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Large Scale Integration of Microgeneration to Low Voltage Grids

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Deliverable DD2

Evaluation of the Emergency Strategies during Islanding and Black Start

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1. Executive Summary

The main objective of this document is to evaluate the quality and performance of MicroGrid emergency control strategies by exploiting the simulation platform developed within Work Package D for different test systems, considering different operating conditions and disturbances.

A summary of the work developed for this deliverable is given next. Sections 2 to 5 include a brief review on the work previously developed within WPD and described in *Deliverable DD1 – Emergency Strategies and Algorithms*, as well as the description of the developments carried out in the last few months.

Section 3 provides an overview on microsource and load modelling. The main issue of this section deals with inverter control during short circuit conditions.

The control modes of a MicroGrid are shortly described in section 4. Also, the need of secondary load-frequency control during MicroGrid islanded operation is addressed.

A possible black start procedure for service restoration in a MG is reviewed in section 5. The need to change the control modes of some MS in the later stages of the MG procedure is also explained.

Section 6 includes the description of the test systems, the operating scenarios and the disturbances considered as the most important to evaluate the performance of the control strategies.

A wide range of simulation results are shown in section 7, both on MicroGrid dynamic behaviour and on MicroGrid black start. A detailed discussion on the results obtained is also provided.

The main conclusions derived from the work described in this document are detailed in section 8.

2. Introduction

In Deliverable DD1 – Emergency Strategies and Algorithms [1] the control strategies to be adopted in a MicroGrid (MG) when the system becomes isolated or has to deal with a Black Start (BS) situation were described. Based on the MG concept developed within this project [2], an intelligent system is responsible for an efficient use of distributed generation resources, aiming at the continuity of service in the Low Voltage (LV) side of the distribution network, if the Medium Voltage (MV) network is disconnected for some planned or unplanned reason. Exploiting the communication capabilities and a centralized approach housed in the MicroGrid Central Controller (MGCC), together with control rules embedded in the local controllers, these control strategies and BS functions will contribute to improve reliability of operation in terms of the reduction of costumer interruption times.

A simulation platform under the *MatLab®/Simulink®* environment was developed in order to evaluate the dynamic behaviour of several microsources (MS) operating together in a LV network under pre-specified conditions, which allowed the identification of the referred control strategies and their evaluation through simulations. Improvements were made in the *MatLab®/Simulink®* simulation platform and are described in the following sections. They include modelling of motor loads (the MG load can be now represented as a combination of constant impedance loads and motor loads for dynamic stability studies) and inverter control during short-circuits. The impact of induction motor reacceleration after a fault in the MV network and the consequent islanding process of the MG will be shown. Another simulation platform was also implemented in the *EMTP – RV®* environment in order to analyse the fast transients associated with the initial stages of the BS procedure. In this simulation platform a sinusoidal PWM modulation technique was implemented in order to evaluate the effects of solid state switches commutations.

In [1] the proposed control strategies and BS functions were tested briefly. During islanded operation microsources (MS) should be able to operate in a stable way, according to the proposed control strategies. The islanding procedure can be considered intentional (due to maintenance requirements) or forced (due to faults in the MV network). A forced islanding is the most critical one. After islanding, frequency and voltage control become the main concern. In the first moments subsequent to the islanding process, economic scheduling policies become a secondary issue and primary control over frequency and voltage are the main concern. This report intends to demonstrate the performance of the control strategies developed previously by evaluating them in several operating conditions exploiting the simulation platforms developed for the studies carried out within Work Package D (WPD).

Two test systems are analysed in this report: one corresponding to an LV distribution network in an urban area, were MS like microturbines and fuel cells are dominant and another one corresponding to a rural LV distribution network, with predominance of photovoltaic and wind generators. Several scenarios characterized by different load and generation levels are defined in order to have a thorough analysis of the performance of the proposed control strategies in different situations. Different types of disturbances are considered and analysed in order to demonstrate the feasibility of the proposed strategies: faults in the MV network causing the islanding of the MG, sudden connection or disconnection of loads in islanded operation.

3. Modelling Review

A detailed description of the MS models used in the simulation platform developed by INESC Porto within WPD can be found in Deliverable DA1 [3] and the main modifications introduced are described in Deliverable DD1 [1]. Several microgeneration technologies were included in the simulation platform: solid oxide fuel cells (SOFC), single shaft microturbines (SSMT), split shaft microturbines (SPMT) and wind and photovoltaic (PV) generators. Storage devices like batteries and flywheels and two main control schemes for static converters were also modelled.

In the last months several enhancements were included on loads and static converters modelling, which are described in this chapter.

3.1. Inverter Modelling

In DD1 [1] two kinds of control strategies that can be used to operate an inverter were described. According to the control strategy followed, the corresponding model is derived:

- 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.

3.1.1. 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 source has a large influence in the global dynamic behaviour of the MG, namely when commands are sent by the MicroGrid Central Controller (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.

A model for a PQ controlled inverter based on the Instantaneous Power Theory was proposed by INESC Porto in [1], [3]. The model is suitable for analysing MG dynamic behaviour if no severe faults are considered. In order to include the effect of faults in the dynamic stability of the MG a new model for a PQ-controlled inverter was derived, which is based on a current-controlled voltage source.

In [4] a method for computing single-phase active and reactive powers in droop-controlled inverters is presented. This method was adapted in order to compute the instantaneous active and reactive components of the inverter current: the active component is in phase with the voltage and the reactive component with a 90 degrees (lagging) phase-shift, being both normalized in the interval [-1, 1].

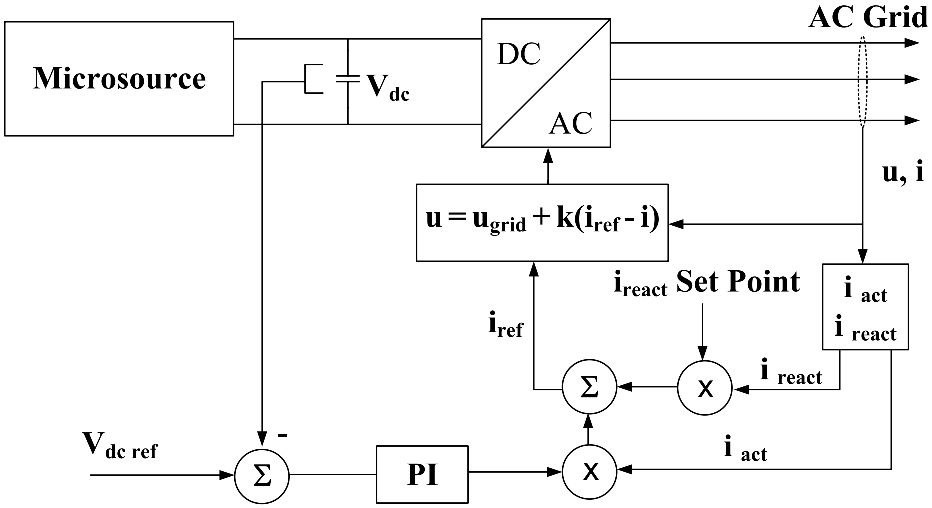

Figure 1: PQ inverter control model

The active component is used to control the DC link voltage and consequently the inverter active output power in order to balance MS and inverter active power output, whereas the reactive component controls the inverter reactive power output. Power variations in the MS lead to a variation of the DC link voltage, which is corrected via the PI regulator by adjusting the active current output This inverter can be operated with a unit power factor (i_{react} Set Point = 0 in **Figure 1**) or receive a set-point (locally or from the MGCC) for the output reactive power.

3.1.1. Voltage Source Inverter Control Logic

In this case the inverter is controlled 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. There is thus a possibility 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 power changes [5].

Considering a VSI operating in parallel with an AC system with angular frequency ω_{grid} the active output power of the VSI is automatically defined by the well known frequency droop characteristic, as described in **Figure 2**.

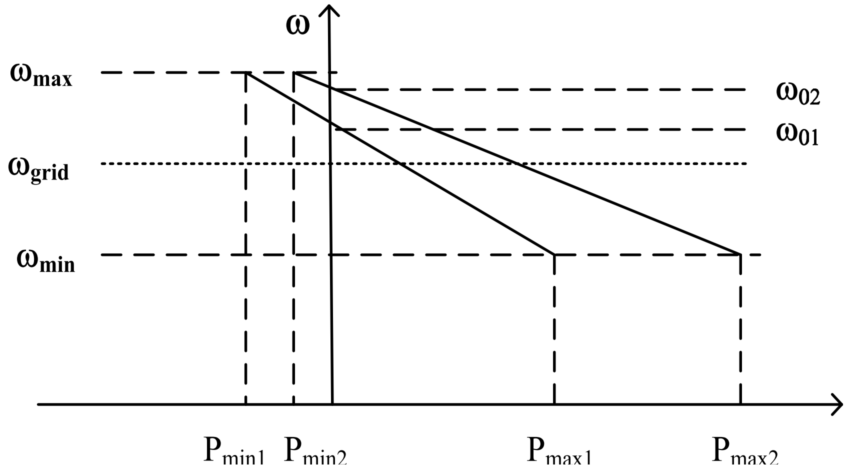

Figure 2: Active power vs. frequency droop

Dispatching the output power of the inverter can be achieved by means of a convenient modification on the idle frequency (ω_{01}, ω_{02}). If the main AC system is lost, the output power of each inverter is adjusted according to the droop settings and the network frequency drifts towards a new value. The active power is shared among the inverters at the new frequency value. Similar considerations can be made in what concerns the voltage/reactive power control, using also a voltage droop concept [5]. A three-phase balanced model of a VSI implementing these two droop concepts was derived from a single-phase version presented in [4], [6] and is shown in **Figure 3**.

The VSI terminal voltage and current are measured in order to compute active and reactive power levels. This measuring stage introduces a delay that corresponds to a decoupling, performed by the Decoupling transfer functions described in **Figure 3**.

The active power determines the frequency of the output voltage by the active power/frequency droop (K_f). Similarly, the reactive power determines the magnitude of the output voltage by the reactive power droop (K_v). A phase feed-forward control was included for stability purposes [4], corresponding to the K_{ff}.

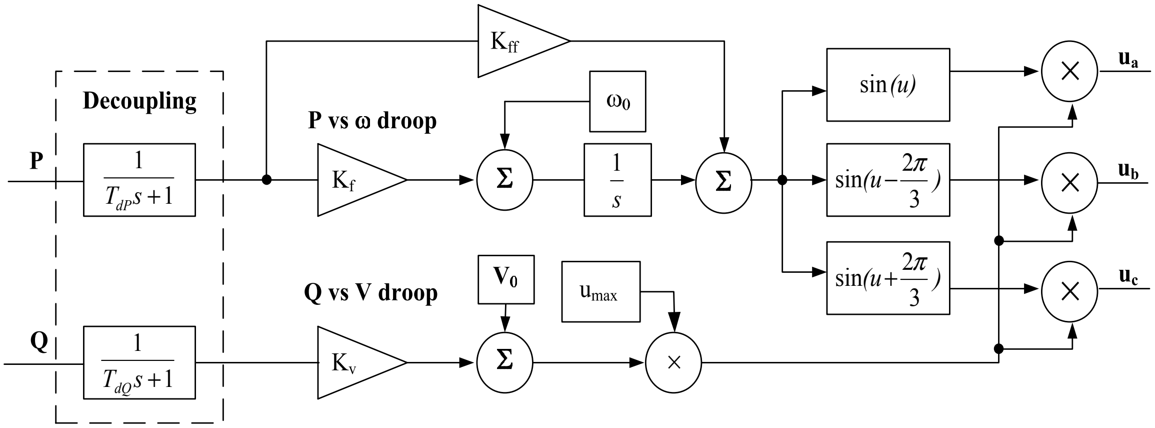

Figure 3: VSI model

3.1.3. Inverter Control during Transient Overloads and Short Circuits

Inverter overcurrents can be caused by transient overloads (due to the connection of a large amount of load in islanded mode) or by short-circuits.

When moving to islanded operation or when a large load is connected during islanded operation, the initial high imbalance between local load and generation may lead to large frequency deviations and transient overload of the VSI, since this unit has a fast response to this type of situations. In order to overcome this problem, two solutions were adopted:

- Allow a temporary disconnection of less important loads (load shedding activated by under frequency relays, using the load shedding scheme described in DD1);
- Up-rate the VSI and allow an overload situation during a certain time interval (at least greater than the one required for load shedding activation).

