CONTROL STRATEGIES FOR MICROGRIDS BLACK START AND ISLANDED OPERATION

J. A. Peças Lopes, C. L. Moreira, F. O. Resende
Power Systems Unit
INESC Porto – Instituto de Engenharia de Sistemas e Computadores do Porto
Rua Dr. Roberto Frias, 378, 4200 – 465 Porto, Portugal
Phone (351) 222094230, Fax (351) 222094050
E-mail: jpl@fe.up.pt

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ABSTRACT

Dissemination of small size dispersed microgeneration connected to Low Voltage (LV) distribution systems is expected to become an effective mean to face the continuous demand growth in power needs. Under normal operation conditions, the LV distribution system is considered as interconnected with the upstream medium voltage network. However, if a severe disturbance occurs in the medium voltage side, a general blackout can take place. The potentialities of distributed generation can be truly realized if islanded operation is allowed and bottom-up black start functionalities are implemented. In this paper are presented the control strategies to be used in such a system to deal with islanded operation and to exploit the local generation resources as a way to help in power system restoration in case of an emergency situation. A sequence of actions for a black start procedure is identified and it is expected to be an advantage for power system operation in terms of reliability as a result from the presence of a very large amount of dispersed generation. The feasibility of the new concepts – islanded operation of small LV distribution systems and LV black start functionalities, up to now only developed for conventional power systems – are tested through simulations, being the results described and discussed in this paper.

1 INTRODUCTION

Microgeneration is expected to become an attractive mean to face the continuous demand growth in the electric power systems. On the other hand, the need of reducing pollutant emissions, recent technological developments related with the improvement of microgeneration efficiency and the possibility of exploiting local renewable energy resources are important factors that will contribute, in a short term, to an effective penetration of microgeneration in LV grids.

The scenario of an extensive penetration of local generation in LV grids leads to the definition of the MicroGrids (MG) concept. Small generation units – the microsources (MS) – with power ratings less than a few tens of kilowatts may increase reliability to final consumers and will bring additional benefits for global system operation and planning. A MG comprises a LV network (for example covering an urban area, a shopping-centre or even an industrial park), its loads, several small modular generation systems connected to it and an embedded control and management system [1]. This concept in under investigation within the framework of an EU R&D project to study the problems challenging the integration of large amounts of different MS in LV grids and involves several institutions and companies [1]. Examples of MS technologies to be used when building a MG include renewable power sources, such as wind and photovoltaic (PV) generators, microturbines working on gas or bio-fuels, different types of fuel-cells, and also storage devices (such as flywheels or batteries).

In this context, MicroGrid Black Start (BS) is a very innovative aspect that can be used in order to fully profit from the potentialities of dispersed microgeneration. Costumer interruption times can be reduced by providing locally a fast BS recovery if MG islanded operation is allowed until the MV network becomes available. Up to now, functionalities for operation restoration are available only for conventional power systems. The tasks related to restoration are usually carried out manually, according to predefined guidelines [2]. Conventional techniques for system restoration are based on a top-down approach, beginning with the start-up of conventional generation units and ending with the connection of loads and dispersed generation units. With the dissemination of the MG concept, new techniques must be derived, since MG can be used for service restoration in their area of influence.

The complexity of a BS procedure in conventional power systems makes decision support tools an extremely valuable resource to assist system operators [3]. In a MG the whole restoration procedure is expected to be simpler because of the reduced number of controllable variables (loads, switches and MS). However, the specific characteristics of MS (like primary source response time constants, intermittency, technical limits) and the control characteristics of the power electronic interfaces require the identification of specific restoration sequences. It will not be common to have fully controllable synchronous generators running in parallel with the LV network for frequency and voltage control, which is a critical issue to allow running into islanded mode. Consequently some of the MS inverters must be responsible for these tasks by means of control techniques capable of emulating a synchronous machine operation.

Under the presented MG concept, the specific control architecture and the possibility of establishing communication among different types of controllers spread over the LV network become possible the identification of a BS procedure. In this paper an identification of a sequence of actions to be carried out during the MG black start is presented and tested through simulations. For that purpose different inverter control techniques, used to allow islanded operation, are also described. Two simulation platforms were developed and exploited when dealing with a LV study case network: an *EMTP-RV*® tool used to analyze the fast transients associated with the initial stages of the BS procedure and a *MatLab*® *Simulink*® platform used to evaluate the longer term dynamics of the MG in islanded mode.

2 MICROGRID ARCHITECTURE

Fig. 2.1 shows a typical MG structure, which comprises a LV network, loads or equivalent groups of loads (assumed to be controlled or interruptible), both controlled and uncontrolled MS, storage devices and a hierarchical-type management and control scheme supported by a communication system used to fulfil the potential of dispersed generation aiming at an optimal technical and economical management [1].

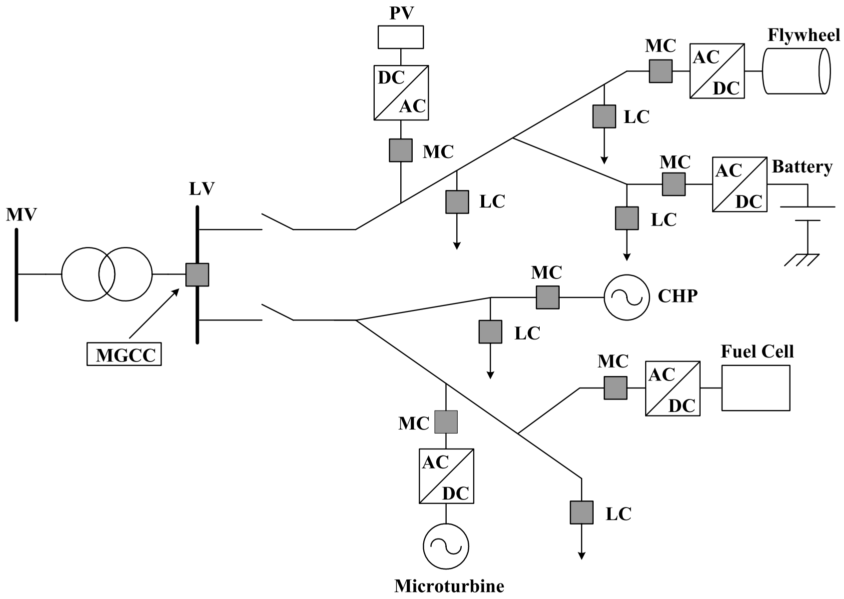

Figure 2.1: MG architecture

The MG is centrally controlled and managed by the MicroGrid Central Controller (MGCC), which is installed at the LV side of a MV/LV substation. The MGCC possesses several management functions, both technical and economical, in order to fully profit from the dispersed generation resources. A second hierarchical control level is established at the MS and loads level: MS are locally controlled by a Microsource Controller (MC) and electrical loads or group of loads are controlled by a Load Controller (LC). A communication infrastructure must also be provided in order to guarantee information exchange between the MGCC and the other controllers.

