteries in their dc bus [11]. Considering the time period under analysis, storage devices are modeled as constant dc voltage sources using power electronic interfaces to be coupled with the electrical network (ac/dc/ac converters for flywheels and dc/ac inverters for batteries) [1]. Thus, the response of the mechanical part of the microturbine is not a concern during service restoration, since it is dominated by the fast response provided by MS level storage, as it can be observed in laboratorial tests described in [11] and [12].

Using a suitable control over the microturbine generators, frequency regulation within the islanded MG can be provided, allowing the integration of intermittent renewable forms of energy: wind and solar. The wind generator is considered to be an induction machine directly connected to the network [1]. Regarding PV, it was assumed that the PV array is always working at its maximum power level for a given temperature and irradiance level. This corresponds to an empirical model based on experimental results, as described in [13].

B. Inverter Modeling

In an MG environment, the inverter interface model can be derived according to two possible control strategies [14]: PQ inverter control and VSI control logic.

The PQ inverter injects the power available at its input into the grid. The reactive power injected corresponds to a pre-specified value, defined locally (using a local control loop) or centrally from the MGCC [1].

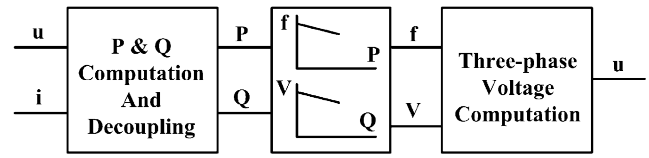

Fig. 2. VSI model.

The VSI emulates the behavior of a synchronous machine controlling both voltage and frequency on the ac system [1], [3], [15]. It acts as a voltage source controlling both magnitude and frequency of the output voltage through the following droop equations:

$$\begin{aligned} w &= w_0 - k_P \times P \\ V &= V_0 - k_Q \times Q \end{aligned} \tag{1}$$

where P and Q are the inverter active and reactive power outputs, k_P and k_Q are the droop slopes (positive quantities), and ω_0 and V_0 are the idle values of the angular frequency and voltage (values of the inverter angular frequency and terminal voltage at no load conditions).

During MG restoration, a cluster of VSI operates in a standalone ac system. In this case, frequency variation defines power sharing among VSI, such that for a system with n VSI, the following equality stands:

$$\Delta P = \sum_{i=1}^{n} \Delta P_i \tag{2}$$

with ΔP_i being the power change in the ith VSI. The frequency variation can be computed as

$$\begin{aligned} \Delta w &= w_{0i} - k_{Pi} \times P_i - [w_{0i} - k_{Pi} \times (P_i + \Delta Pi)] \\ &= k_{Pi} \times \Delta Pi. \end{aligned} \tag{3}$$

Similar considerations can be made for the voltage/reactive power VSI control mode based on droops [3], [15]. However, as voltage has local characteristics, network cable impedances do not allow a precise sharing of reactive power among VSI.

A three-phase balanced model of a VSI implementing the described droop concepts was derived from a single-phase version presented in [16] and shown in Fig. 2. The VSI terminal voltage and current are measured in order to compute active and reactive powers. This measuring stage introduces a delay for decoupling purposes. The output voltages are the reference signals that control the VSI switching sequence using a PWM modulation technique.

In terms of standalone ac system operation, this control principle allows VSI to react to system disturbances (for example, load or generation changes) based only on information available at its terminals [15]. In this way, the operation of an MG does not rely on fast communications among MS controllers and the MGCC, which could be impractical. VSI operating according to this principle allow the standalone ac system to react autonomously to disturbances; later, a secondary control approach can be used to improve system performance.

Additionally, droop control techniques allow the operation of multiple VSI in parallel, even if they are connected in different points along the electrical network. Such a situation is not possible using the commercially available SSMT since, when they operated in standalone mode, a fixed frequency inverter is used, with the other generators being operated in PQ controlled mode [11], [12]. Fixed frequency and fixed voltage controlled inverters cannot operate in parallel since there are always voltage differences due to tolerances on inverter sensors, temperature drifts, and also ageing. Deviations in voltage phase and magnitude cause high current circulation between inverters that make system operation unfeasible [16].