Due to the nature of the control of PQ inverters, they are not affected by transient overloads.

Conventional power plants comprising synchronous machines directly connected to the network provide large short-circuit currents, which are very helpful for fast and efficient fault detection and elimination. However, in a MG where generation units are mainly connected to the grid through power electronic interfaces, it is difficult to obtain high fault currents. Solid state switching devices used in inverters are selected based on voltage, current carrying capability (under certain cooling conditions for a defined switching frequency) and safe operating areas. The islanded system can ride through short-circuits if there is sufficient oversizing of power electronic interfaces [7], since they have no thermal short-term overcurrent capabilities, in contrast to synchronous generators. Accordingly, the following considerations are in order:

- The VSI was selected to be up-rated in order to provide a significant contribution to short-circuit currents (ranging from 3 to 5 p.u.) due to conventional overcurrent protection devices;
- PQ inverters can provide only a small amount of short circuit current (around 1.5 p.u.).

During and after the short-circuit, the time interval in which large current outputs are admissible in the VSI, as well as the output current magnitude, is also dependent on the impact caused by the dynamics of motor loads and asynchronous generators. A storage device and a VSI are the most important requirements for islanded operation. Therefore, adequate sizing of these devices is quite important in order not to waste potentialities of distributed generation in such events.

The PQ inverter control scheme allows a simple control over the output inverter current during short-circuit conditions. In this case, the voltage drop at the inverter terminals leads to a reduction of the active power output. Therefore, the DC link voltage increases and the PI controller tries to increase the active output current of the inverter. By limiting the total gain of the PI controller, the output current of the inverter can also be limited. Simultaneously, an increase in the DC link voltage will be experienced. The adoption of this philosophy aims at the reduction of the impact of transient power variations in the primary energy source.

Acting as a voltage source, the output current of a VSI tends to be very high (similarly to what happens in a conventional synchronous machine). In order to limit its output current, a control technique such as the one presented in **Figure 1** is used. The main difference is that in this case the current reference has a maximum peak value dependent on the characteristics of the solid state switches and its frequency is imposed by inverter frequency/active power droop.

3.2. Load Modelling

MG dynamic behaviour was evaluated considering only three-phase balanced operation and two load types: constant impedance loads (power dependent on frequency and voltage) and motor loads (an induction motor with constant mechanical torque). As it will be shown, load characteristics influence greatly the dynamic behaviour of the MG, mainly in short-circuit conditions.

Controllable loads, available for load-shedding, have also been modelled. The amount of load to be shed is defined based on the amplitude of frequency deviation. Induction motor loads have not been considered as sheddable by under frequency relays.

4. MicroGrids Operation and Control

While the MG is being operated in interconnected mode, all inverters are operated in PQ mode. However, a sudden disconnection of the main power supply (the upstream MV network) would lead to the loss of the MG, since there would be no possibility for load/generation balancing, and therefore for frequency and voltage control. The unit that can be used to achieve these requirements is the VSI. Using its control capabilities by means of droop settings adjustment, a VSI can be operated in parallel with the main grid without injecting active or reactive power. When disconnection from the main grid happens, the VSI output is automatically determined by the deviation between load and generation in the MG. After identifying the key solution for MG islanded operation and based on the control strategies of the inverters, two main control strategies are possible:

- Single Master Operation (SMO): A VSI or a synchronous machine directly connected to the grid (with a diesel engine as the prime mover, for example) can be used as voltage reference when the main power supply is lost; all the other inverters can then be operated in PQ mode;
- Multi Master Operation (MMO): More than one inverter is operated as a VSI, corresponding to a scenario with dispersed storage devices; other PQ inverters may also coexist.

As described in **Figure 4**, 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 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 (for example 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 objectives for any control strategy.

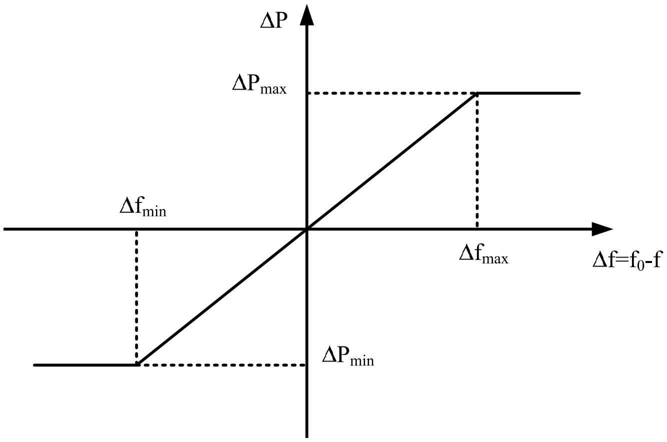

Figure 4: Steady state active power characteristic of a VSI

In order 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 [8]. Measurements from Load Controllers (LC) and Microsource Controllers (MC) can be used by the MGCC in order to optimize periodically the reactive power dispatch for the MG.

4.1. Emergency Strategies and Algorithms

In Deliverable DD1 [1] the main requirements for a successful passage to islanded operation were identified: storage devices and load shedding.

Storage devices must be installed in a MG to perform load following during and subsequent to the islanding process. Load following capabilities are of the utmost importance due to the imbalance between local load and generation when moving to islanded operation and to face natural variation of loads and production in non-controllable MS.

The possibility of disconnecting controllable loads plays an important role in the operating scenarios where load is larger than local generation. This is important especially due to the limited capacity of the storage devices and to the large time constants of MS with load-frequency control functions (SOFC and SSMT). The load shedding mechanism was implemented as a resource in order to aid frequency restoration to its nominal value after the islanding of the MG and is based on the frequency deviation error. The percentage of load to be disconnected depends of the frequency deviation and its reconnection is done in small load steps in order to avoid large frequency excursions.

5. MicroGrid Black Start

A sequence of actions was identified for MG black start [1] and is shortly described in this document. Improvements were made, regarding the energization of the MV/LV transformer and changing the control scheme of the inverters after restoring service in the MG.

During normal operation the MGCC periodically receives information from LC and MC about consumption levels and electric production and stores this information in a data base. It also has information about the technical characteristics of the different MS, like active and reactive power limits. Microgrid BS procedure involves a set of rules and conditions to be checked during the restoration stage, which are identified in advance and embedded in MGCC software. These rules and conditions define a sequence of control actions carried out during the restoration procedure.

The implementation of a BS procedure requires the availability of some MS with BS capability, which involves an autonomous local power supply in order to feed local auxiliary control systems and launch generation. Hence, MS restart procedure is not reflected in the electrical network and there is a certain time interval that must be considered for MS start-up. Beyond this essential condition it is also required availability for:

- Bidirectional communication between the MGCC and MC / LC.
- Updated information, obtained before disturbance about the status of load/generation in the MG and about availability of MS to BS.
- Automatic load disconnection after system collapse.

- MV/LV distribution transformer disconnection from the MV network, before starting the BS procedure.
- LV network area separation.

During the BS procedure development it was assumed that MS with BS capability are the SOFC and the SSMT; MS with BS capability have batteries at their DC bus and it was adopted, at least during the first stages of this sequence, a multi master control approach, being switched to SMO in the later stages of the BS procedure.

5.1. Black Start Procedure

After a general blackout, the MGCC will try service restoration in the LV area supplied by MS based on the information stored in a data base about the last MG load scenario, by performing the following sequence of actions:

1. <u>Disconnection of all loads</u> 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. These actions lead to the creation of small islands inside the MG that will all be synchronized later.
2. <u>Building the LV network</u>. The inverter associated with the storage device is responsible for LV and Distribution Transformer (DT) energization. In order to follow the earthing LV protection guidelines, presented in [9], 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, that cannot be supported by the inverters. To overcome this problem, transformer energization should be performed using a ramp-wise voltage wave form.
3. <u>Small islands synchronization</u>. 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 and power exchanges.
4. <u>Connection of controllable loads</u> to the LV network is performed if the MS running

in the LV network have 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 moments.

5. 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 be connected to the grid and even absorb power to restart.
6. Load increase. In order to feed as much load as possible, depending on production capability, other loads can now be connected.
7. 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. This type of load variation is usually challenging for batteries because the combination of low and high power loads makes their design difficult to optimize [10].
8. 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 while is islanded operation. In this case, remaining unsupplied loads can be restored after MG reconnection to the MV network.

6. Low Voltage Test Systems and Scenarios

In order to test the performance of the developed emergency strategies, two LV test systems were defined. The simulation platforms described in Deliverable DD1 were adapted to include the test systems, which are described next.

For each test system and operating conditions, the passage to islanded operation after a fault in the MV network was simulated. An intentional islanding for the same operating conditions was also simulated.

6.1. Urban LV Test System

The Urban LV test system is shown in **Figure 5**. The following MS were included in the simulation platform:

- Photovoltaic panel;
- Split-shaft microturbine;
- Single-shaft microturbine (available for load-frequency control);
- Fuel cell (available for load-frequency control);
- Storage device.

Two simulation scenarios were defined for this test system. Scenario **Urban_1** corresponds to a situation where the MG is importing 29.4+j2.2 kVA from the MV network; in the scenario **Urban_2** the MG is exporting 12.7-2.4 kVA to the MV network. The total load includes 70% of the impedance type and 30% of the motor load type.

	Total Load		Total Distributed Generation	
	P (kW)	Q (kvar)	P (kW)	Q (kvar)
Urban_1	66.5	23.8	36.8	21.5
Urban_2	69.5	25.5	89.3	25.0

Table 1: Scenarios for the urban LV test system

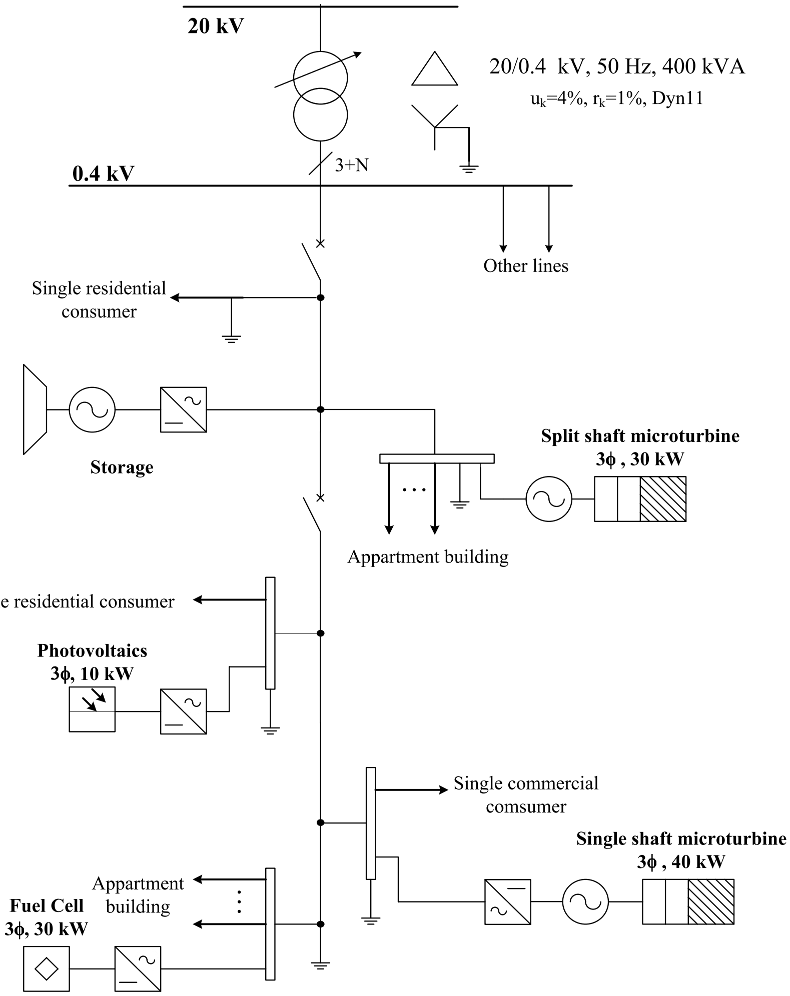

Figure 5: Urban LV test system

6.2. Rural LV Test System

The rural LV test system is shown in **Figure 6**. The MS included in the simulation platform are:

- Photovoltaic panels;
- Single-shaft microturbine (available for load-frequency control);
- Wind generators;
- Storage device.