The communication among the described controllers is as follows:

- LC are interfaces to control loads through the application of an interruptability concept;
- MC control locally the MS active and reactive power production levels;
- The MGCC, as central controller, promotes adequate technical and economical management policies and provides set-points to LC and MC; it is also responsible for the local BS functionalities.

The amount of data to be exchanged between network controllers is small, as it includes mainly messages to control the switching functions during the BS procedure, messages with set-points to LC and MC, as well as information requests sent by the MGCC to LC and MC about active and reactive powers and voltage levels and bids provided by MS or interruptible loads to optimize the management of emergency situations. The small geographical area covered by a MG is another important factor that eases the establishment of the communication infrastructure.

3 DYNAMIC MODELS

MS dynamic models used in the simulation platforms are briefly described in this section. The characteristics of the electric energy produced in some MS (high frequency AC power in single shaft microturbines or DC power in PV and fuel cells) requires the presence of power electronic stages (AC-DC-AC or DC-AC), whose modelling is also presented.

3.1 Microsource Modelling

Several MS technologies were considered to coexist in the MG and the corresponding dynamic models were derived. A detailed description of the models adopted for solid oxide fuel cells (SOFC) and single shaft microturbines (SSMT) can be found in [4] and [6]. A small asynchronous wind generator (fixed speed) directly connected to the LV grid was also included in the simulation platform. Details of the maximum power tracking control system were not included in the PV model. Instead, it was assumed that the array is always working at its maximum power level for a given temperature and irradiance as described in [5-6]. Storage devices like flywheels and batteries are modelled as constant DC voltage sources (taking into account the time span under analysis). Its interface with the grid is done through inverters. From the AC side, storage devices act as controllable AC voltage sources (with very fast output characteristics) to face transients like in load-following situations. Despite acting as voltage sources, they have physical limitations and have a finite capacity for storing energy.

3.2 Inverter Modelling

As MG are inverter dominated networks, the use of adequate control strategies in the solid state converters are crucial for MG operation. These techniques are usually divided into two types [7]:

- 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.

When analyzing the long term dynamic behaviour of the MG, inverters are modelled only by their control functions. This means that fast switching transients, harmonics and inverter losses are neglected.

3.2.1 PQ Inverter Control

A PQ controlled inverter injects into the AC grid the power available at its input terminals. An example of the application of a PQ control is a PV unit, where the DC power produced in the PV array is time-varying and the inverter continuously adapts its output to match the power produced in the PV array. Since the response of the inverter control systems is usually very fast (few milliseconds), the main dynamic behaviour of the primary energy sources has a large influence in the global dynamic behaviour of the MG, namely when commands are sent by the MGCC to the primary energy sources of the controllable MS. The reactive power injected by PQ-controlled inverters corresponds to a set point that can be defined locally or centrally in the MGCC.

The PQ control of an inverter can be performed using a current control technique: the inverter current is controlled in amplitude and phase to meet the desired set-points of active and reactive power [8]. In this sense, a PQ controlled inverter is a current source controlled by the variations the primary energy source to which it is coupled.

3.2.2 Voltage Source Inverter Control

As mentioned previously, a VSI is controlled in order to feed the load with pre-defined values for voltage and frequency, according to a specific control strategy described next. The control principle of a VSI emulates the behaviour of a synchronous machine. Thus it is possible to control voltage and frequency on the AC system by means of inverter control. Frequency variation in the MG provides an adequate way to define power sharing among several VSI, since it is related with system frequency [9-10].

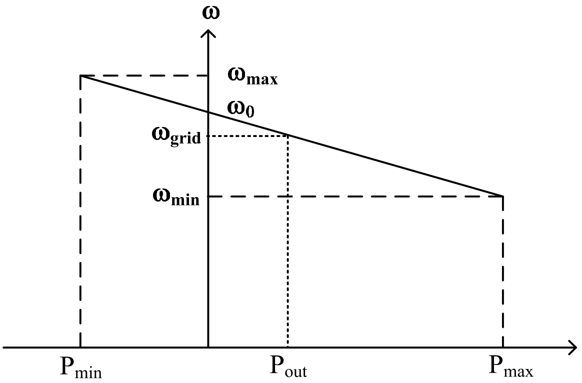

Figure 3.1: Frequency vs active power droop

Fig. 3.1 shows a frequency/active power characteristic to be implemented in a VSI. When a VSI is operating in parallel with a stiff AC system with angular frequency ω_{grid}, the output power of the VSI is defined from the droop equation derived. Changing the output power of the inverter can be accomplished by a change in the idle frequency (ω_0). If the AC system is not available, the output power of the inverter depends on the network load and droop settings so that the network frequency reaches a new value. The active power is shared among all the inverters at the new frequency value according to the droop settings of each VSI. Similar considerations can be made about voltage and reactive power control. A three-phase balanced model of a VSI implementing these two droop concepts was derived from a single-phase version presented in [10] and is shown in Fig. 3.2.

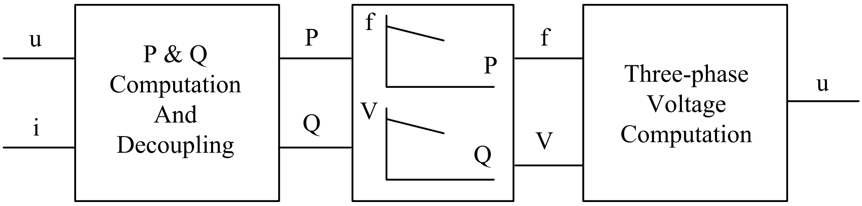

Figure 3.2: VSI model

4 MICROGRID OPERATION AND CONTROL

In conventional power systems, synchronous generators are used for voltage and frequency control of the entire system. In a MG inverters should be responsible for controlling frequency and voltage during islanded operation. Otherwise the MG could experience voltage and/or reactive power oscillations [11-12].

