Control Strategies for MicroGrids Emergency Operation

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***Abstract*--Under normal operating conditions, a MicroGrid (MG) is interconnected with the Medium Voltage (MV) network. However, planned or unplanned events like maintenance or faults in the MV network, respectively, may lead to MG islanding. In order to deal with islanded operation and even black start following a general blackout, an emergency operation mode must be envisaged. Two possible control strategies were investigated and are described in this paper in order to operate a MG under emergency mode. A sequence of actions for a well succeeded black start procedure, involving microgeneration units, has also been identified contributing for an increase in distribution network reliability.**

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

I. Introduction

CONNECTING to Low Voltage (LV) networks small generation units – the microsources (MS) – with power ratings less than a few tens of kilowatts may increase reliability to final consumers and bring additional benefits for global system operation and planning. In this context, a MG can be defined as an LV network, plus its loads and several small modular generation systems connected to it, providing both power and heat to local loads (Combined Heat and Power – CHP) [1]. MG flexibility can be achieved by allowing its operation under two different conditions:

- Normal Interconnected Mode – the MG is connected to a main Medium Voltage (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.

The successful design and operation of a MG requires solving a number of demanding technical and non-technical issues, in particular related to system functions and controls [2-3]. The presence of power electronic interfaces in fuel cells, photovoltaic panels, microturbines or storage devices characterizes a new type of power system when compared with conventional systems using synchronous generators. The dynamic behaviour of a system with low global inertia, comprising some MS with slow responses to control systems, is also quite different from traditional power systems. Furthermore, classic power systems have the possibility of storing energy on the rotating masses of synchronous generators, which provides energy balance in the moments subsequent to a load connection. A MG requires some form of energy storage (batteries or flywheels) in order to be able to face transients during islanded operation [2], [4].

The MG islanding process may result from an intentional disconnection from the MV grid (due to maintenance needs) or from a forced disconnection (due to a fault in the MV network). MG dynamic behaviour in islanded operation needs to be analysed under different load conditions. Since there is little inertia in a MG, load-shedding strategies and storage devices must be used for an efficient frequency control scheme [2].

Exploiting MG capabilities to provide fast Black Start (BS) at the LV level is an innovative aspect that has been developed and tested in this research [3]. Such an approach will enable fast restoration times to final consumers, thus improving reliability. In large conventional systems, tasks related to power restoration are usually carried out manually by system operators, according to predefined guidelines. These tasks must be completed speedily, in real-time basis and under extreme stressed conditions. In an MG, the whole restoration procedure is much simpler because of the small number of control variables (loads, switches and MS). However, specific characteristics of most MS (such as primary energy source response time constants, intermittency, technical limits) and control characteristics of power electronic interfaces require the identification of specialized restoration sequences [3].

II. MicroGrid Architecture

The MG architecture developed within the EU R&D Microgrids project [1] is presented in Fig. 1; it comprises a LV network, loads (some of them interruptible), both controllable and non-controllable 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 MicroGrid Central Controller (MGCC) installed at the MV/LV substation. The MGCC includes several key functions (such as economic

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managing functions and control functionalities) and heads the hierarchical control system. At a second hierarchical control level, controllers located at loads or at groups of loads (Load Controllers – LC) and controllers located at MS (Microsource Controllers – MC) exchange information with the MGCC and control local devices. LC serve as interfaces to control loads through the application of an interruptibility concept, and MC control microgeneration units, for example in terms of active and reactive power production levels.

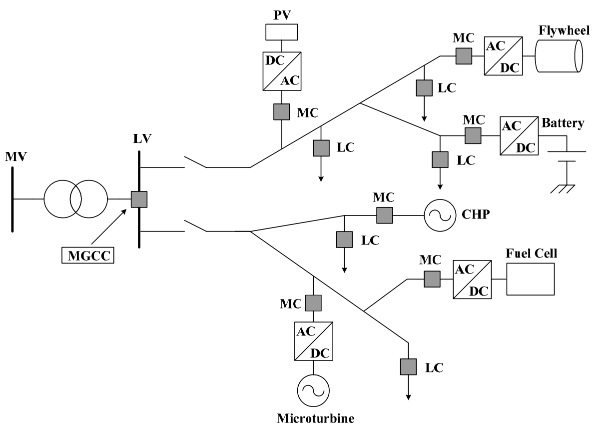

Fig. 1. MG architecture, comprising MS, loads and control devices

III. MicroGrid Control For Islanded Operation

In this section different approaches to deal with MG islanded operation are described. In the first approach, the main concern is related to inverter control modes. As the MG is an inverter dominated grid, frequency and voltage control during islanded operation is performed through inverters. In this case, the main issue is how to get a voltage and frequency reference in the islanded MG. The other approach closely follows concepts related to conventional synchronous machine control.