Two simulation scenarios were defined for the rural LV test system. Both scenarios correspond to a situation where the MG importing 16.3+j0.1 kVA and 38.4+j1.7 kVA respectively. The total load includes 70% of the impedance type and 30% of induction motor load type.

	Total Load		Total Distributed Generation	
	P (kW)	Q (kvar)	P (kW)	Q (kvar)
Rural_1	51.3	18.3	35.0	18.1
Rural_2	66.5	21.6	28.1	19.9

Table 2: Scenarios for the rural LV test system

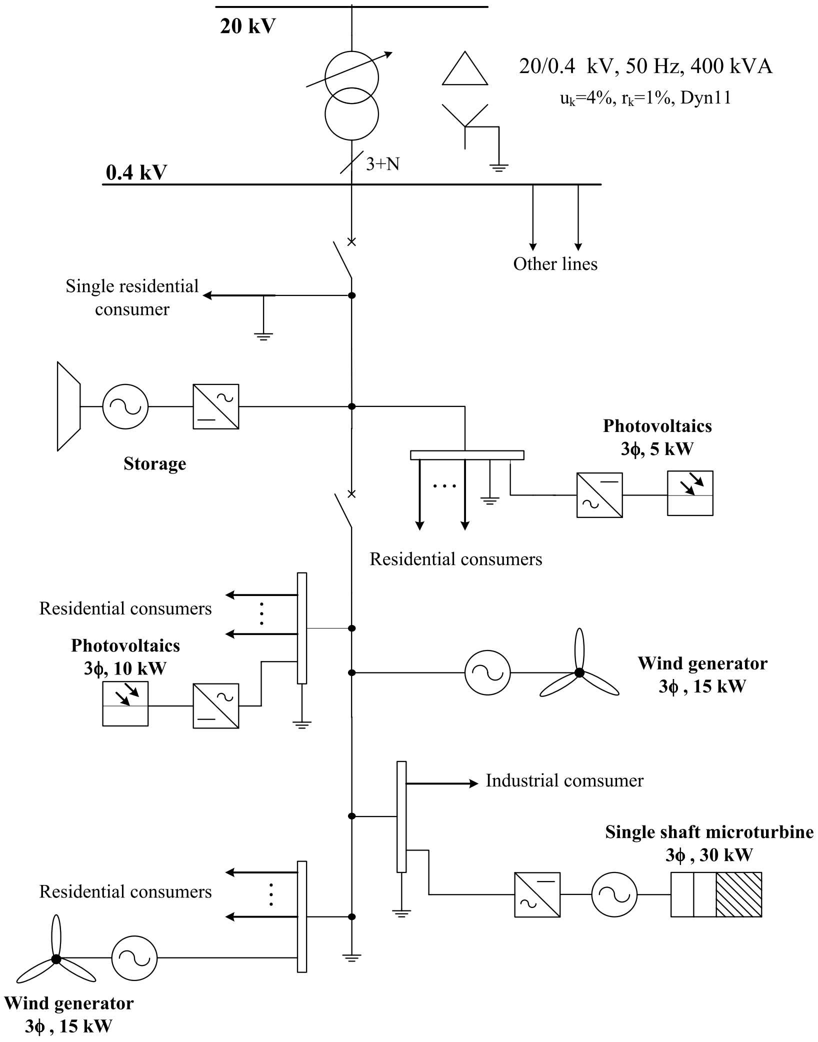

Figure 6: Rural LV test system

7. Results from Simulations

In this section an extensive overview of the results obtained from a large number of simulations is presented, where the dynamic behaviour of the MG during and subsequent to the islanding process is evaluated. The fast and long term dynamics associated with the identified BS procedure for MG service restoration after a general blackout are analysed for a given scenario. The main objective is to have a detailed evaluation of the MG behaviour under several operating conditions in order to validate the feasibility of the proposed control strategies.

7.1. Dynamic Behaviour of the MicroGrid

The simulation results show the dynamic behaviour of the MG in the scenarios defined above, after a three-phase solid fault in the MV network followed by MG islanding in 100 ms (MG islanding takes place at t=10.1 s). The MG is assumed to be operating under a single master control approach. For each analysed scenario a comparison between the MG frequency for a forced and for an intentional islanding procedure is also presented.

The next subsections show the main results obtained for each scenario described in section 6, being the results discussed in section 7.1.5.

7.1.1. Scenario Urban_1

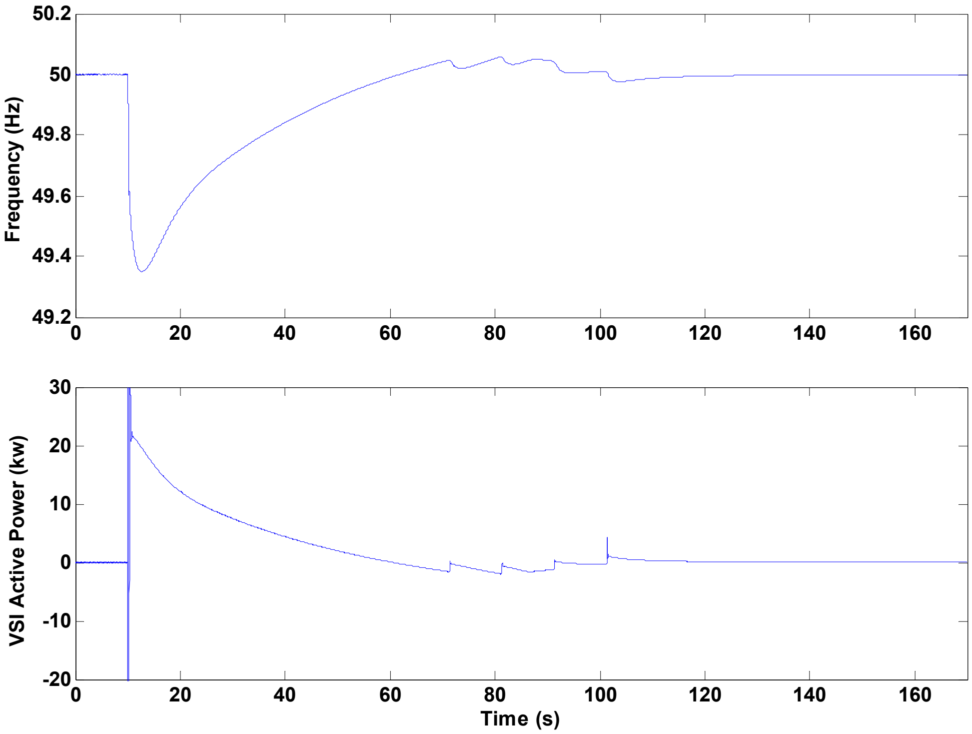

Figure 7: MG frequency and VSI active power

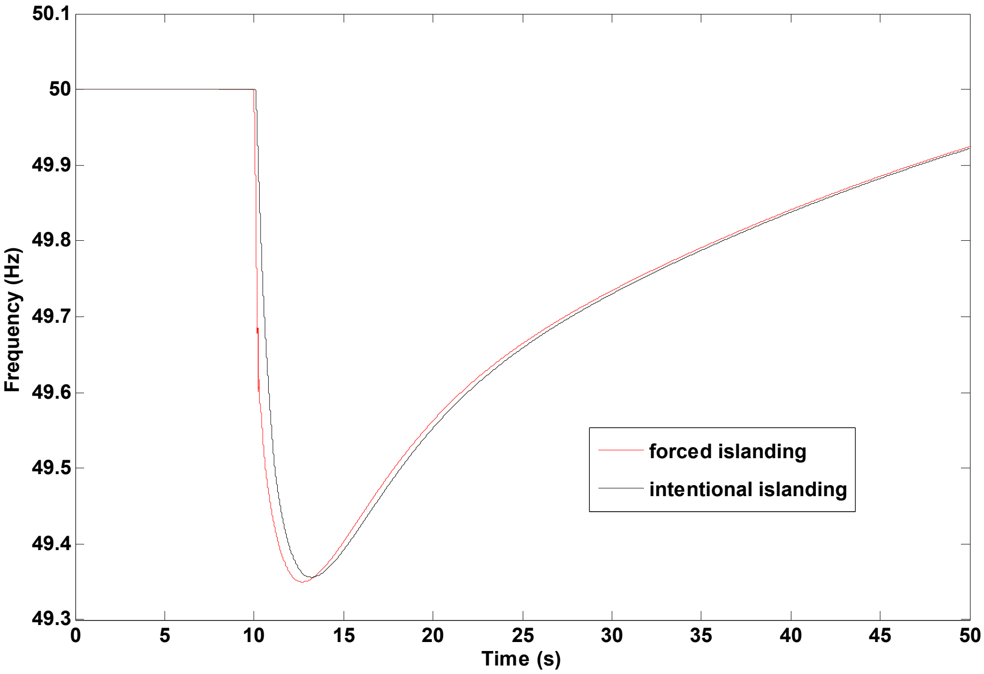

Figure 8: MG frequency for a forced and intentional islanding

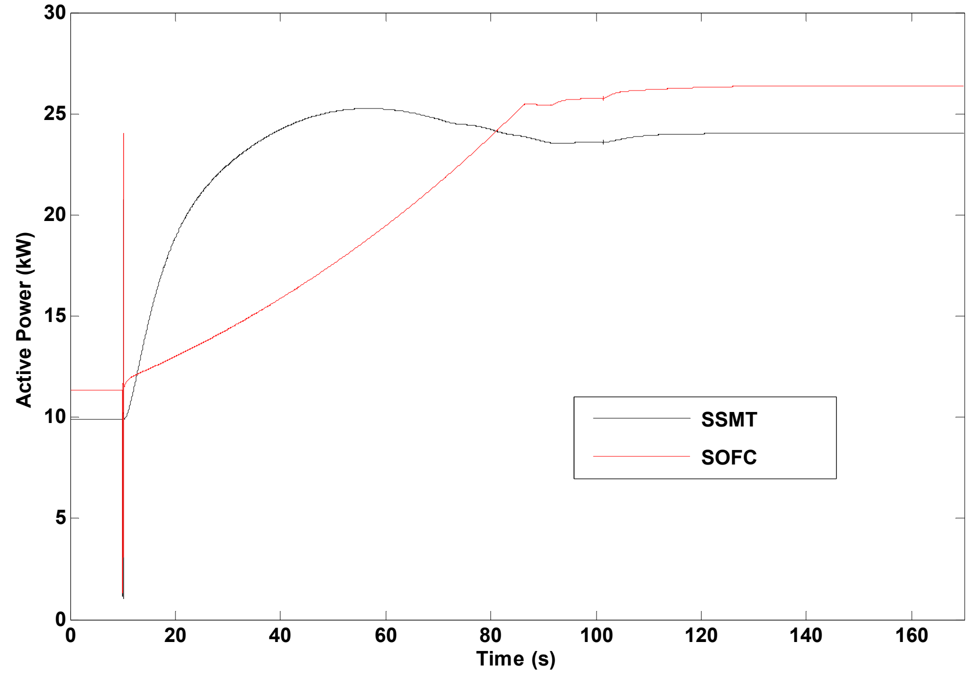

Figure 9: Active power in the MS selected for load-frequency control

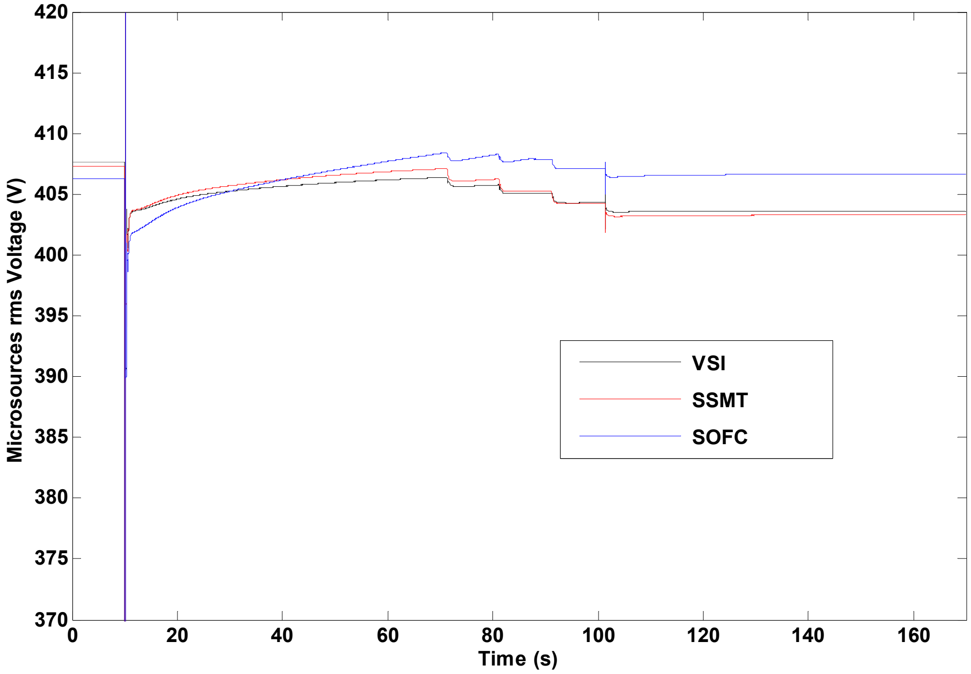

Figure 10: MS terminal voltages (long term behaviour)