If a cluster of MS is operated within a MG and the main power supply (the MV network) is available, providing voltage and frequency references, all the inverters can be operated in the PQ mode. However if the MV network is lost all the inverters will shut down because there will not be a voltage reference within the MG and it will not be possible to obtain a precise balance between load and generation. 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:

- Single Master Operation (SMO): A single VSI is used to provide the reference voltage when the main power supply is lost;
- Multi Master Operation (MMO): Two or more inverters are operated as VSI; eventually, other PQ controlled inverters may also coexist.

Due to the requirements for BS strategies described in section 5, the most suitable option to implement the BS functionalities in a MG is the MMO. A general overview of a MMO approach is shown in Fig. 4.1.

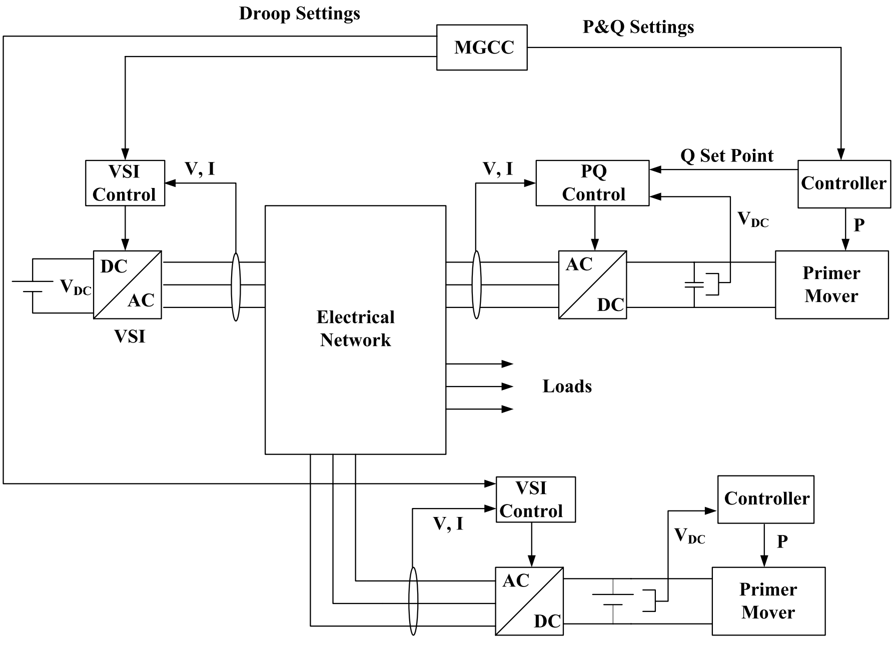

Figure 4.1: MMO architecture

As described in Fig. 4.2, storage device active power output 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 microsource 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. Storage devices (batteries or flywheels with high capabilities for injecting power during small time intervals) have a finite storage capacity and can be loaded mainly by absorbing power from the LV grid. Therefore, correcting permanent frequency deviations during any islanded operating conditions should then be considered as one of the key objective for any control strategy. Other MS are also assumed to be interfaced with the LV grid through a VSI with high storage capacity in its DC link. However, these storage devices are continuously loaded by the primary energy source (Fig. 4.1) and its discharge is not the key concern.

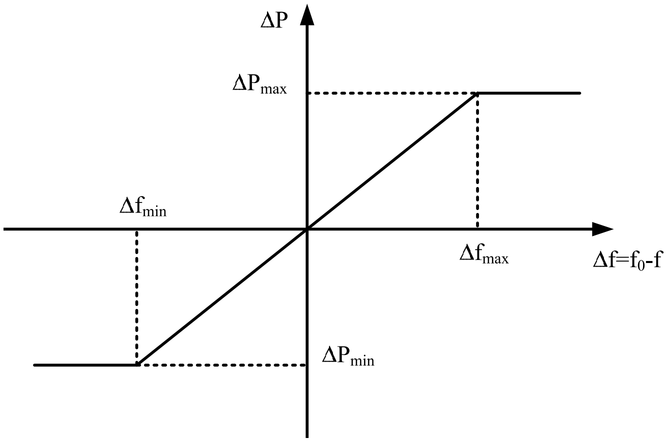

Figure 4.2: Steady state active power characteristic of a VSI

To correct permanent frequency deviations, convenient secondary load-frequency control must be installed in some controllable MS, in order to define target values for primary energy sources active power output. This corresponds to changing the MG active power dispatch to correct permanent frequency deviations. The load-frequency secondary control can be implemented as local secondary control, by using a local PI controller at each controllable MS, or as a centralized secondary control mastered by the MGCC [15]. Measurements from LC and MC can be used by the MGCC to optimize periodically the reactive power dispatch for the MG. However, this is not in the scope of the work described in this paper.

5 MICROGRIDS BLACK START

The MG black start involves a sequence of control actions, defined through a set of rules and conditions to be checked during the restoration stage. These rules are identified in advance and embedded in MGCC software.

5.1 General Assumptions

A crucial condition for the MG restoration procedure success is the availability of some MS with BS capability, which requires an autonomous local power supply feed local auxiliary control systems and to launch generation. However it was assumed that the MS restart procedure is carried out previously and no direct effect is transmitted to the LV network. The implementation of the BS functionalities in the MG described before is possible since there is also availability for:

- Bidirectional communication between the MGCC and MC / LC.
- Updated information, obtained before disturbance, about the status of load and generation in the MG and about availability of MS to black start.
- Automatic load disconnection after system collapse;
- Capability to disconnection the MV/LV distribution transformer from the MV network, before starting the BS procedure;
- Capability for LV network area separation.

The BS procedure was developed assuming that MS with BS capability (SSMT and SOFC) have batteries in the DC bus of their inverters and the MG adopts a multi master control approach, at least during the first stages of this sequence. In this way, the SSMT and SOFC inverters are operated as VSI in a MMO mode. During MG service restoration a set of electrical problems that are reflected in the BS procedure identification must be dealt with. These electrical problems include:

- Building the LV network (including the distribution transformer energization);
- Connecting micro-generators;
- Controlling both voltage and frequency;
- Connecting controllable loads.

During normal operation the MGCC periodically receives information from LC and MC about consumption levels and electric production and stores this information in a database. It also has information about the technical characteristics of the different MS, like active and reactive power limits. Based on such assumptions, a set of rules is created and embedded in the MGCC software for BS purposes. During BS procedure the MGCC will try to restore a scenario very similar to the last one stored in the data base.