A. MicroGrid Operation Regarding Inverters Control Modes

The approach focused on inverter control modes required the modelling of MS and storage devices, as well as inverters. MG loads are modelled as a combination of impedance type and induction motor type loads. Load shedding mechanisms based on MG frequency deviation were also considered to be implemented in the LC.

1) Microsource and Storage Devices Modelling

Several MS models have been developed including fuel-cells, microturbines, wind generators and photovoltaic arrays [5]. A Solid Oxide Fuel-Cell (SOFC) was used in this research. Its model includes a Fuel Processor, which converts fuels like natural gas to hydrogen, a Power Section, where chemical reactions take place, and a Power Conditioner that converts DC to AC power. More details about the used dynamic model of the SOFC can be found in [6] and [7].

The GAST dynamic model [6] was adopted for the primary unit of microturbines, since they are small simple-cycle gas turbines. Both high-speed single-shaft units (with a synchronous machine) and split-shaft units (using a power turbine rotating at 3000 rpm and a conventional induction generator connected via a gearbox) were modelled. The single-shaft unit requires an AC/DC/AC converter for grid connection. The wind generator is considered an induction machine directly connected to the network. Concerning the PV generator, it was assumed that the array is always working at its maximum power level for a given temperature and irradiance. Basically, it is an empirical model based on experimental results as described in [5], where a detailed description on MS modelling adopted in the Microgrids project can also be found.

Considering the time period under analysis, storage devices, such as flywheels and batteries, are modelled 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).

2) Inverter Modelling

Two kinds of control strategies may be used to operate an inverter [8]. The inverter model is derived according to the control strategy followed:

- PQ inverter control: the inverter is used to supply a given active and reactive power set-point;
- Voltage Source Inverter control logic: the inverter is controlled to "feed" the load with pre-defined values for voltage and frequency. Depending on the load, the Voltage Source Inverter (VSI) real and reactive power output is defined.

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.

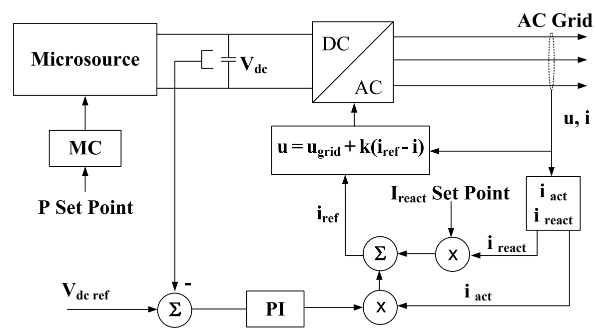

Fig. 2. PQ inverter control system

The control principle of a PQ controlled inverter is shown in Fig. 2. It is based on the computation of the normalized active and reactive current components [2] that are used to control active and reactive output powers of the inverter, respectively.

The Voltage Source Inverter (VSI) emulates the behaviour of a synchronous machine, thus controlling voltage and frequency on the AC system by using droop concepts as in Fig. 3. Frequency variation in the MG provides an adequate way to define power sharing among VSI [9-10]. A three-phase balanced model of a VSI including the droop concepts was derived from a single-phase version presented in [10]. More details on VSI operation can be found in [2-3].

Another important issue is the behaviour of power electronic interfaces during short circuits [2]. Special control functions and sufficient oversizing is required because, in contrast to synchronous generators, power electronics have no thermal short-term overloading capabilities. The current limiting function is easily implemented in the PQ controlled inverters by limiting the total gain of the PI controllers shown in Fig. 2 In order to limit the output current of a VSI, a control technique like the one presented in Fig. 2 is also used. The main difference is that in this case the reference current has a maximum peak value dependent on switching devices characteristics and its frequency is imposed by the inverter frequency/active power droop.