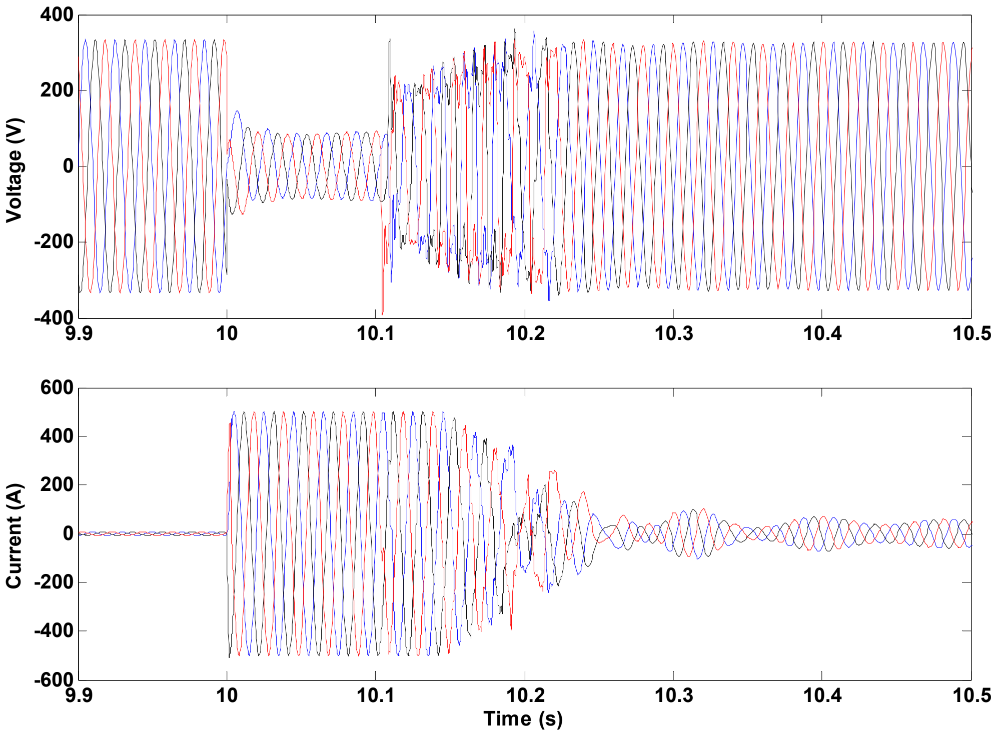

Figure 11: Detail of the VSI terminal voltage and output current during and subsequent to the fault in the MV network

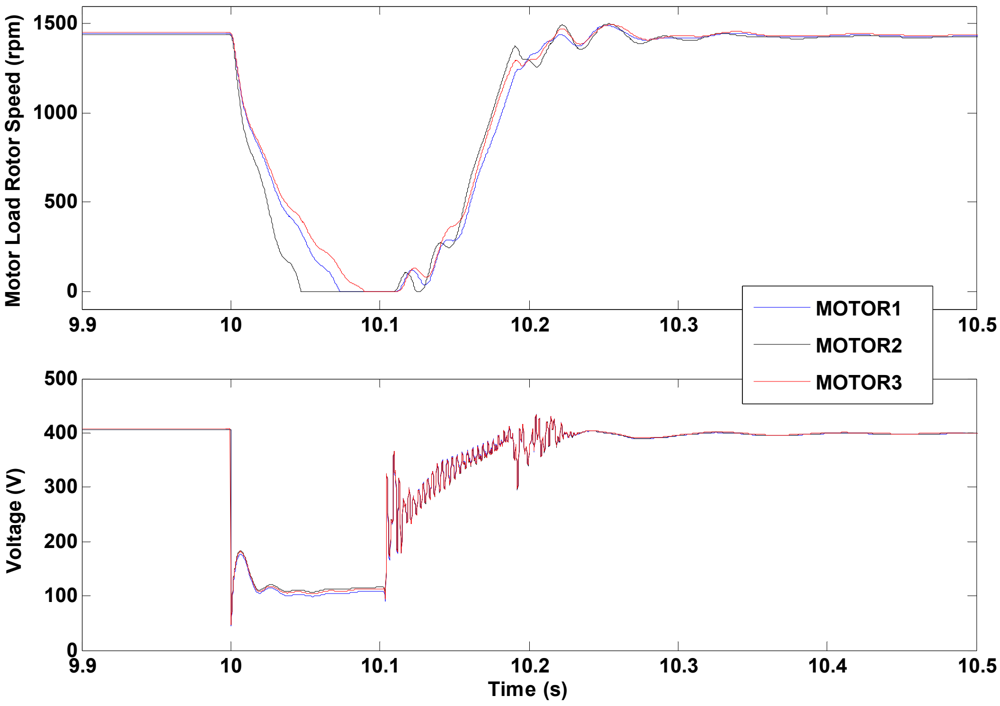

Figure 12: Detail of motor loads rotation speed and terminal voltages during and subsequent to the fault in the MV network