5.2 Sequence of Actions for MicroGrid Black Start

The following sequence of actions should be carried out in order to restore the LV grid after a general blackout:

- Disconnection of all loads in order to avoid large frequency and voltage deviations when energizing the LV network. The MG should also be sectionalized around each MS with black start capability in order to allow it to feed its own (protected) loads and to run, in this way, in a standalone mode. These actions lead to the creation of small islands inside the MG to be synchronized later.

- Building the LV network. The storage device receives an order from the MGCC to energize the LV cables and the distribution transformer (DT). In order to comply with the LV grid earthing safety procedures [13], it is necessary to energize the DT as soon as possible, since the earth connection is performed at the DT neutral point and it is restored only after its energization. A large inrush current is experimented when energizing the DT by the LV side, which cannot be supported by the power electronic components of the inverters. To overcome this problem, transformer energization should be performed using a ramp-wise voltage generated by the inverter of the MS selected for this task.

- Small islands synchronization. MS already in operation in standalone 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 and power exchanges.

- Connection of controllable loads to the LV network is performed if the MS running in the LV network are not at fully loaded. 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.

- Connection of non-controllable MS or MS without BS capability, like PV and wind generators. At this stage the system has MS and loads capable of smoothing voltage and frequency variations due to power fluctuations in non-controllable MS, so they can now be connected. Other MS without BS capability can then be supplied by the LV grid to restart.

- Load increase. In order to feed as much load as possible, depending on production capability, other loads can then be connected.

- MG synchronization with the MV network when it becomes available. The synchronization conditions should be verified again. Before a general blackout two situations can occur: the MG is importing power or the MG is exporting power to the MV network. If the MG was importing power, it will not be possible to connect all the local loads. In this case, remaining unsupplied load can then be restored.

6 SIMULATION PLATFORMS

Two simulation platforms were implemented under *EMTP-RV*® and *MatLab*® *Simulink*® environments in order to evaluate the transient and dynamic behaviour of the several MS and the corresponding power electronic interfaces during the BS sequence. To analyse, in a more detailed way, the initial behaviour of the MG restoration process the *EMTP-RV*® platform was used. This required the transposition of the MS models and their controls to these simulation platforms. At this stage of the carried research only three-phase balanced operation of the MG was considered. A LV test system was defined by NTUA within the Microgrids project [14] and was used in this research. This network is shown in Fig 6.1.

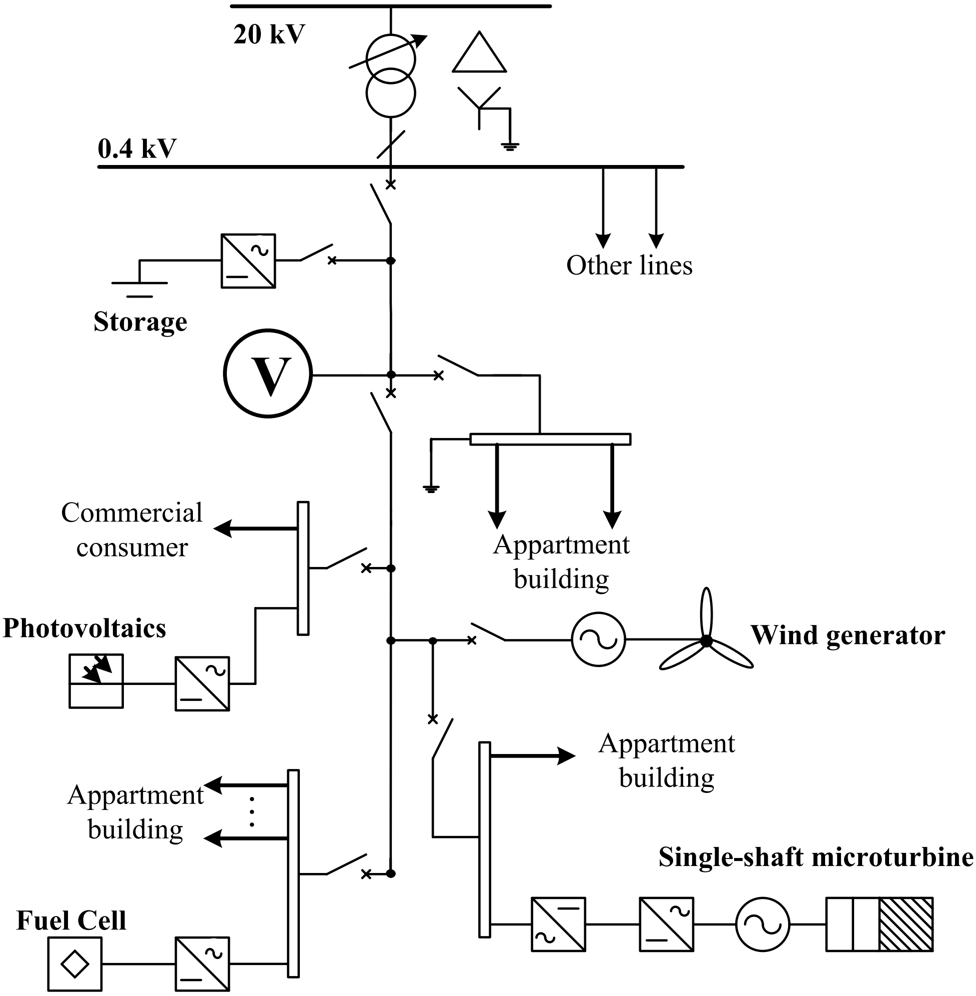

Figure 6.1: LV test system

The implementation of the LV test system under the *MatLab*® *Simulink*® environment is shown in Fig. 6.2. This is a modular simulation platform, where the control parameters and models can be easily included and modified using the “mask” functionalities provided by *MatLab*® *Simulink*®. A similar platform was implemented under the *EMTP-RV*®. For this one, a very simple sinusoidal PWM control switching scheme for VSI inverters was implemented to analyse the fast transients associated with the initials moments of the BS procedure.