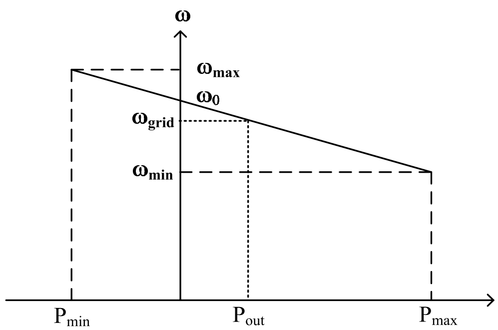

Fig. 3. Frequency / active power droop characteristic

3) Control Schemes for MicroGrid Islanded Operation

If a cluster of MS is operated within a MG and the main power supply (the MV network) is available, all the inverters can be operated in PQ mode, because there are voltage and frequency references. However, a VSI can be used to provide a reference for frequency and it will be possible to operate the MG in islanded mode and to smoothly move to islanded operation without changing the control mode of any inverter [2-3]. After identifying the key solution for MG islanded operation, two main control strategies are possible:

- Single Master Operation (SMO): A VSI is used as voltage reference when the main power supply is lost (in order to balance local load and generation); all other inverters can then be operated in the PQ mode;
- Multi Master Operation (MMO): More than one inverter is operated as a VSI. However, other PQ controlled inverters may coexist.

During islanded operation, the power injected by the storage devices is proportional to MG frequency deviation. Therefore, correcting permanent frequency deviation during islanded operation should be considered a key objective in any control strategy in order to avoid storage devices to keep injecting (or absorbing) active power whenever MG frequency deviation differs from zero [2-3]. The combination of primary frequency regulation provided by storage devices, load shedding schemes for less important loads and secondary load frequency control are the key for successful MG islanded operation.

B. MicroGrid Operation Regarding Primary Energy Source Control

In this representation, the MS and storage device (flywheel) can be represented by synchronous generators or by STATCOM Battery Energy Storage (STATCOM-BES). In grid-connected mode, the frequency of the MG is maintained within a tight range. However, following a disturbance, the frequency of the MG may change rapidly due to the low inertia present in the MG. The control of the MS and storage devices (flywheel) is very important in order to maintain the frequency of the MG during islanded operation. The controllers of MS and flywheel inverters respond in milliseconds. For basic operation of the MG, the controllers should use only local information to control the flywheel and MS.

1) Local Frequency Control Strategies

The possible control strategies of the MS and the storage device may be:

- PQ control (fixed power control);
- Droop control;
- Frequency/Voltage control.

PQ control is adopted so that the MS and the flywheel run on constant power output. The electricity generated by the MS may have to be constant because of the needs of the related thermal loads. In addition, the power output of the flywheel may be fixed at zero when the MG is operated in grid-connected mode. As PQ control delivers a fixed power output, it makes no contribution to local frequency control of the MG. Therefore, the control scheme of the flywheel has to be changed from PQ control to droop control or frequency/voltage control during islanded operation. Droop control is similar to the function of primary frequency control in a conventional synchronous generator. The frequency of the MG can be restored to a steady-state value determined by the droop characteristic. Frequency/voltage control is similar to the function of secondary frequency control in the conventional synchronous generator. The power output of the flywheel is regulated according to predetermined droop characteristics.

With droop control action, a load change in the MG will result in steady-state frequency and voltage deviations, depending on the droop characteristics and frequency/voltage sensitivity of the load. The flywheel will contribute to the overall change in generation. Restoration of the frequency/voltage of the MG to their normal values requires a supplementary secondary frequency control action to adjust automatically the output of the flywheel.