IV. MicroGrid Control for Black Start

In an MG, inverters should be responsible for controlling frequency and voltage during islanded operation. A cluster of MS operating in islanded mode requires at least a master inverter to define the voltage and frequency references for the entire network [1]. This means that a general frequency and voltage control strategy should be followed in order to operate the MG in islanded mode. Combining the inverter control techniques, two main strategies are possible [1], [2].

- Single Master Operation: A single VSI is used to provide the reference voltage for the islanded system.
- Multi Master Operation: Two or more inverters are operated as VSI; eventually, other PQ controlled inverters may also coexist.

MMO is the most adequate option to allow the implementation of a BS strategy, as described in the next section.

Equation (3) shows that active power output of a VSI is proportional to the MG frequency deviation. If the MG frequency stabilizes in a value different from the nominal one (due to the use of only MS proportional droop controls), storage devices would keep on injecting or absorbing active power. This should be only admissible during transient situations, where storage devices have high impact in the primary load-frequency control. Two situations must be distinguished regarding storage needs for frequency control: one corresponds to MG main storage and the other regards the capability some individual MS have in providing energy stored in their dc links. Regarding MG main storage with high capabilities for injecting power during small time intervals, one must remember they have a finite storage capacity and can only be loaded by absorbing power from the LV grid. Microsources with storage devices can be continuously loaded by the primary energy source, and its state of charge can be managed locally by the MC. These MS are also assumed to be interfaced with the LV grid through a VSI. Therefore, energy storage management used to correct frequency deviations during BS and islanded operating conditions should be considered as one of the key concerns for the success of the implementation of these strategies.

In order to promote adequate secondary control aiming to restore frequency to the nominal value after a disturbance, two main strategies can be followed [1]: local secondary control, by using a PI controller at each controllable MS, or centralized secondary control mastered by the MGCC. In both cases, target values for active power outputs of the primary energy sources are defined based on the frequency deviation error. In an MMO, the target value can be both an active power set-point for a controllable MS connected to a PQ inverter or a new value for the idle frequency of a VSI.

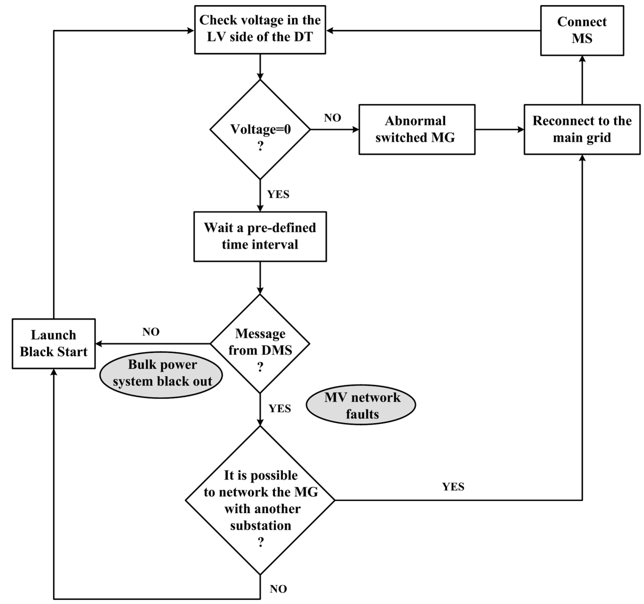

Fig. 3. Flowchart defining the conditions to trigger MG black start procedure.

V. MicroGrid Black Start

The MG black start will be guided centrally by the MGCC software. Under this philosophy, the BS software module is responsible for controlling a set of rules and conditions to be checked during the restoration stage, which should be identified in advance. These rules and conditions define a sequence of control actions to be carried out during the restoration procedure. The main steps to be considered include building the LV network, connecting MS, controlling voltage and frequency, connecting controllable loads and MG synchronization with the upstream MV network, when it is available.

The restoration procedure will be triggered if a general or local blackout occurs or if major injuries affecting the MV network do not allow feeding the MG from the MV side after a predefined time interval. The MGCC should also receive information from the DMS about the service restoration status at the MV level in order to help in deciding to launch the local BS procedure. The flowchart shown in Fig. 3 delineates the procedure followed by the MGCC to detect the occurrence of a blackout and decide when to trigger the MG black start procedure.