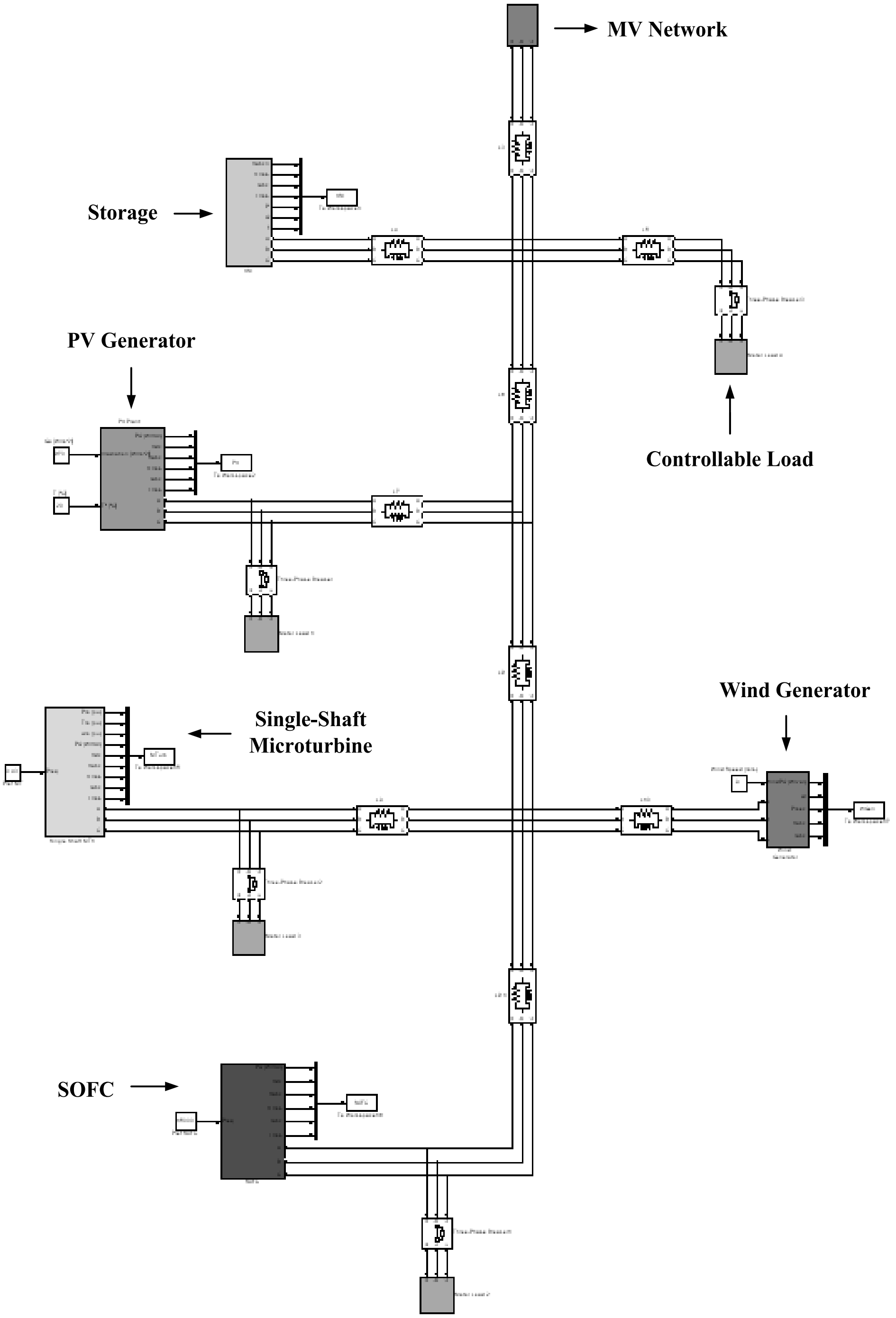

Figure 6.2: *MatLab® Simulink®* simulation platform

7 RESULTS

For the LV test system shown in Fig. 6.1 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 some of the loads and c) the automatic creation of islands operating in standalone mode with the SSMT and the SOFC. The sequence of actions defined for MG black start, described in section 5, was tested in the simulation platforms and analyzed through the results obtained.

The first action to build the LV network is the energization of the LV cables and the DT by the LV side. The storage device inverter is used to perform this task at t=0,5s. The typical overcurrent transients during the energization of a power transformer must be limited in order to avoid damage to the static switches used in the inverters. This limitation can be easily performed using a raping voltage control from zero to its nominal value during 0,5s. The output current of the storage device inverter is shown if Fig. 7.1 for the simulation time. As it can be observed, the energization current does not shown any transient peak and is perfectly controlled and limited through this energization process.

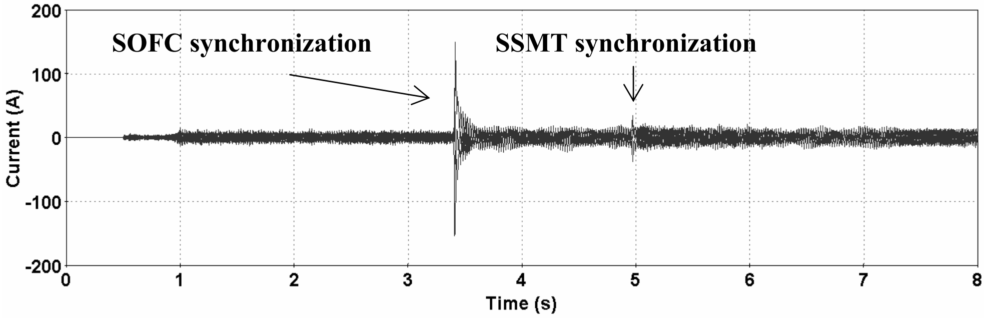

Figure 7.1: Output current of the storage device inverter

As mentioned previously, after energizing the DT and building the LV network, the next step of the MG black start procedure is the synchronization of both SOFC and SSMT with the LV network (up to now, this MS are operating in standalone mode and feeding their own loads). To check the synchronization conditions (phase sequence, frequency and phase angles errors) the MGCC sends instructions to the VSI inverters (initially to the SOFC and later to the SSMT) to produce a small frequency change, as it can be seen in Fig. 7.2 (at t=1.8s and t=4.5s). After synchronizing the SOFC and the SSMT some controllable loads and non-controllable MS are connected. Fig. 7.2 and 7.3 show the impact of these control actions in the VSI frequencies active power outputs, with SOFC and SSMT being synchronized at t=3,4s and t=4,9s respectively. After synchronizations the frequency of the inverters involved in the process match perfectly.

It can be observed in Fig. 7.3 that active powers present some small oscillations. These oscillations are the result of VSI filter interactions and occur in the absence of active damping of the loop formed by the filter capacitors and the tie-line inductance [9]. These oscillations are not uncommon in power systems and can be damped by the inverters, given sufficient inverter bandwidth [9]. One effective mean of damping these oscillations is the introduction of a series active filter between the capacitor and the AC system bus [16].