IV. MICROGRID BLACK START

The MicroGrid Black Start functionalities were developed using the control strategy described in section *III.A*. During normal operation, the MGCC periodically receives information from the LC and MC about consumption and power generation levels, storing this information in a database. Information about technical characteristics of the different MS in operation is also stored. MG Black Start involves the identification of a set of rules and conditions to be checked during the restoration stage, which should be identified in advance and embedded in the MGCC software. The implementation of a BS procedure requires the availability of some MS with BS capability, which involves an autonomous local power supply to feed local auxiliary control systems and launch MS generation. During the restoration of the LV network, the storage will also contribute to face load-tracking problems, since some microgenerators (fuel-cells, microturbines) have a slow response and are inertia-less. For the development of the BS procedure it was assumed that MS with BS capability are the single-shaft microturbine (SSMT), the SOFC and the storage device. MS with BS capability should have batteries in their DC bus. It was also assumed that, at least during the first stages of this sequence, a multi master control approach is adopted, being switched to SMO in the final stages of the BS procedure. The strategies to be followed make use of the hierarchical control system of the MG, namely of LC, MC and the MGCC.

A. Sequence of Actions for MicroGrid Black Start

After a system blackout, the MGCC will try to restore the last MG load scenario. The main problems to deal with during the restoration procedure include building the LV network, connecting microgenerators, controlling voltage, controlling frequency and connecting controllable loads. Considering these problems the following sequence of actions for MG restoration should be carried out [3]:

- Disconnection of all loads in order to avoid large frequency and voltage deviations when energizing the network. The MG should also be sectionalized around each MS with BS capability in order to allow it to feed its own (protected) loads.
- Building the LV network. The inverter associated with the storage device will be responsible for LV and Distribution Transformer (DT) energization. In order to follow the earthing LV protection guidelines, the MG should keep the earth reference, available in the earth connection of the neutral of the DT. Therefore, when building the LV network it is necessary to energize the DT as soon as possible. When energizing the DT by the LV side, a large inrush current is experienced. In order to overcome this problem, transformer energization should be performed using a ramp-wise voltage wave form.
- Small islands synchronization. MS already in operation in stand alone mode should be synchronized with the LV network. The synchronization conditions (phase sequence, frequency and voltage differences) should be verified by local MC in order to avoid large transient currents.
- Connection of controllable loads to the LV network is performed if the MS running in the LV network have the capacity to supply these loads taking into account the available energy storage.
- Connection of non-controllable MS or MS without BS capability, like PV and wind generators.
- Load increase. In order to feed as much load as possible, depending on production capability, other loads can now be connected.
- Change the control scheme of the inverters: after service restoration on the MG, the control schemes of the SSMT and SOFC inverters are changed from VSI to PQ control. This is required because batteries that are assumed to be installed in the DC link of these MS are not suitable to respond to frequent load variations, since charge and discharge cycles reduce significantly their life-cycle. On the other hand, flywheel life is almost independent of the depth of discharge. Flywheel storage systems can operate equally well on frequent shallow discharges and on very deep discharges.
- MG synchronization with the MV network when it becomes available. The synchronization conditions should be verified again.

National Technical University of Athens (NTUA) developed an approach for MG service restoration based on similar concepts and making use of a Multi Agent System (MAS). An important issue is that both procedures have a common rational due to the specific nature of the MS and to the dimension of the MG. The general idea is that the agents will execute all the necessary actions (decided in advance) without human interaction. This approach has two main advantages. The first advantage is that the computational demand during the critical event is limited and this is very important considering that the time limits are very strict and the processors that will be used in a future MG are not powerful supercomputers, as in large centralized power systems. The second advantage lies in the fact that during the black out there are several communication problems that can be avoided by using a MAS. Therefore the data exchange should be even more limited.

V. MicroGrid Simulation Platforms

A simulation platform under the *Matlab/Simulink* environment was developed to study the dynamic behaviour of several MS operating together in a LV network and controlled according to what was described in section *III.A*. The fast transients associated with the initial moments of the MG restoration procedure were studied in another simulation platform developed in *EMTP-RV*, where the switching details of the power electronic interfaces were included. The longer term dynamic behavior of the MG during the restoration procedure was also evaluated using the *Matlab/Simulink* platform. As an illustrative example, Fig. 4 shows the study case LV network in the *Matlab/Simulink* simulation platform.

Another simulation tool was also developed in PSCAD/EMTDC to evaluate MG control functionalities described in section *III.B*. Two situations were assumed:

- MS and the storage device represented by synchronous generators;
- MS and storage represented by STATCOM-BES devices.

Again, the purpose of this approach was to evaluate the robustness of the control schemes adopted.