The MG protection scheme is also a concern during service restoration. Conventional power systems comprising synchronous generators provide large fault currents that are helpful for fast and efficient fault protection. In MG, generation is mainly connected to the grid using inverters that can provide sufficient fault currents only by a convenient oversizing [1]. Due to economic reasons, inverters oversizing is limited, and during islanded operating conditions, the load current/fault current ratio is quite small when compared to conventional systems. Therefore, a novel protection scheme must be developed. A simple solution may use current sensing relays and section breakers (instead of conventional fuses) conveniently placed in the LV feeders in order to trip them when faults occur and isolate the smallest possible faulted section of the MG [17]. As the BS procedure involves a step-by-step connection of MS to the LV grid, the short-circuit power at the point where protection devices are installed changes. Thus, under such protection strategy, the MGCC should be responsible for changing protection devices settings, while the restoration procedure takes place, in order to efficiently detect and isolate MG faults.

A. General Assumptions

MG local controllers and the MG communication infrastructure are of utmost importance for the success of the restoration scheme. Thus, small auxiliary power units are required to power the communication network elements and local controllers. Another basic requirement is the availability of MS with BS capability, which involves an autonomous power supply to launch this kind of generation. MS restart procedure is carried out previously to building the LV network so it is not reflected in the LV network. Beyond this essential condition, it is also required availability for the following:

- Updated information, obtained before disturbance, about the status of load/generation in the MG and about availability of MS to restart: During normal operation, the MGCC periodically receives information from the LC and MC about consumption levels and power generation, storing this information in a database. It also stores information about technical characteristics of the different MS in operation, such as active and reactive power limits. This information will be used to restore the critical loads of the consumption scenario before blackout occurrence.
- Preparing network for re-energization: MG loads and generators must be disconnected from the LV grid after system collapse. Also, the DT should be disconnected from the LV and MV networks.

During the BS procedure development, it was assumed that MS with BS capability are the SSMT and the MG main storage unit. It was also assumed that, at least during the first stages of this sequence, a multimaster control approach is adopted, since several VSI can operate in parallel, which can be turned into an SMO in the final stages of the BS procedure.

B. Sequence of Actions

After a general blackout, the MGCC will perform service restoration in the LV area based on the information stored in a database about the last MG load scenario, as described before, by performing the following sequence of actions:

- Sectionalizing the MG around each MS with BS capability in order to allow it to feed its own (protected) loads: these actions lead to an initial creation of small islands inside the MG, which will be all synchronized later. In this case, each MS with BS capability is running and feeding a load, which helps to stabilize its operation.
- Building the LV network: the MG main storage device is used for energizing an initial part of the LV network, followed by the switching on of the remaining LV switches not connected to loads or MS. An additional issue during LV energization is related to MG neutral earthing, since the TN-C-S system is suggested to be adopted [18]. MG neutral earthing should be created at the MG storage unit.
- Small islands synchronization: MS already in standalone operation mode should then be synchronized with the LV network. The synchronization conditions (phase sequence, frequency, and voltage differences) should be verified by local MC, after the procedure is enabled by the MGCC, in order to avoid large transient currents that may compromise inverters operation.
- Connection of controllable loads to the LV network is performed if the MS running in the LV network has the capability to supply these loads. The amount of power to be connected should take into account the available storage capacity in order to avoid large frequency and voltage deviations during load connection. Motor load starting is a critical issue due to the large current absorbed in the first instants.
- Connection of noncontrollable MS or MS without BS capability, such as PV and wind generators: at this stage, the system MS are sufficiently loaded in order to smooth voltage and frequency variations due to power fluctuations in noncontrollable MS, so they can now be connected. LV network paths can be created so that MS without BS capability can absorb power from the grid in order to restart.
- Load increase: in order to feed as much load as possible, depending on generation capability, other loads can then be connected. Motor load startup is a critical issue due to the large current absorbed in the first moments. Thus, it must be connected when the main MS are feeding the LV grid in order to increase the short-circuit power.
- Changing the control mode of MS inverters: the MG main storage inverter is controlled as a VSI, providing system voltage and frequency references. Then the MS with BS capability inverters operated as VSI may be changed to PQ control.
- MG synchronization with the MV network when it becomes available: the synchronization conditions should be verified again, after the order is given by the MGCC. This means the DT should be previously energized from the MV side with this synchronization then being performed through LV switches.