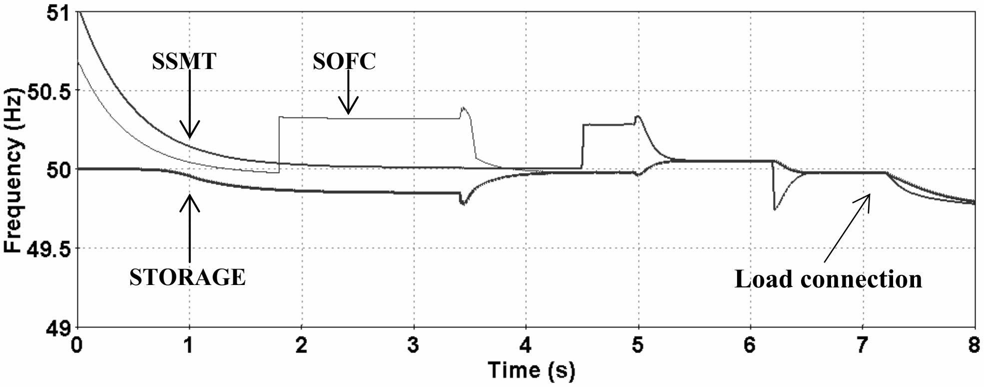

Figure 7.2: Frequency in each VSI

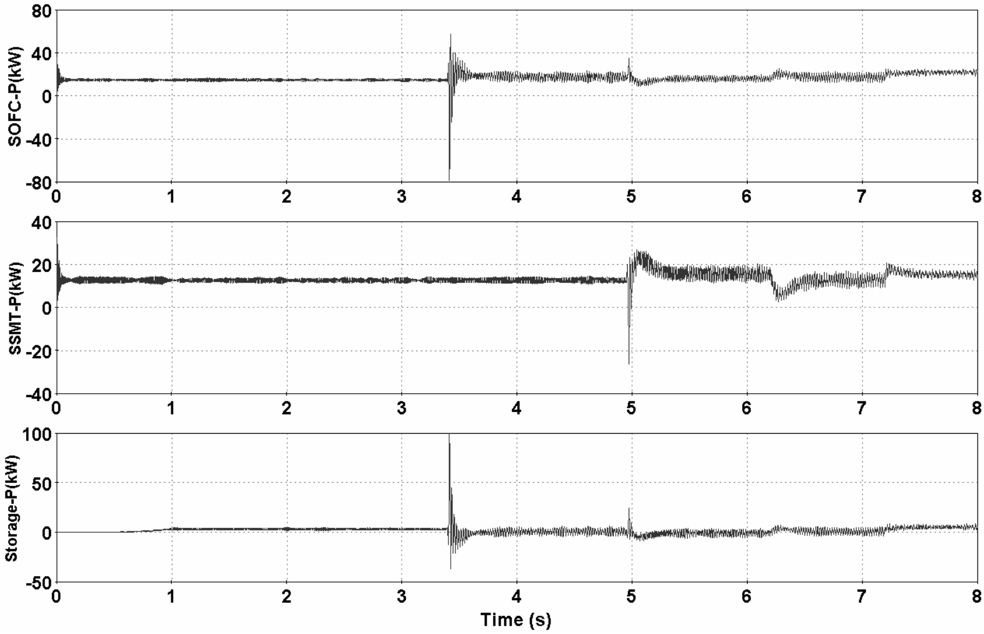

Figure 7.3: Active power in each VSI

In order to get an extended overview of the BS sequence, the MG *MatLab® Simulink®* platform was used. The results obtained for VSI frequencies, active and reactive power outputs and bus voltage marked in Fig. 6.1 are shown in next figures. The simulations starts considering that the LV cables and the distribution transformer are energized. The sequence of actions involves:

- Connection of protected loads of the SOFC and SSMT (t=1s)
- Synchronizing the SOFC with the LV network (t=23s)
- Synchronizing the SSMT with the LV network (t=42.5s)
- Connecting controllable loads (t=60s)
- Connection of the PV (t=80s)
- Connecting controllable loads (t=100s)
- Connecting the wind generator (t=120.8s)
- Connecting controllable loads (t=145s)
- Connecting controllable loads (t=165s)
- Wind increase (t=185s)
- Connecting controllable loads (t=205s)
- Synchronization with the MV network(t=238.2s)

Figures 7.4 and 7.5 show the most important results during the BS procedure. A frequency deviation after a load connection is a critical issue in this procedure, requiring therefore a special attention, as mentioned previously. If a frequency deviation remains for some time a local secondary control is used to correct it. This can be observed in Fig. 7.4. After synchronizing the MS, a load variation is shared among the several MS. By correcting permanent frequency deviations, the active power injection by the storage device is taken to zero and increases in the other MS.

For VSI synchronization purposes, the necessary conditions are checked carefully. This requires correction in the voltage magnitude and phase angle (frequency) of the VSI and can be observed in Figures 7.4 and 7.5. A detail of storage device current during and in the moments subsequent to the connection of the SOFC inverter to the LV grid is shown in Fig. 7.6. The transient current resulting from the synchronization is quite reduced and its impact perfectly negligible. Comparing the steady state current in the storage device inverter before and after the synchronization, it is possible to observe an increase in its magnitude. This is due to the increase of the idle frequency in the storage device inverter during a short time interval (for the same time interval, the SOFC idle frequency is constant). Consequently, a certain amount of power is temporarily supplied by the storage device (Fig. 7.4). In its reactive power output it is possible to observe just a small variation due to a little error in the voltage magnitudes of the SOFC and storage inverter before synchronization. At t=25s the storage device idle frequency is set to its normal value (50 Hz). Therefore active and reactive powers return to the values they had prior to synchronization (Figures 7.4 and 7.5).