7.1.2. Scenario Urban_2

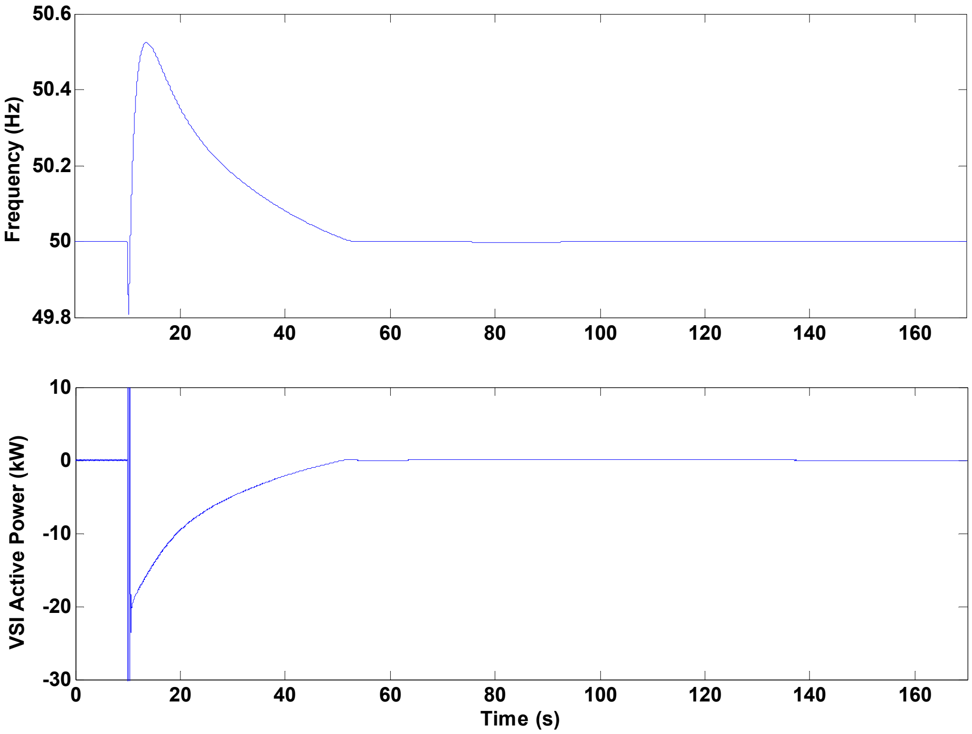

Figure13: MG frequency and VSI active power

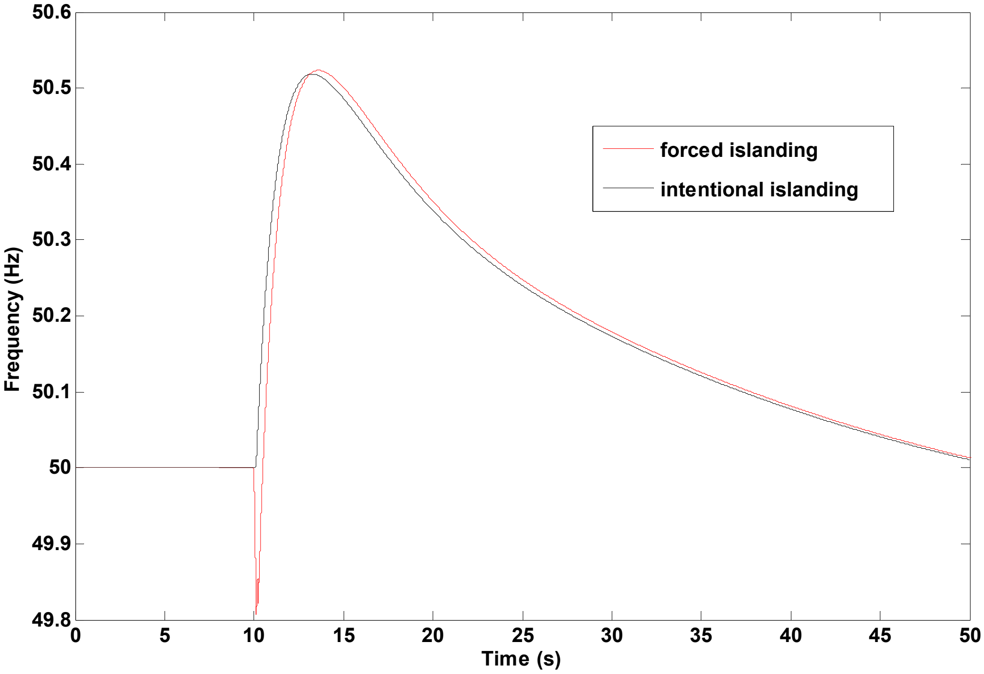

Figure 14: MG frequency for a forced and intentional islanding

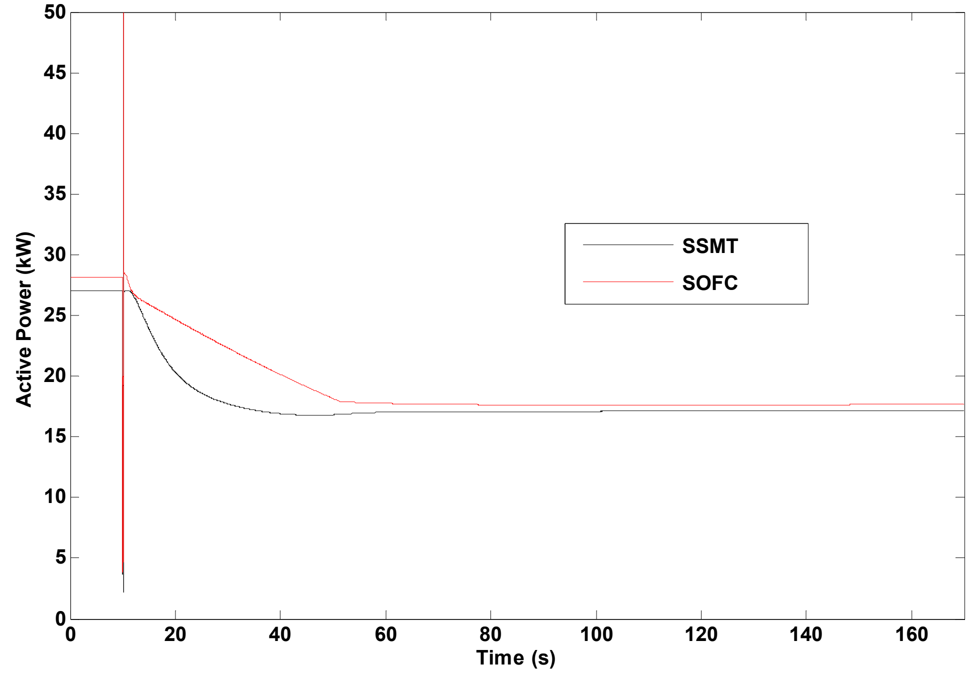

Figure 15: Active power in the MS selected for load-frequency control

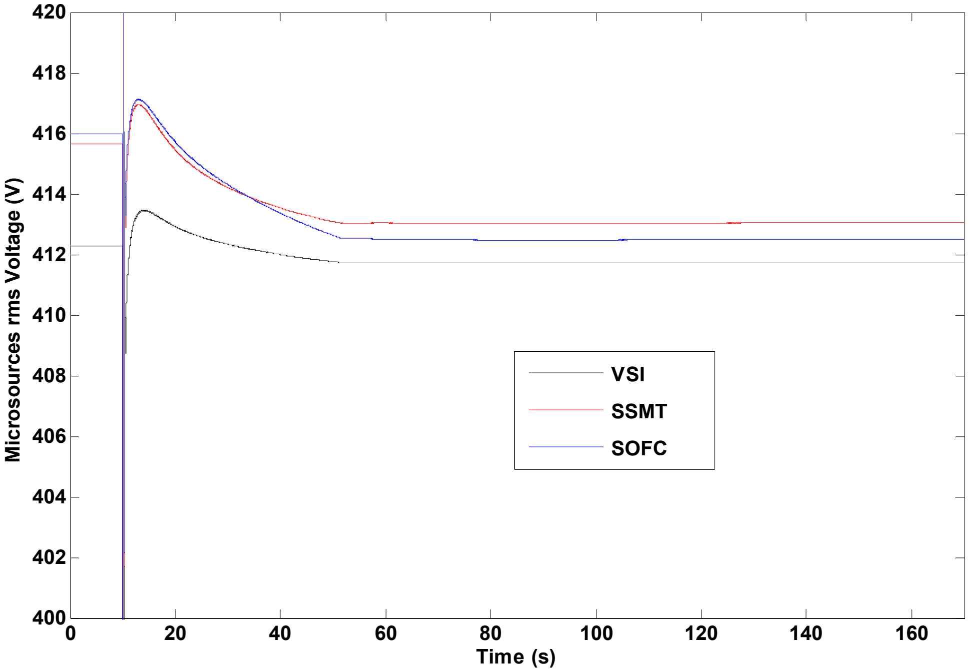

Figure 16: MS terminal voltages (long term behaviour)

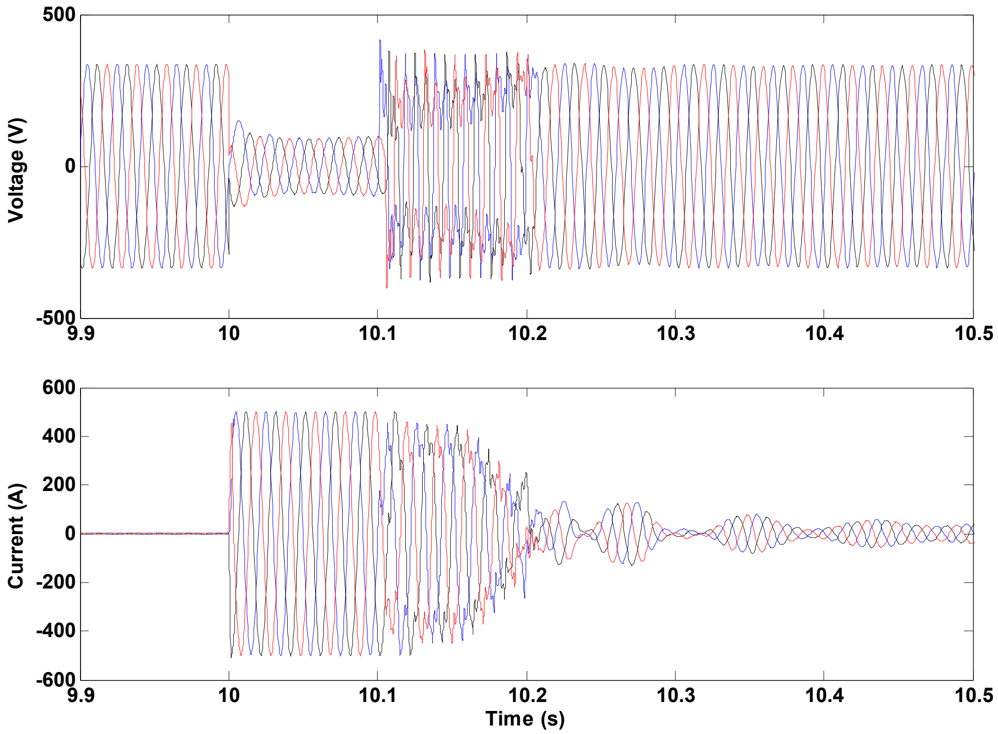

Figure 17: Detail of the VSI terminal voltage and output current during and subsequent to the fault in the MV network

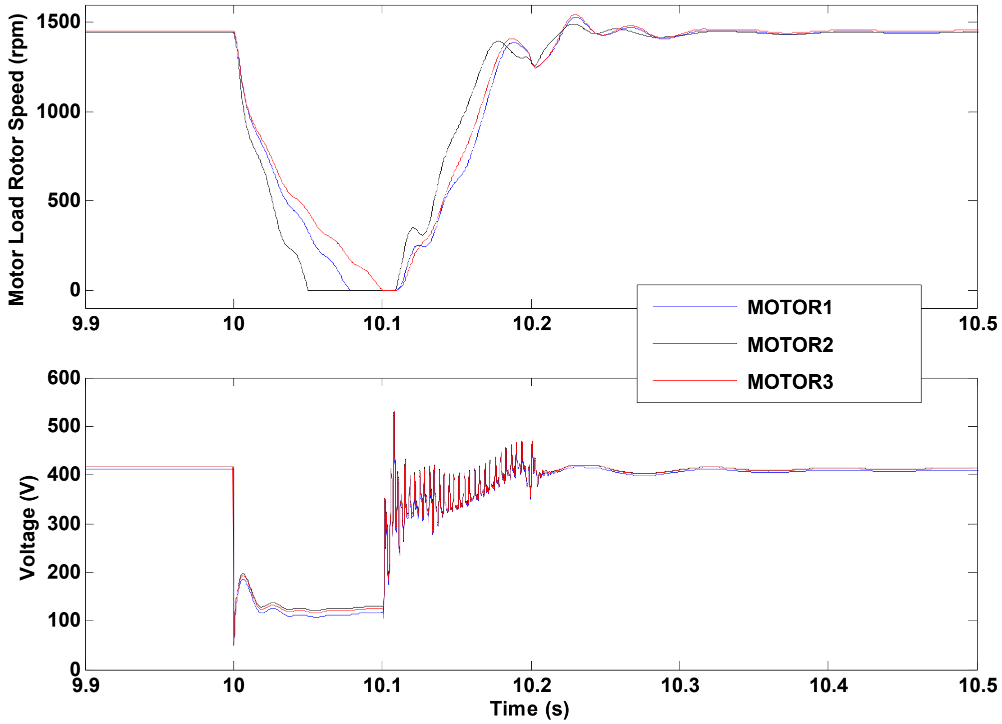

Figure 18: Detail of motor loads rotation speed and terminal voltages during and subsequent to the fault in the MV network