VI. Test System and Simulation Platforms

In order to evaluate the transient and dynamic behavior of an MG during BS sequence, the LV test system presented in Fig. 4 was implemented in two simulation platforms. The fast transients associated to the initial stages of the MG restoration process (including power electronic controls and commutation details) were analyzed using an *EMTP-RV* tool, being the long-term dynamic behavior of the restoration procedure evaluated using a tailor-made *MatLab Simulink*-based simulation platform that uses specific MG models [1], [2].

The evaluation of the feasibility of MG service restoration after a general blackout was performed through the analysis of the LV network dynamic behavior considering only three-phase balanced operation, despite the fact that this is not the most common situation in LV distribution networks. The single line

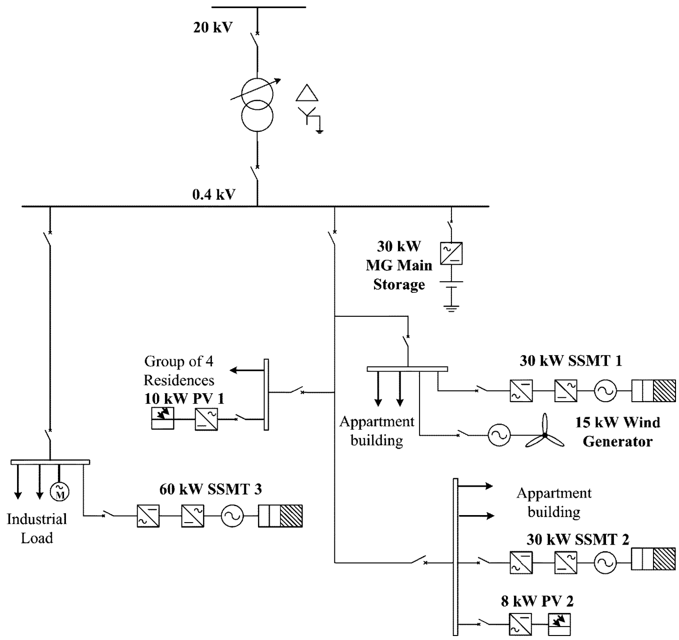

Fig. 4. Low voltage test system.

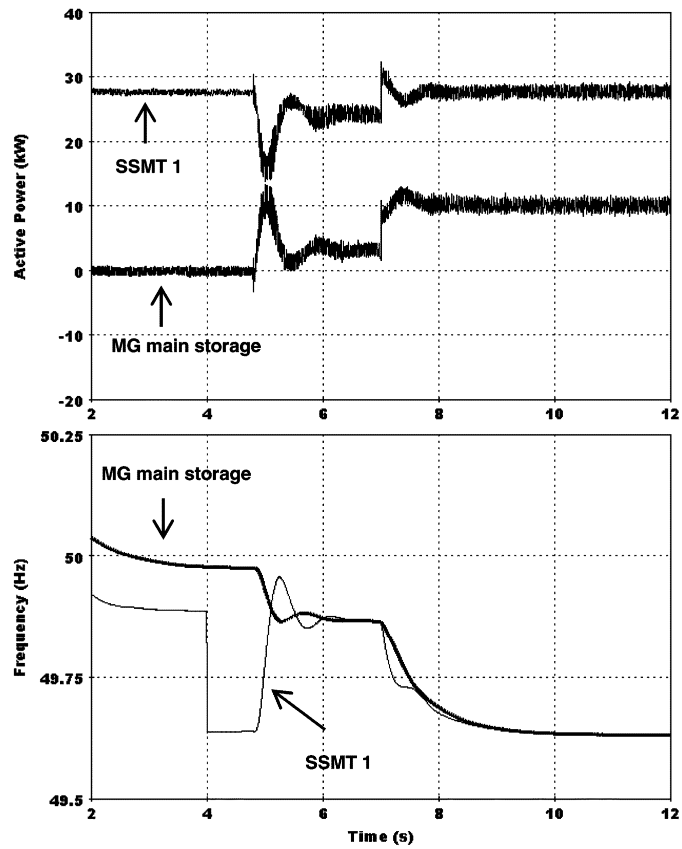

Fig. 5. SSMT 1 and MG main storage active powers and frequencies.

diagram of the LV test system used in this research is shown in Fig. 4, and the main electrical data for this test system can be found in [19]. The LV test system comprises an industrial load, a LV distribution feeder serving a residential area, and several MS connected to the grid.