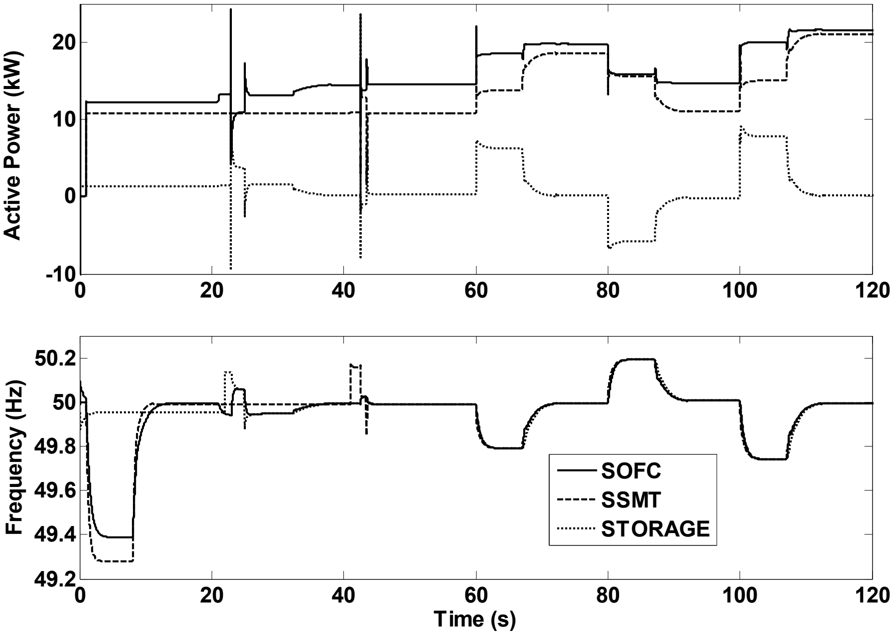

Figure 7.4: Inverters active power and frequency during the first stages of the BS procedure

The results of the MG long term dynamic behaviour are obtained using a voltage droop control scheme in all MS with BS capability. 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 voltage regulation through droop ensures stability of the MG and no reactive power oscillations among MS are observed. To the contrary of what happens in the active power sharing situation (where active power generation sharing is defined by droops), 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. Thus, a convenient voltage-reactive secondary control should be installed in the MGCC, otherwise overload of VSI can occur.

When the MV network becomes available, the MGCC requires all the VSI to change frequency and voltage, to check synchronization conditions, by slightly and equally changing their idle frequencies and voltages. This procedure guarantees that no significant changes occur on the active and reactive power output of each inverter.

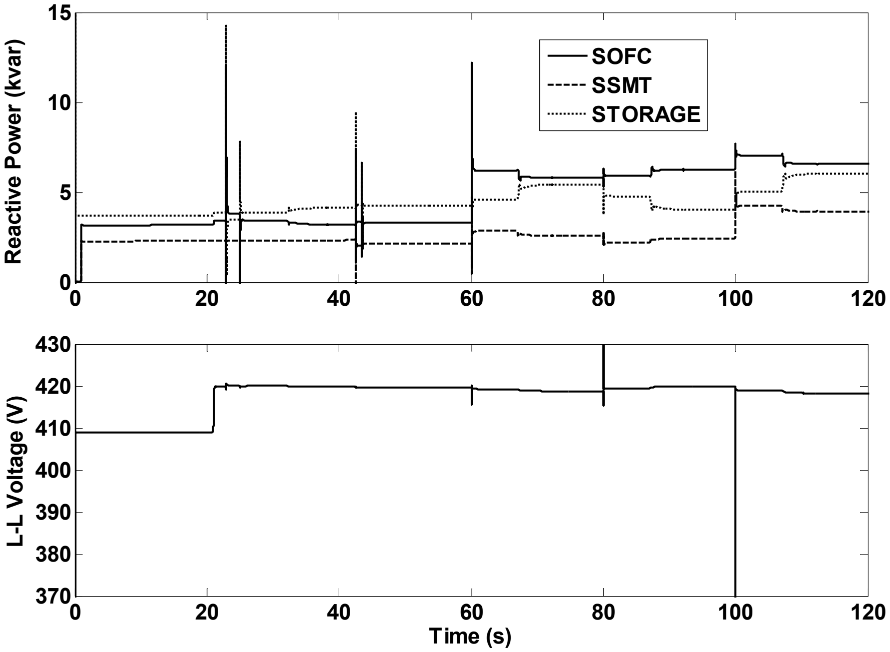

Figure 7.5: Inverters reactive power and node voltage, marked as “V” in Fig 6, in the first stages of the BS procedure

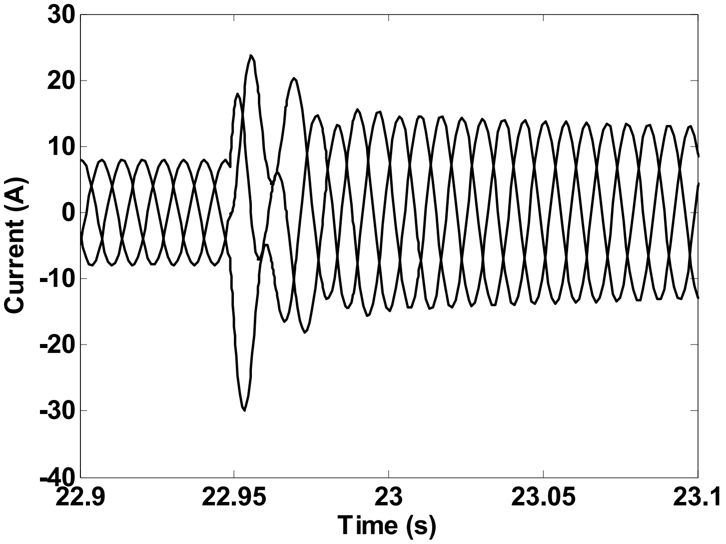

Figure 7.6: Storage device output current detail during synchronization with the SOFC inverter

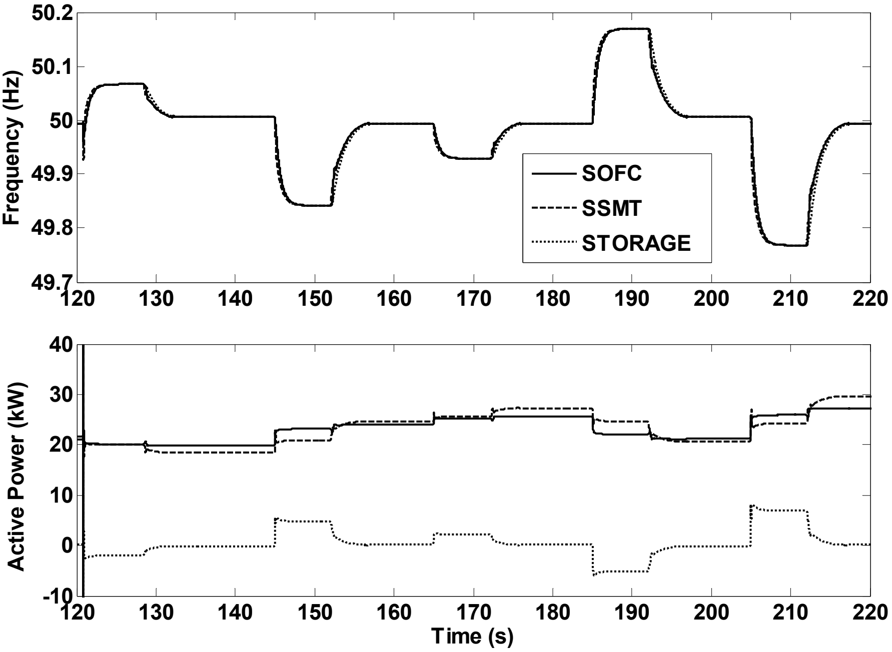

Figure 7.7: Inverters active power and frequency during the second part of the BS procedure