VI. Results And Discussion

This section includes results showing the dynamic behaviour of the MG (using the different control approaches previously described) during and subsequent to the islanding process. Results describing the fast and long term dynamic behaviour obtained in the MG during the adopted BS sequence are also described next.

A. Moving to Islanded Operation

Disconnection from the upstream MV network and load-following in islanded operation was simulated using a SMO control strategy described in the section *III.A*. The scenario is characterized by a local load of 80 kW (65% of impedance type and 35% of induction motor type) and a local generation of 50 kW. A fault occurred at t=10s in the MV network followed by MG islanding, 100 milliseconds after.

Due to the large initial frequency deviation, an amount of load was automatically shed through the activation of load shedding relays in order to aid frequency restoration. This load was later reconnected in small load steps (Fig. 5). MS selected for the secondary load-frequency control (the SOFC and the SSMT) participate in frequency restoration using a proportional integral control strategy in the MC. The large time constants of the MS lead to a relatively slow process for restoring frequency to its nominal value.

From the frequency behaviour, it may be observed that MG stability is not lost when facing the short-circuit at the MV grid side. Speed rotation of motor loads drops considerably during the fault, which has a great impact in the MG current and voltage after fault elimination, as can be observed in Fig. 6. The principles presented for current limitation in VSI can also be observed in Fig. 6.

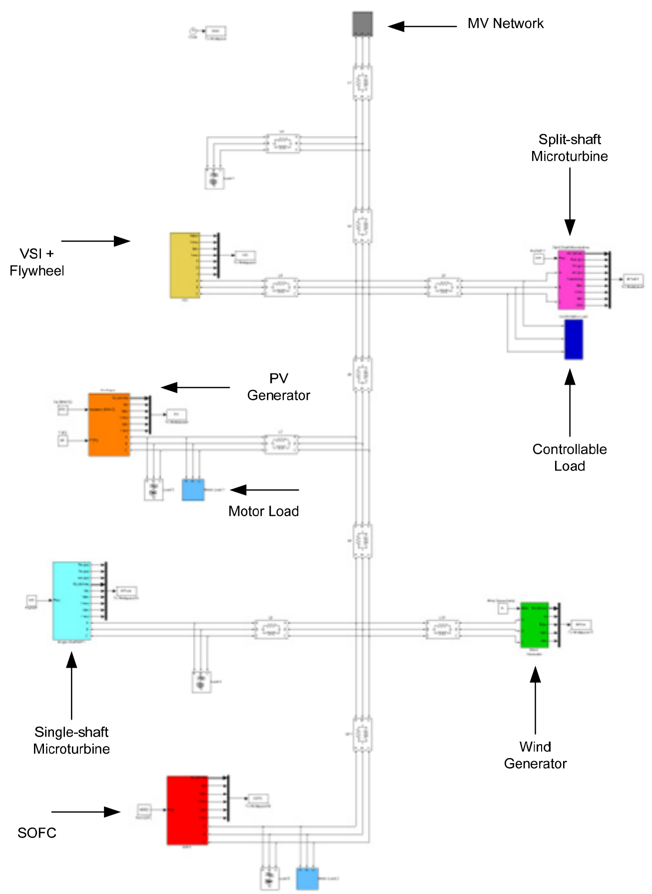

Fig. 4. LV test network in the *Matlab/Simulink* simulation platform

Fig. 7 shows the response of the MG when the control strategy described in section *III.B* is used and the MS are represented as STATCOM-BES. The flywheel is using frequency/voltage control during islanded mode. Results have shown that after intentional disconnection of the MG from the main network at t=10s, the output of the MS is still retained at 30 kW. However, the output of flywheel is changed from zero to around 180kW+j120kvar. Due to the frequency/voltage control, the frequency and voltage of the MG are restored to the nominal values.

B. MicroGrid Black Start

In order to study this case it was assumed that a general collapse took place and was followed by: a) the disconnection from the MV grid of the MV/LV transformer; b) the disconnection of loads and c) the automatic creation of islands operating in standalone mode to supply protected loads associated with the SSMT and the SOFC.