VII. Results and Discussion

In order to evaluate the performance of the proposed restoration technique in an LV area, it was assumed that a general blackout took place and was followed by:

- disconnection of the LV grid from the distribution transformer;
- disconnection of loads and renewable energy sources;
- MG sectionalization and automatic creation of islands operating or to be operated in standalone mode to supply protected loads associated with each microturbine.

Assuming that all SSMT restarted successfully after system collapse, the main storage device is selected to energize the LV network. The small islands formed by SSMT and their protected loads can be synchronized later. The *EMTP-RV* tool was used to test the feasibility of the restoration procedure initial steps.

After energizing the LV network using the MG main storage, the next step of the restoration procedure is to synchronize a SSMT (in this case, SSMT 1) with the LV grid. To check the synchronization conditions, the MGCC sends instructions to the SSMT 1 inverter to produce a small frequency change, as it can be seen in Fig. 5 at $t = 4$ s. After synchronizing the SSMT ($t = 4.8$ s), it was connected to a controllable load at $t = 7$ s and system frequency decreases due to VSI droop control mode.

Results shown in Fig. 5 prove the feasibility of the initial stages proposed for the LV service restoration procedure considering a detailed representation of MG components, mainly the full modeling of VSI. However, this approach requires high computational effort and does not allow simulation of the entire BS procedure. In order to get an extended overview of the long-term dynamic behavior induced by the overall BS procedure, the *MatLab Simulink*-based simulation platform was used. In this case, inverters are only modeled through their control functions so that fast switching transients and harmonics are neglected [1], without compromising results accuracy.

After energizing the LV network, the restoration procedure consists of the following sequence of actions:

- synchronizing the SSMT 1 with the LV network ($t = 32.3$ s);
- synchronizing the SSMT 2 with the LV network ($t = 57.0$ s);
- synchronizing the SSMT 3 with the LV network ($t = 86.5$ s);
- connecting controllable loads ($t = 100$ s);
- connecting wind generator ($t = 119.7$ s);
- connecting PV 1 ($t = 130$ s);
- connecting PV 2 ($t = 140$ s);
- motor loads startup ($t = 170$ s and $t = 175$ s);
- changing the control mode of the SSMT ($t = 190$ s, $t = 195$ s, and $t = 200$ s);
- synchronizing the MG with the MV network ($t = 250.2$ s).

The VSI synchronizations require a careful verification of the necessary synchronization conditions, involving correction in the voltage magnitude and phase angle (frequency) of each VSI to be synchronized with the LV network. The procedure is enabled centrally by the MGCC, but the synchronization conditions are checked locally by each MC. For example, when synchronizing the SSMT 1 with the LV network, the procedure is

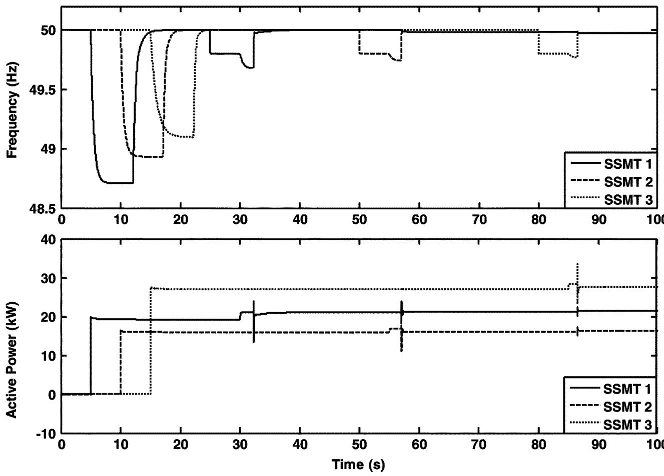

Fig. 6. SSMT frequencies and active power during the first stages of the black start procedure.