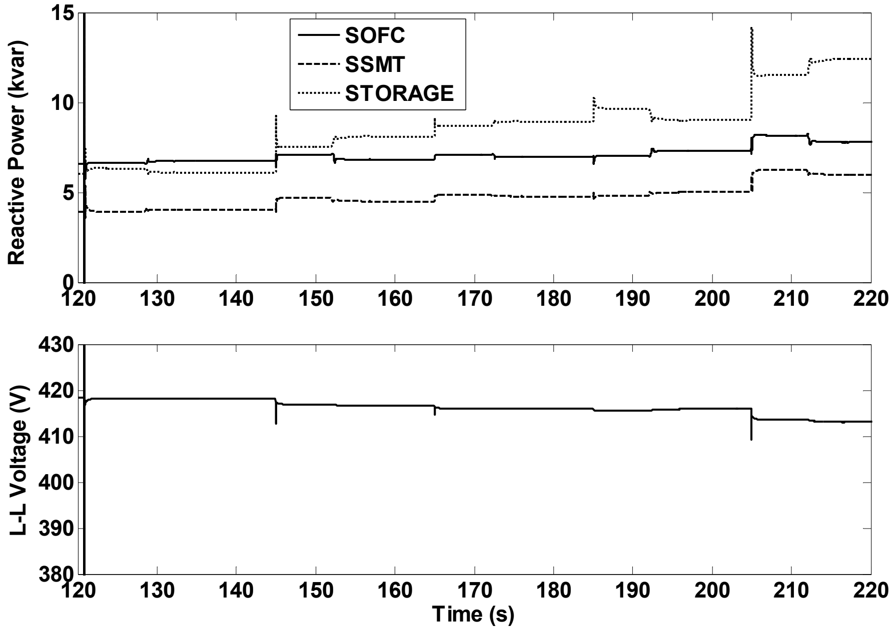

Figure 7.8: Inverters reactive power and node voltage, marked as "V" in Fig 6.1, during the second part of the BS procedure

Fig. 7.9 shows the impact of the described procedure in the storage device inverter. At t=225s there is a correction in the magnitude of the MG voltage to comply with the magnitude of the main power supply. Then, a slight frequency change is imposed and the synchronization conditions start to be checked (t=227s). As can be observed in Fig. 7.9, no significant changes occur in the power output of the inverter. However, as MG loads are of the impedance type (power consumption in dependent both on voltage and frequency), the slight changes on voltage and frequency cause small active and reactive power variations in the inverters as can be observed in Fig. 7.9 at t=225s. The synchronization with the main power supply occurs at about t=238.2s and a transient current can be observed. At t=245s, the idle frequency of the inverters are restored to the values they have before this procedure was started. Otherwise, the dispatch inside the MG is significantly modified and active power would be injected to the MV network. When synchronizing two VSI the transient current observed (Fig. 7.6) is damped quickly because of droop control implemented in both inverters. When synchronizing the MG with the MV network, several VSI are being synchronized with a fixed frequency voltage source, which has slow damping effects in the inverter output current (Fig 7.9).

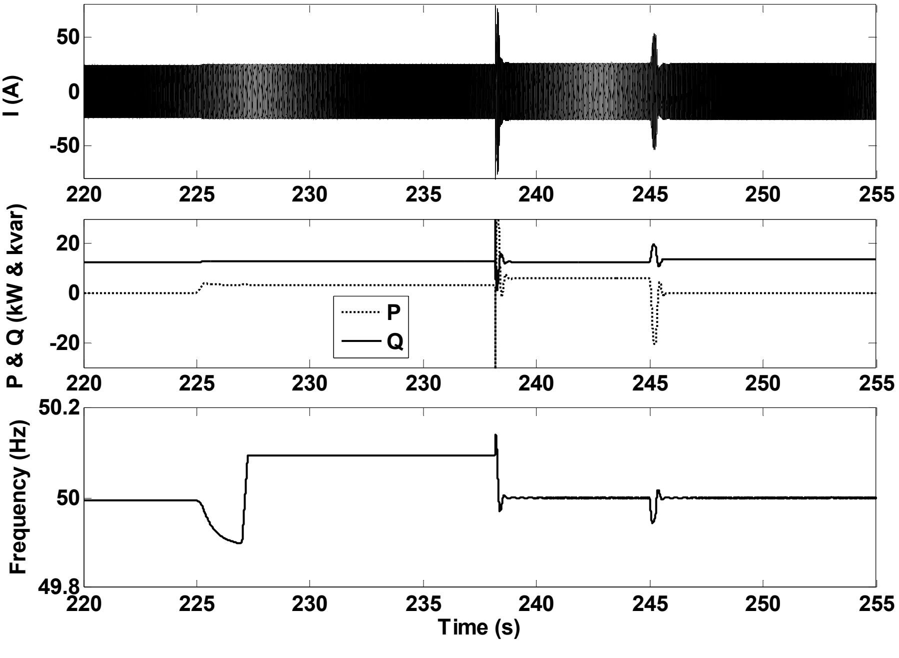

Figure 7.9: Impact of the synchronization procedure in the storage device inverter

8 CONCLUSIONS

This paper describes the possible control strategies to be adopted for Microgrids islanded and black start operation, in the case where no directly grid connected synchronous generators are used. The identification of a set of rules and conditions to be checked during the restoration stage by the Microgrid components was derived and evaluated through numerical simulation, proving the feasibility of such procedures. The results obtained show that storage devices are absolutely essential to implement successful control strategies during the initial stages of a black start procedure and for MG operation in islanded mode.

The described black start strategy was a centrally based procedure. However, other approaches based on the use of autonomous agent concepts are under development within the framework of this project, involving other partners [14]. More ambitious targets can be defined for higher level BS functionalities under the concept of the development of multi-microgrids – microgrids interconnected through a MV network.

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