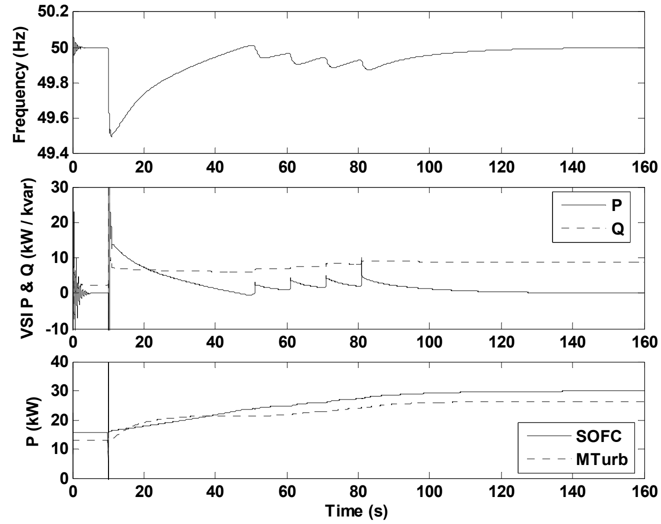

Fig. 5. MG Frequency, VSI active and reactive power and SOFC and single-shaft microturbine active power

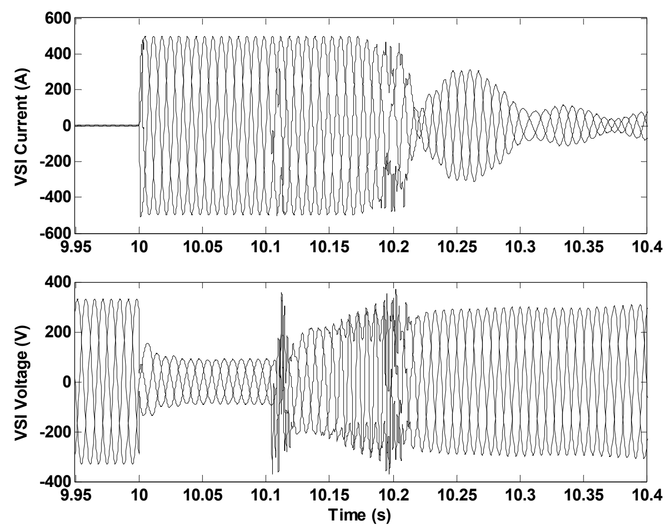

Fig. 6. VSI current and voltage during and after the fault

Network behaviour during BS initial stages was evaluated with the *EMTP-RV* platform described in [3], including in this case the fast inverter commutation transients. The VSI shown in Fig. 4 was selected for energizing the LV network and the MV/LV transformer, at t=0.2s, using a voltage ramping control during 0.5s to reduce the magnetizing current of the DT. The inverter current thus obtained is presented in Fig. 8 where it is possible to observe that the DT magnetizing current was kept at low values.

In order to get an extended overview of the long term dynamic behaviour induced by the overall BS procedure, the *MatLab/Simulink* simulation platform was used. The simulations starts considering that the MS are feeding the protected loads and the LV network and the DT are energized. The sequence of actions involves:

- Synchronizing the SOFC with the LV network (t=12.8s)
- Synchronizing the SSMT with the LV network (t=30.6s)
- Starting-up of a motor load (t=50s)
- Connecting the wind generator (t=71s)
- Connecting controllable loads (t=100s)
- Connecting the PV (t=120s)
- Connecting controllable loads (t=140s)
- Changing the SSMT and SOFC inverters to PQ control (t=165s and t=170s respectively)
- Synchronizing the MG with the MV network