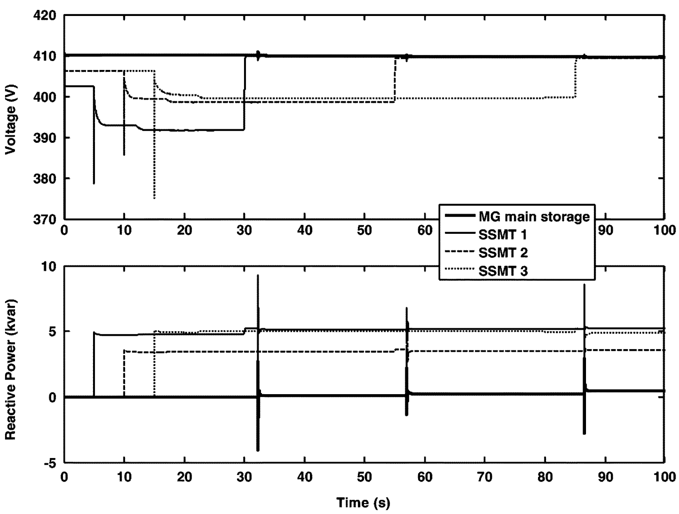

Fig. 7. MS voltages and reactive power during the first stages of the black start procedure.

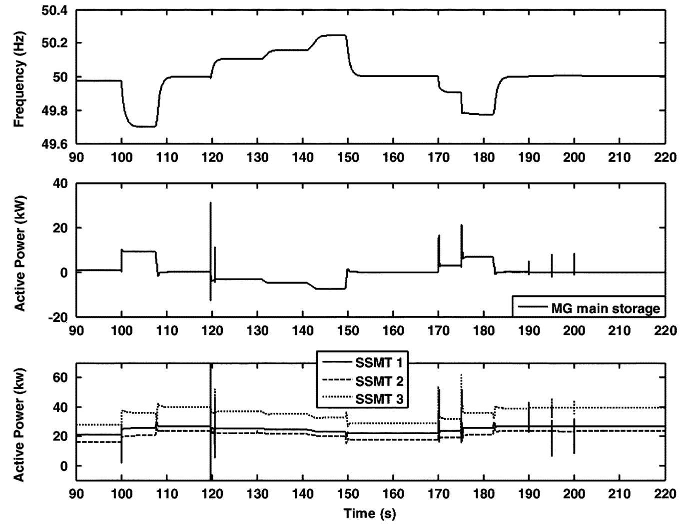

Fig. 8. MG frequency and MS active power.

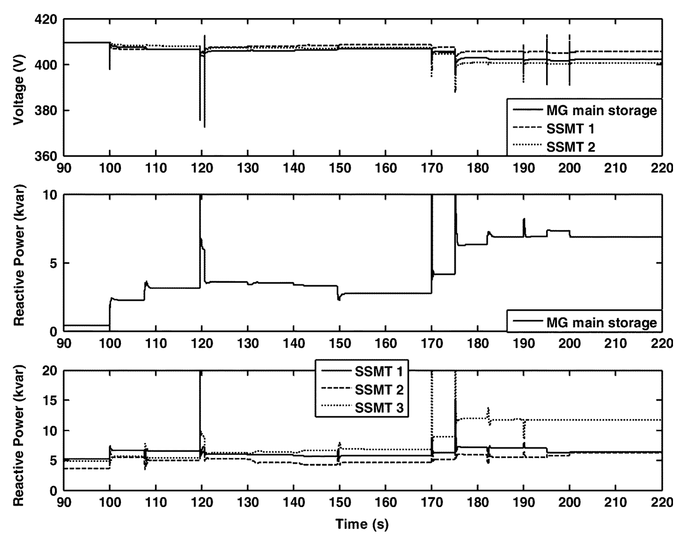

Fig. 9. MS voltages and reactive power.

enabled at $\mathrm{t} = 25$ s; at the same time, a slight frequency variation is made upon the SSMT 1 inverter so that a small phase error can be achieved between the SSMT1 and MG voltages in order to synchronize them with negligible impact in the network (see Fig. 6). The voltage magnitude is also corrected so that it matches the grid voltage, as it can be observed from Fig. 7 at about $\mathrm{t} = 30$ s. As MG loads are modeled as constant impedances, voltage correction causes a small power increase that can be observed in Fig. 6 around $\mathrm{t} = 30$ s. For synchronizing SSMT2 and SSMT3 with the LV grid, a similar procedure is used.