7.1.3. Scenario Rural_1

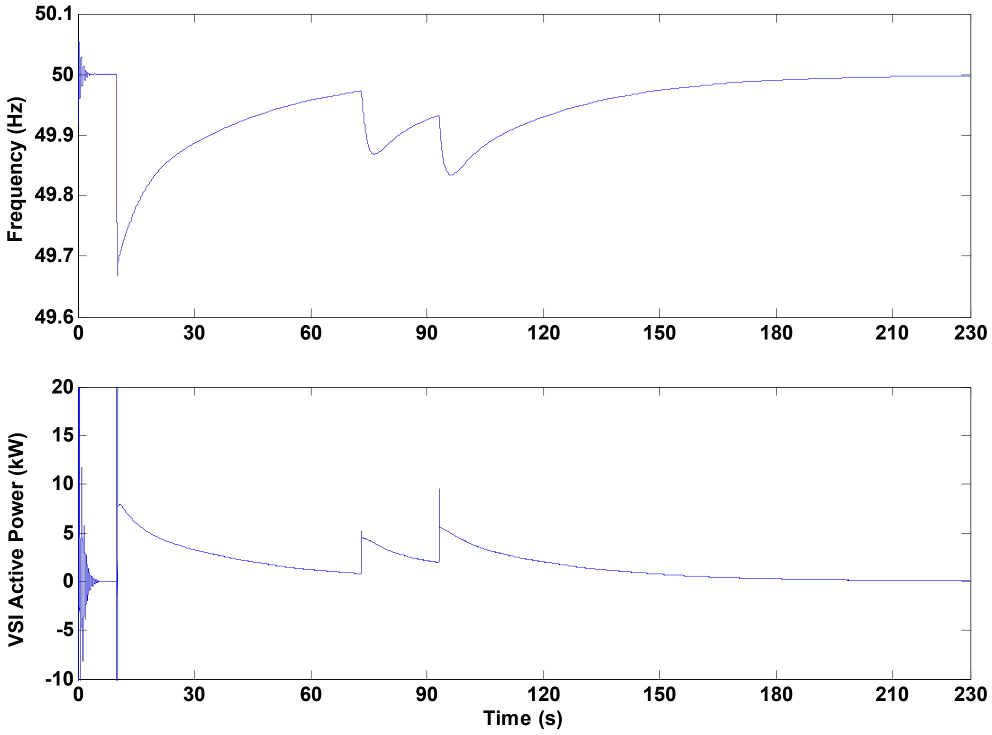

Figure 19: MG frequency and VSI active power

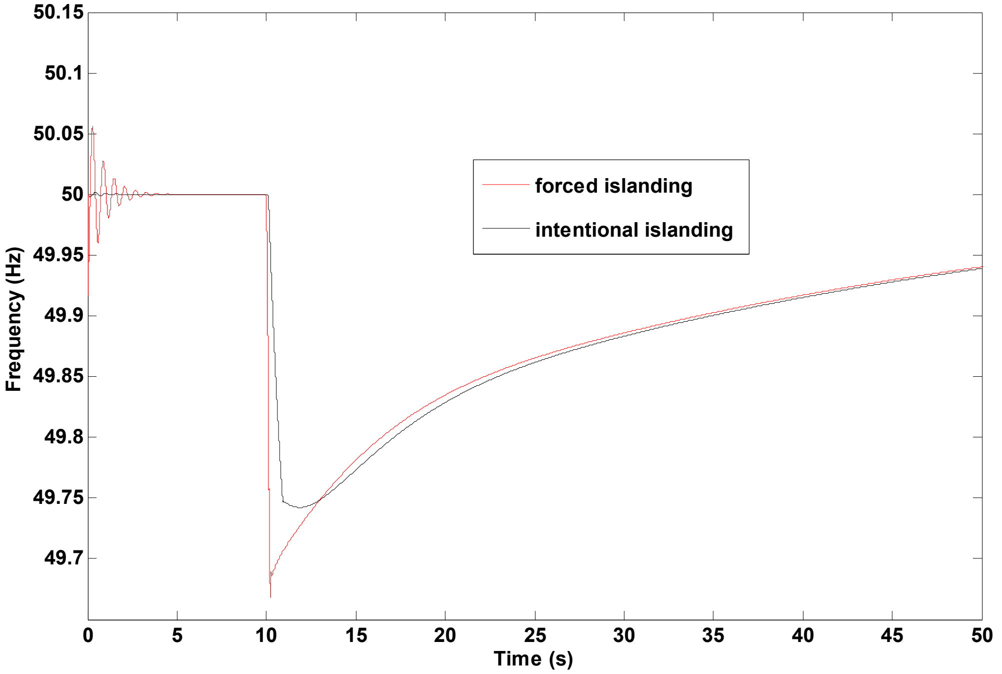

Figure 20: MG frequency for a forced and intentional islanding

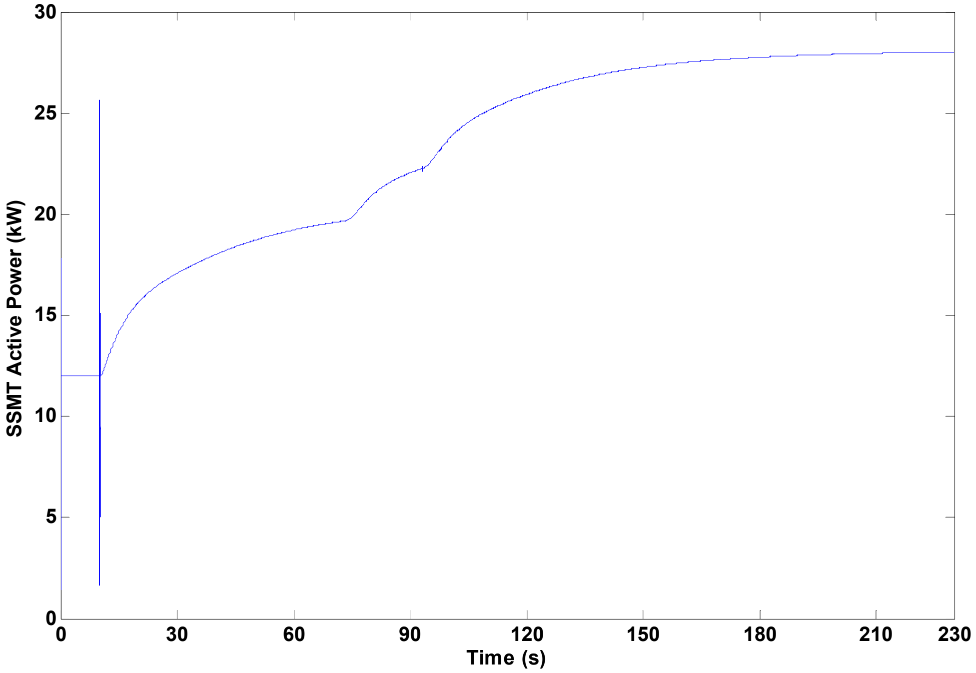

Figure 21: Active power in the SSMT (used for load-frequency control in the islanded MG)

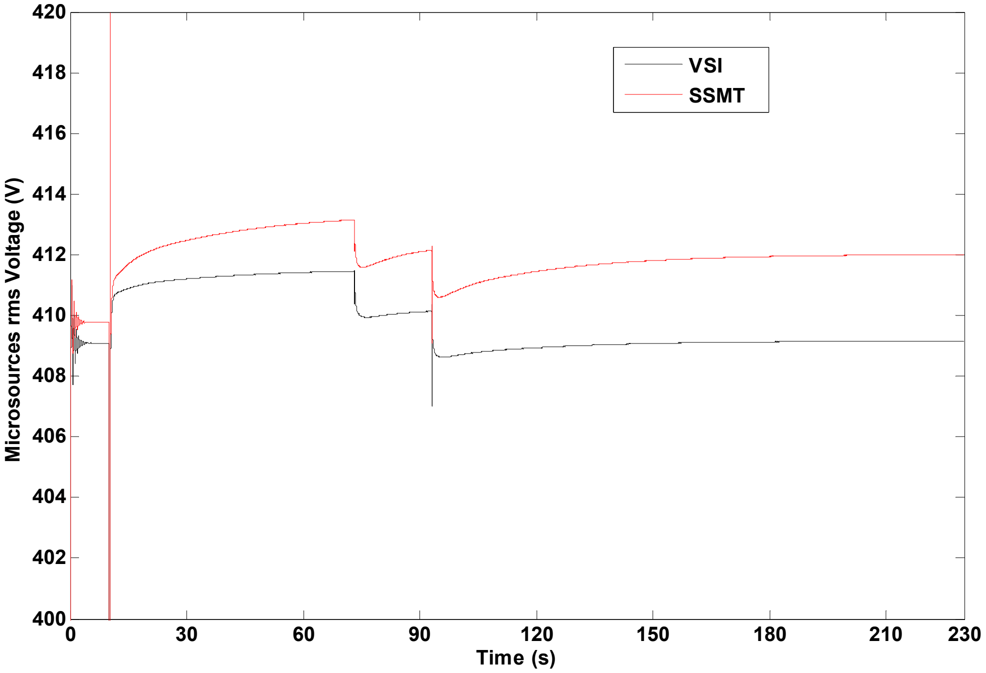

Figure 22: MS terminal voltages (long term behaviour)

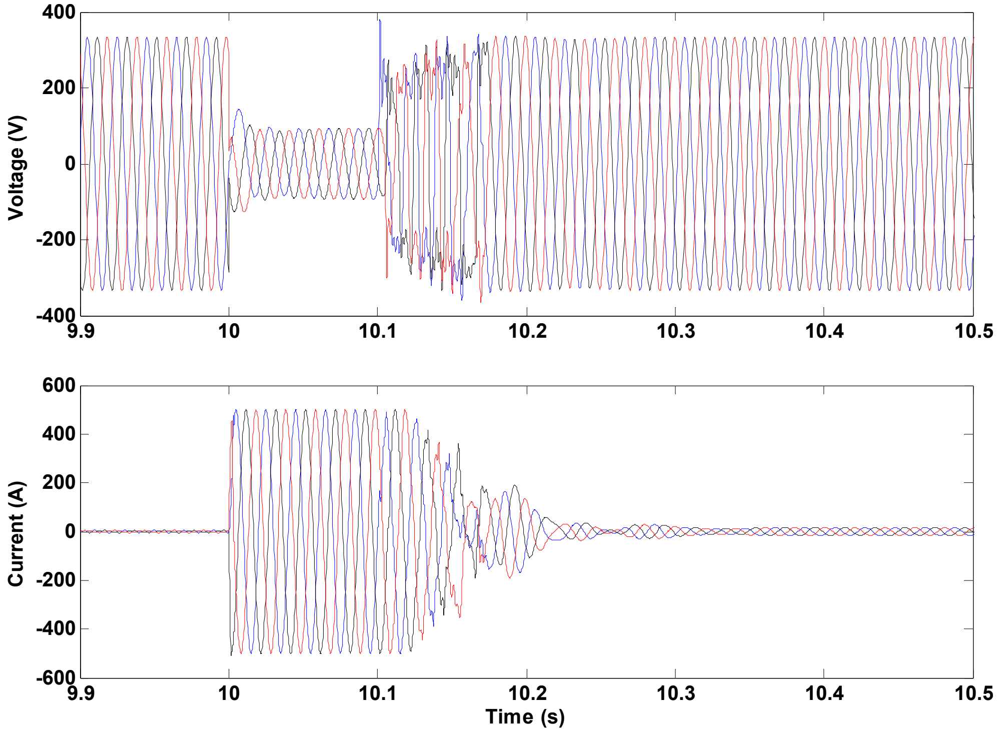

Figure 23: Detail of the VSI terminal voltage and output current during and subsequent to the fault in the MV network

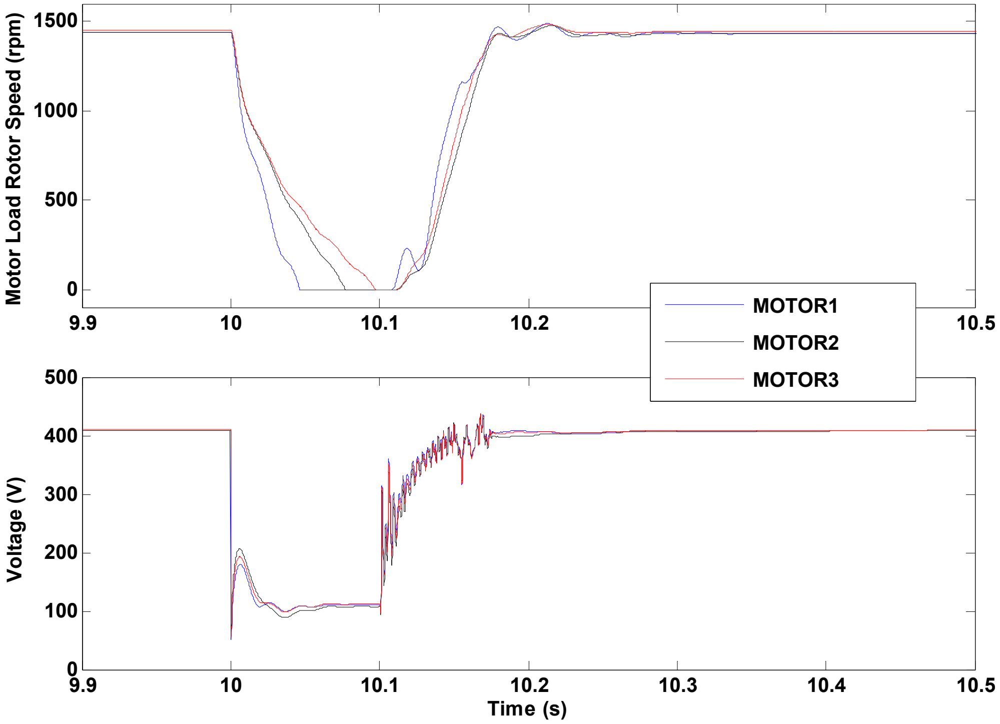

Figure 24: Detail of motor loads rotation speed and terminal voltages during and subsequent to the fault in the MV network

7.1.4. Scenario Rural_2

This scenario is characterized by importing 57% of the active power consumed in the MG. Although this scenario is quite demanding for islanding tests, no stability problems were identified, as can be seen in the results presented next. The results shown are intended to highlight the poorer load-frequency regulation capabilities of such a MG and the need of more restrictive load-shedding policies. In fact, only one MS (a SSMT) is used for secondary load-frequency control. In order to illustrate this important aspect, a comparison between MG frequency in two situations is presented (**Figure 26**): one corresponds to a scenario where load shedding mechanisms are not available in the MG and the other one corresponds to a scenario where load shedding mechanisms are activated after islanding and 40% of MG load is disconnected and its reconnection was not allowed due to the reduced load-following capabilities of the islanded MG. Concerning voltage and motor loads dynamic behaviour, the results obtained are very similar to those already presented.

It must be stressed that, in either of the two scenarios presented (**Rural_1** and **Rural_2**), the stability of the MG is guaranteed only by the action of the main storage device combined with the VSI. Hence, the main preoccupation should be not to lose the VSI, since it would definitely endanger MG operation in islanded mode. In cases where the load/generation imbalance is high, the stability of the MG may be jeopardized if the only controllable microsource is operating near its technical limits, and considering the limited capacity of the storage device. In such situations, an alternative mean of leveling generation and consumption must be envisaged in order to preserve stability. In this case, load shedding is the only solution to balance generation and consumption. This may be done using a centralized scheme for an emergency load shedding action, to be embedded in the MGCC.