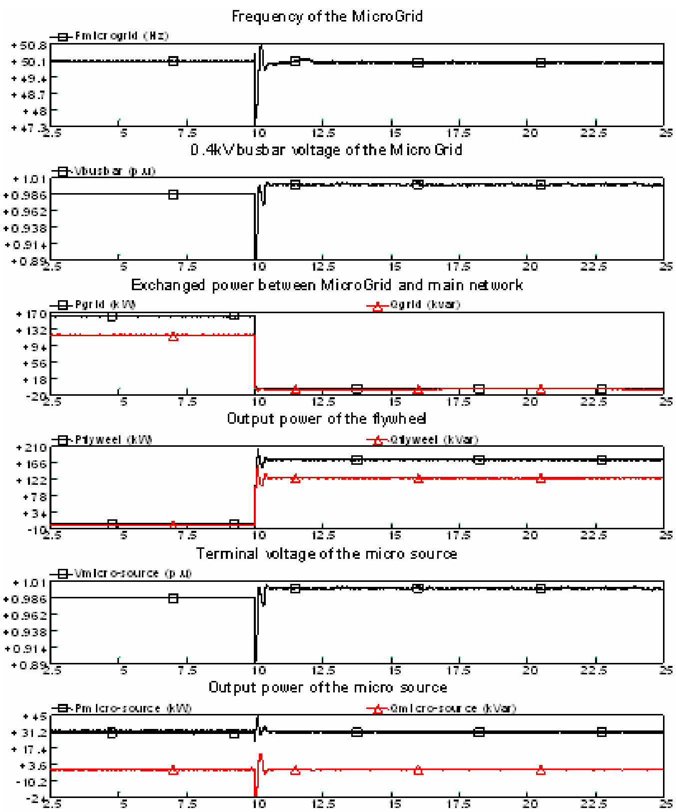

Fig. 7. Dynamic performance of the MG (using STATCOM-BES representation)

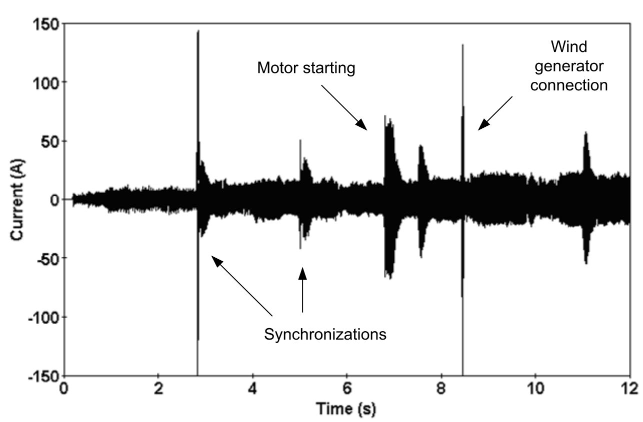

Fig. 8. Storage inverter current during initial BS stages

Fig. 9 shows the impact of the referred sequence of actions in frequency and MS active power production levels. Frequency deviation after load reconnection was identified to be a critical issue in this procedure, requiring a special attention. If a frequency deviation remains for some time, a local secondary control was used to restore frequency to the nominal value.

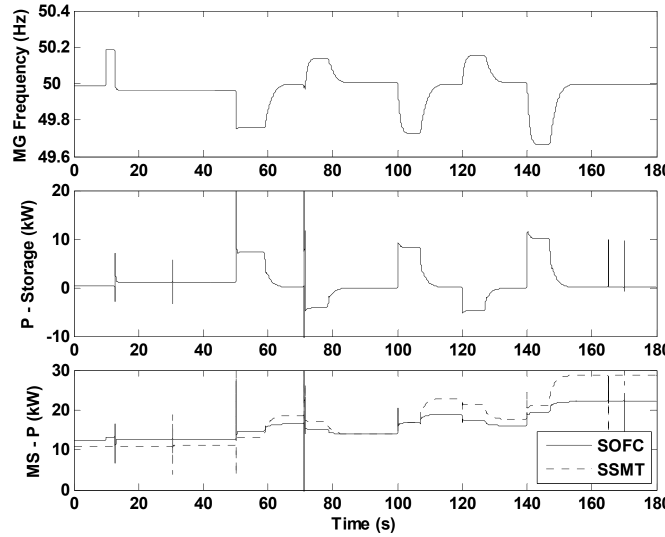

Fig. 9. MG frequency and MS active power

VII. Conclusions

Simulation results indicate that MG islanding can be performed satisfactorily even after a fault in the upstream MV network. Storage devices are absolutely essential to implement successful control strategies for MG islanded operation; the load-shedding procedure is also very important to avoid fast and long frequency deviations.

Rules and conditions to be checked during the restoration stage by the MG components were derived and evaluated through numerical simulation, proving the feasibility of such procedures.

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