Frequency deviation after load reconnection is a critical issue in this procedure, requiring special attention. If a frequency deviation of ± 0.2 Hz remains for some time, a local secondary control is used to restore MG frequency to nominal value, as can it be observed in Fig. 8 at $\mathrm{t} = 100$ s and at $\mathrm{t} = 170$ s following load connections. After synchronizing all the MS, load variation can be shared among the several MS. By correcting permanent frequency deviations, the active power injection provided by the MG main storage device is brought to zero, and the active power output increases in the other MS, according to the secondary control parameters. At $\mathrm{t} = 150$ s, the same procedure can be observed; however, in this case, it is used to reduce power production in SSMT due to the connection of wind and PV generators.

Voltage control in the islanded MG is performed through a droop proportional control. Only small adjustments on the idle voltage of inverters are performed in order to minimize the errors in the voltage magnitude before the synchronization. The results obtained demonstrate that the used voltage regulation principle ensures MG stability and no reactive power oscillations among MS are observed (see Fig. 9). To the contrary of what happens in the active power sharing situation (where active power generation sharing is defined by a droop control approach), LV network impedances do not allow a reactive power sharing proportionally to the inverter ratings: the node where load is connected influences the reactive power sharing due to its specific node voltage drops.

The effect of small motor loads startup can be observed in Figs. 8 and 9 around $\mathrm{t} = 170$ s and $\mathrm{t} = 175$ s. Although starting

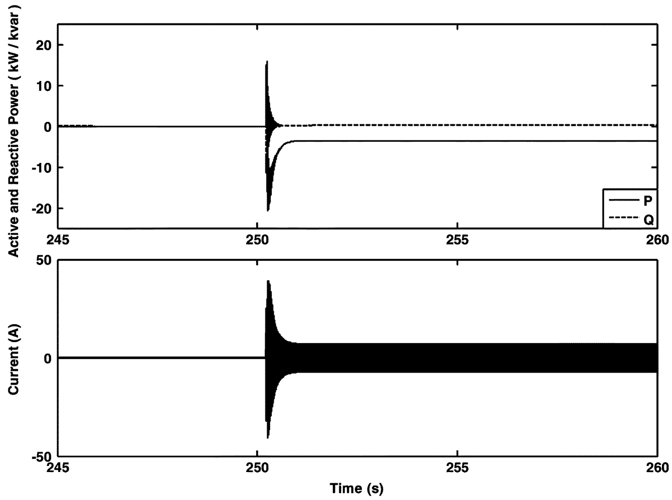

Fig. 10. Synchronization current, active, and reactive power in the low voltage side of the distribution transformer.

up from the stall position, the effect on the system is not a critical issue because motors are starting up under an MMO scheme as it can be observed in Fig. 9 when analyzing node voltage drop.

After restoring the full operation of the MG, the control scheme of the SSMT inverters is changed from VSI to PQ control, which is the normal operation mode whenever an external source is used to define MG frequency and voltage. It is possible to observe in Figs. 8 and 9 that changing the control mode has no significant impact in the MG.

When the MV network becomes available, the MGCC requires the VSI of the MG main storage device to change slightly its frequency and voltage in order to check the synchronization conditions. Fig. 10 shows a detail of the impact of the synchronization procedure in terms of current, active, and reactive power flowing in the LV side of the DT. As the majority of the MG loads is represented as constant impedances, voltage correction (increase) prior to synchronization provokes an increase in the active power consumption within the islanded MG. After synchronization, this power surplus is supplied by the MV network (see Fig. 9), since the MG main storage droop imposes a zero power output after synchronization.

VIII. Conclusion

This paper demonstrated the feasibility of using the MG concept for service restoration. Such achievement was accomplished in a situation where no synchronous generators were available and only electronic interfaced microgenerators and asynchronous generators were assumed to be in operation.

The control strategies to be adopted for MG black start and subsequent islanded operation as well as the identification of the set of rules and conditions were derived and evaluated by numerical simulations. The results obtained prove the feasibility of such procedures and show that storage devices are absolutely essential to implement successful control strategies during all restoration stages.

Such a successful verification constitutes a significant contribution, showing that MS resources can be exploited further to develop local self-healing strategies and to reduce local restoration times.

Future research is needed to address properly the issue of black starting in an unbalanced system, as the LV grid can be.

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