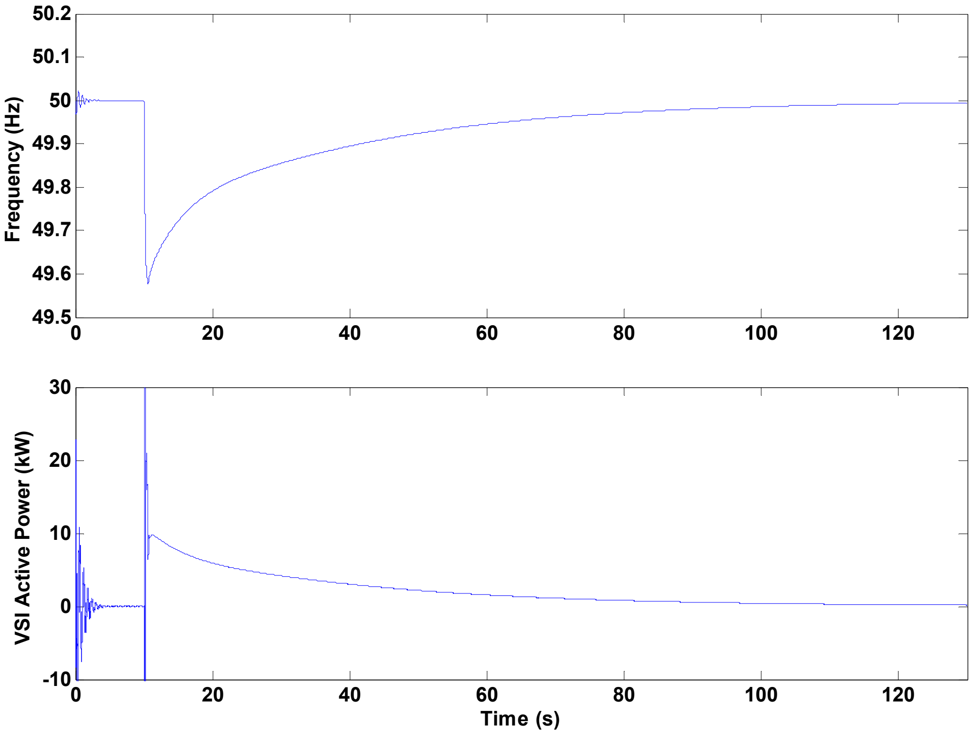

Figure 25: MG frequency and VSI active power (load-shedding mechanisms activated)

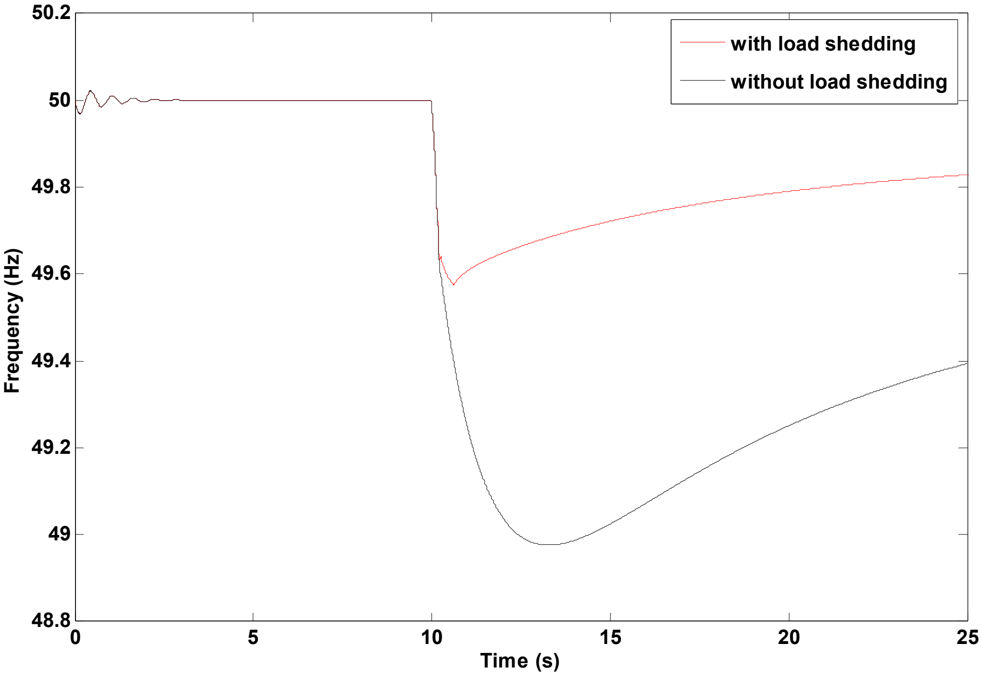

Figure 26: Detail of the MG frequency in a forced islanding with and without load shedding mechanisms

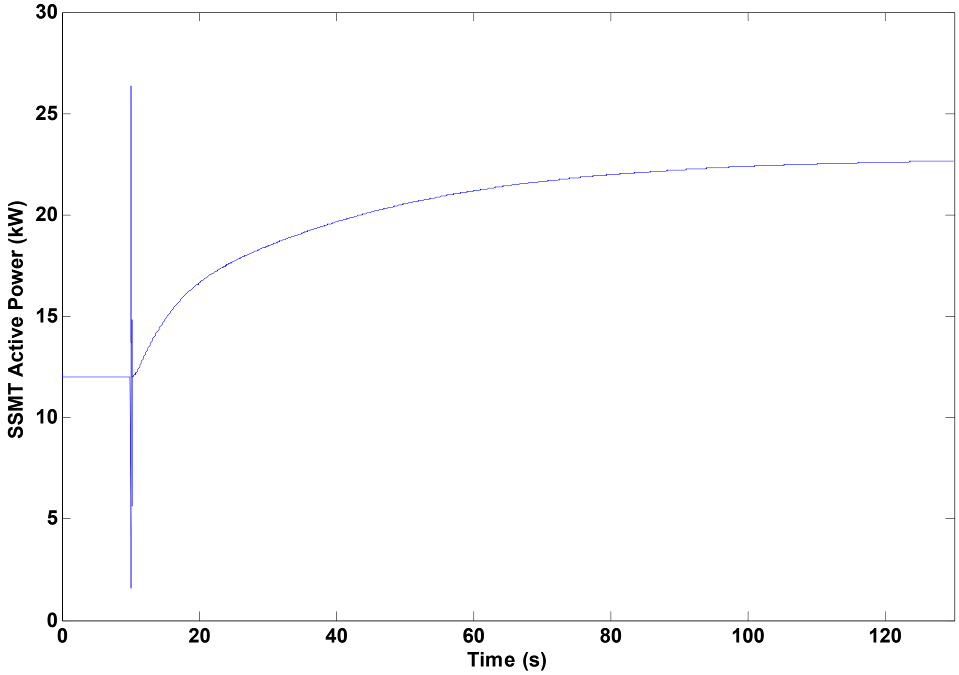

Figure 27: Active power in the SSMT (used for load-frequency control in the islanded MG)

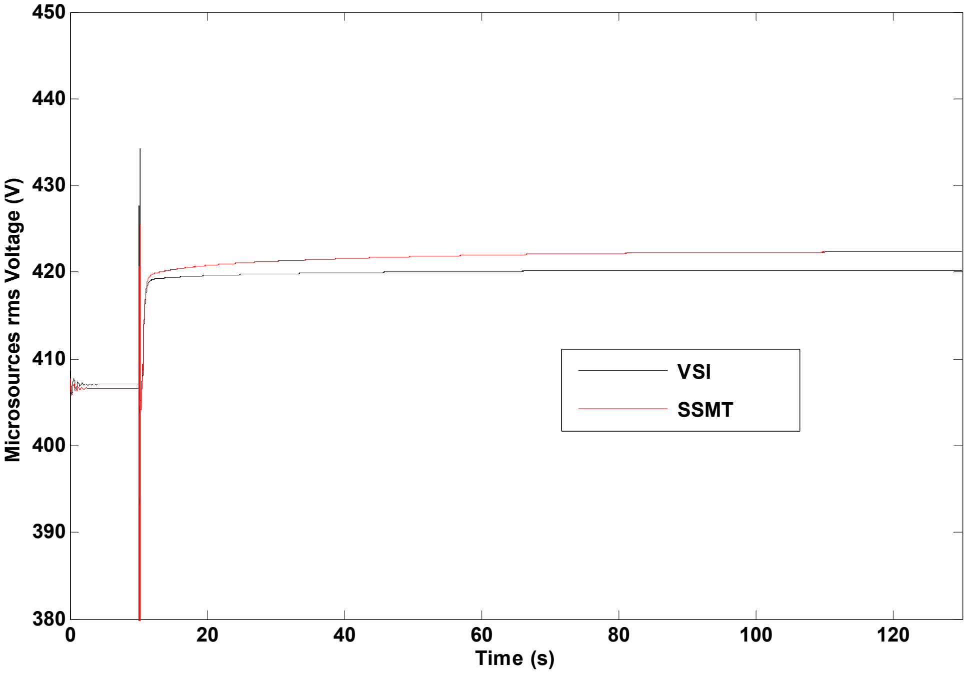

Figure 28: MS terminal voltages (long term behaviour)

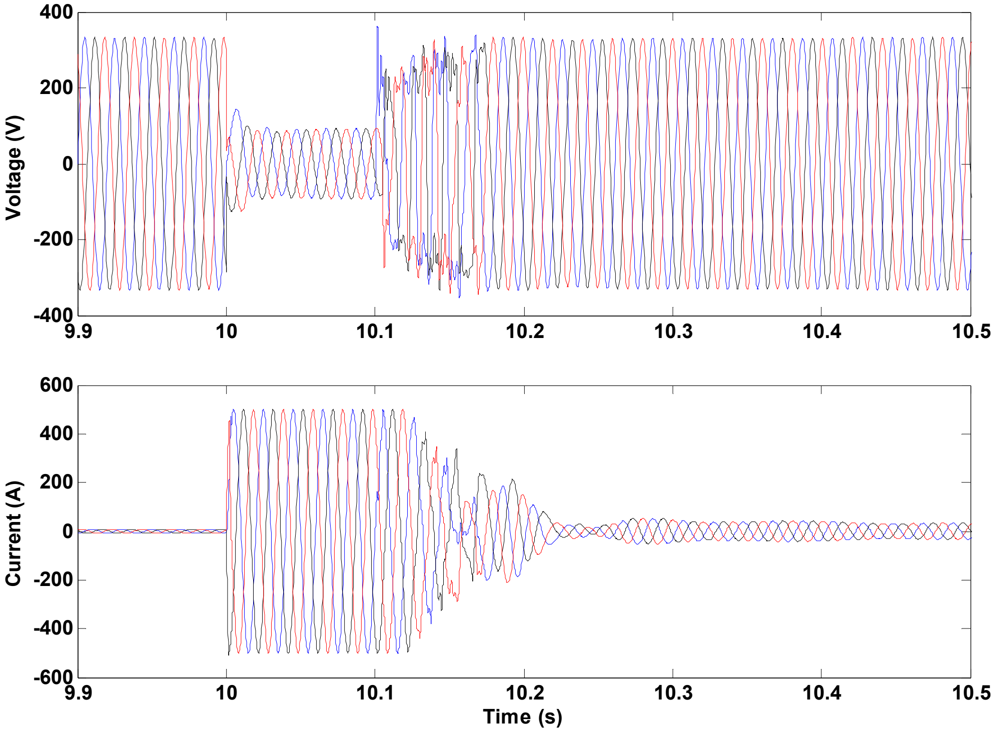

Figure 29: Detail of the VSI terminal voltage and output current during and subsequent to the fault in the MV network

7.1.5. Results Discussion

Disconnection from the upstream MV network and load-following in islanded operation was simulated using a SMO control strategy in order to evaluate the effectiveness of the control approaches presented. MG islanding was investigated for two different situations: intentional islanding and forced islanding (after a fault in the MV network). For an intentional islanding, the local generation profile of the MG may be modified in order to reduce a possible imbalance between local load and generation and smoothly move to islanded operation. However, this is not done because the aim is to evaluate and compare the impact of two factors in the MG dynamic behaviour: the fault and the imbalance between load and generation in the MG. Consequently, for the intentional islanding, there was an initial imbalance between local load and generation before the disconnection of the MV grid in order to highlight its impact in the MG dynamic behaviour.

Figures 7, **13**, **19** and **25** illustrate the long term behaviour of the MG frequency after islanding for the defined scenarios. When the MG is importing power from the main power supply (**Figures 7**, **19** and **25**) a large initial frequency deviation is experienced and an amount of load is automatically shed through the activation of under load frequency (ULF) relays in order to aid frequency restoration. This load is later reconnected in small load steps, to avoid new ULF relay operation (**Figures 7** and **19)**. Load reconnection in steps allows afterwards the success of the MG operation under load-following conditions, confirming the adequacy of the approach described in DD1 [1]. When the MG is exporting power to the main power grid, the initial frequency deviation observed (**Figure 13**) is due to the contributions of the MG to the fault. However, the MGCC should disable ULF because after fault elimination this may lead to even more pronounced overshoots in MG frequency.

By comparing MG frequency for forced and intentional islanding (**Figures 8**, **14** and **20**), no significant differences can be observed. So, the main problem to face when moving to islanded operation is the imbalance between local load and generation. The main influence on the dynamic behaviour is the time constants associated with the VSI control. Due to the adopted inverter control strategies, the critical problem results from the evaluation of an adequate combination of a load shedding strategy with the capacity of the storage devices. A more detailed evaluation on the influence of fault clearing times in MG stability should be carried out, but is out of the scope of this report.

The MS selected for load-frequency control participate in frequency restoration using the proportional integral control strategy described in section 4 (**Figures 9**, **15**, **21** and **27**). The large time constants of the MS lead to a relatively slow process for restoring frequency to its nominal value. Primary frequency control is performed by the storage device and its power electronic interface (the VSI). The storage device is responsible for matching local load and generation during this process. Its contribution in terms of active power injected in the MG and its evolution according to the MG frequency can be observed in **Figures 7**, **13**, **19** and **25)**.

Primary voltage control in the islanded MG is performed by the droop control installed in the VSI. The other MS are operating with fixed reactive power output, but they can receive settings locally or from the MGCC in order to optimize the reactive power dispatch in the islanded MG. The voltage control strategy used ensures MG stability and no reactive power oscillations are observed among the MS.

Several small motor loads are considered to spread in the MG. Due to the fault in the upstream MV network, motor loads terminal voltage drops considerably leading to a reduction of its electrical toque and to motor stalling (**Figures 12**, **18** and **24**). Also, induction generators affect the transient behaviour in this situation. The reacceleration of motor loads leads to a relatively slow ramping up of the voltage after fault clearing. As can be observed in **Figures 11**, **17**, **23** and **29**, motor loads and asynchronous generators absorb high currents, which lead to the activation of the short-circuit current limitation function in the VSI and to a more pronounced reacceleration process. The electrical data for the used motor loads is available in the *MatLab®/Simulink® SimPowerSystems* toolbox. Motor loads are considered to be operating at full load conditions. Depicting motor loads steady state torque characteristic, it is possible to observe that their start-up electromagnetic torque is higher than the nominal load (**Figure 30**), allowing motor reacceleration after fault clearance. In this case, the critical issue for motor loads reacceleration is the current carrying capability of VSI. If this device can not provide enough reactive power for motor reacceleration, special policies like under voltage load shedding must be evaluated carefully in order to preserve MG stability.

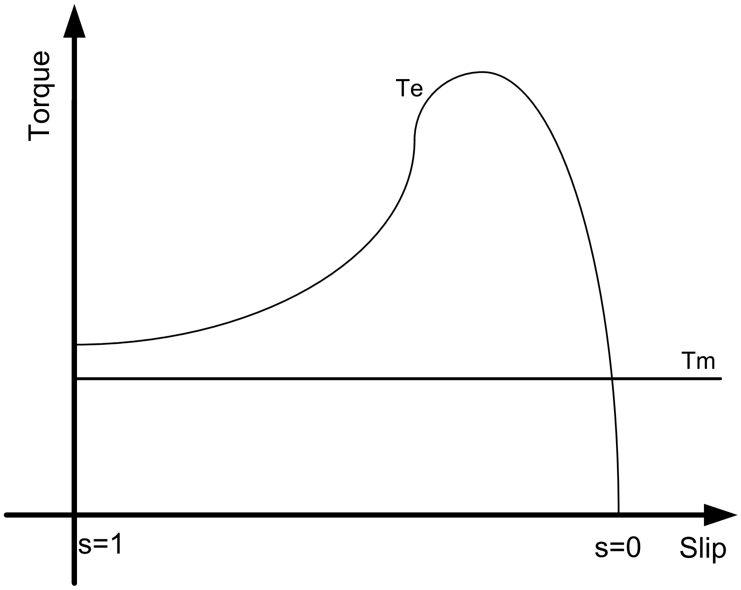

Figure 30: Speed-Torque characteristic of the motor loads used

Simulation results obtained for the scenario **Rural_2** highlight the importance of MS with load following capabilities. LV distribution networks will be more propitious to the penetration of renewable energy sources such as photovoltaic generators and small wind turbines. The uncertainty associated with these primary energy resources and the relatively reduced capability or even the absence of controllable MS for load-frequency control carries additional difficulties for MG load following control during islanded operation. This means that after the initial period following islanding, where the VSI is able to balance generation and consumption, a load shedding scheme need to be used. On the other hand, urban LV distribution systems will have more controllable MS (like microturbines and fuel cells) that can be used for load-following, creating favourable conditions for a more robust islanded operation.

7.2. MicroGrid Black Start

It was assumed that a general collapse took place in the urban LV test system shown in **Figure 5** (operating in the scenario defined as **Urban_1**). The general blackout was followed by:

- disconnection from the MV grid of the MV/LV transformer;
- disconnection of some of the loads;
- automatic formation 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 in order to evaluate the feasibility of restoring as much load as possible. As stated before, a multi master approach is more suitable for the initial moments of the BS procedure, but should be changed to a single master operation in the later stages of the BS procedure. In this way, the feasibility of operating an islanded MG using a multi master approach is also tested.

In this section the results and a simple methodology to reconnect the islanded MG with the upstream MV network are also presented.

The first action to build the LV network is the energization of the LV cables and the DT from 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 implemented by using a ramping voltage control from zero to its nominal value during 0,5s. The output current of the storage device inverter is shown in **Figure 31** for the simulation time. As can be observed, the energization current does not show any transient peak and is perfectly controlled and limited throughout the energization process.

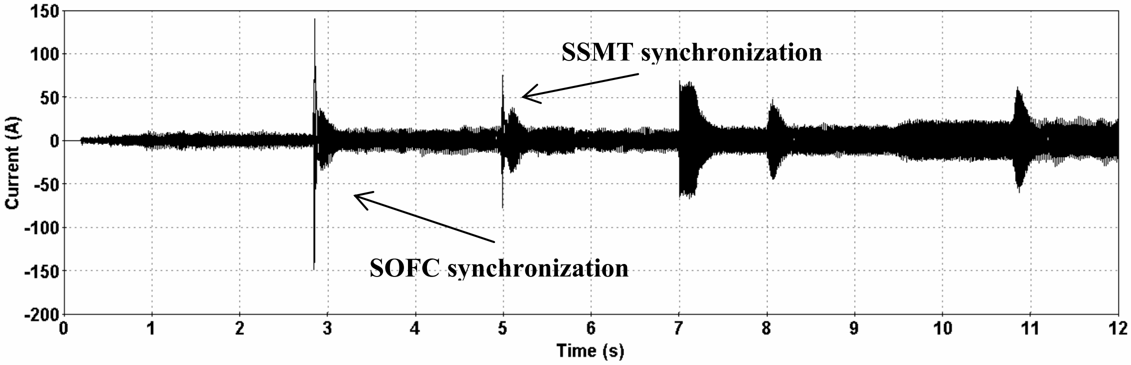

Figure 31: Output current of the storage device inverter

As previously mentioned, 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, these MS are operating in standalone mode and feeding their protected loads). In order 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 can be seen in **Figure 32** (at t=1.3s and t=3.9s). After synchronizing the SOFC and the SSMT some controllable loads and non-controllable MS are connected. **Figure 32** and **33** show the impact of these control actions in the VSI frequencies and on active power outputs, with SOFC and SSMT being synchronized at t=2,85s and t=4,95s respectively. A motor load is started-up at t=7s and a frequency adjustment occurs at t=8s; at t=9.5s a load is connected and another frequency adjustment occurs at t=10.8s.

It can be observed in **Figure 33** 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. These oscillations are not uncommon in power systems and can be damped by the inverters, given sufficient inverter bandwidth [6].

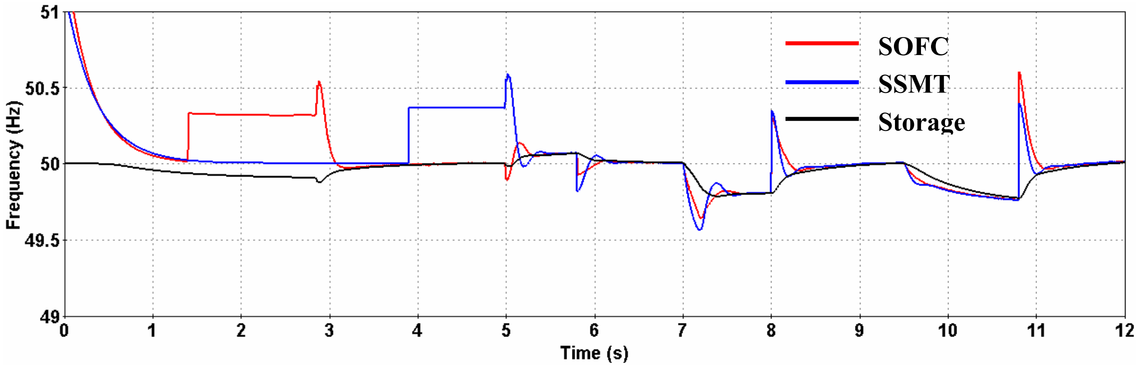

Figure 32: Frequency in each VSI

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 MS terminal voltages are shown in next figures. The simulation starts considering that the LV cables and the distribution transformer are energized and the protected loads of the SOFC and SSMT are connected. The sequence of actions involves:

- Synchronizing the SOFC with the LV network (t=13.2s);
- Synchronizing the SSMT with the LV network (t=42.2s);
- Starting-up of a motor load (t=70s);
- Connecting the PV (t=100s);
- Connecting controllable loads (t=130s);
- Connecting controllable loads (t=160s);
- Starting-up of a motor load (t=190s);

- Changing the SOFC and SSMT inverters to PQ control (t=222s and t=225s respectively);
- Synchronizing with the MV network (t=239.1s).

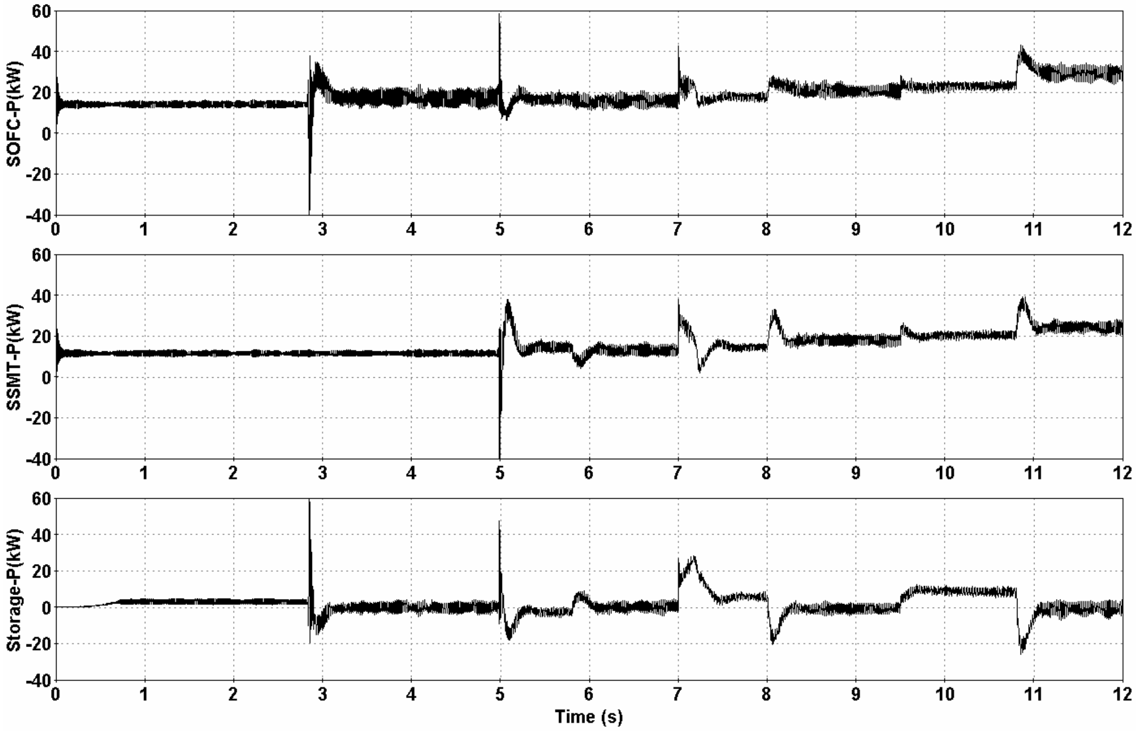

Figure 33: Active power in each VSI

Figures 34 and **35** 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 previously mentioned. If a frequency deviation remains for some time, a local secondary control is used to correct it. This can be observed in **Figure 34**. 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, as previously stated in section 4.

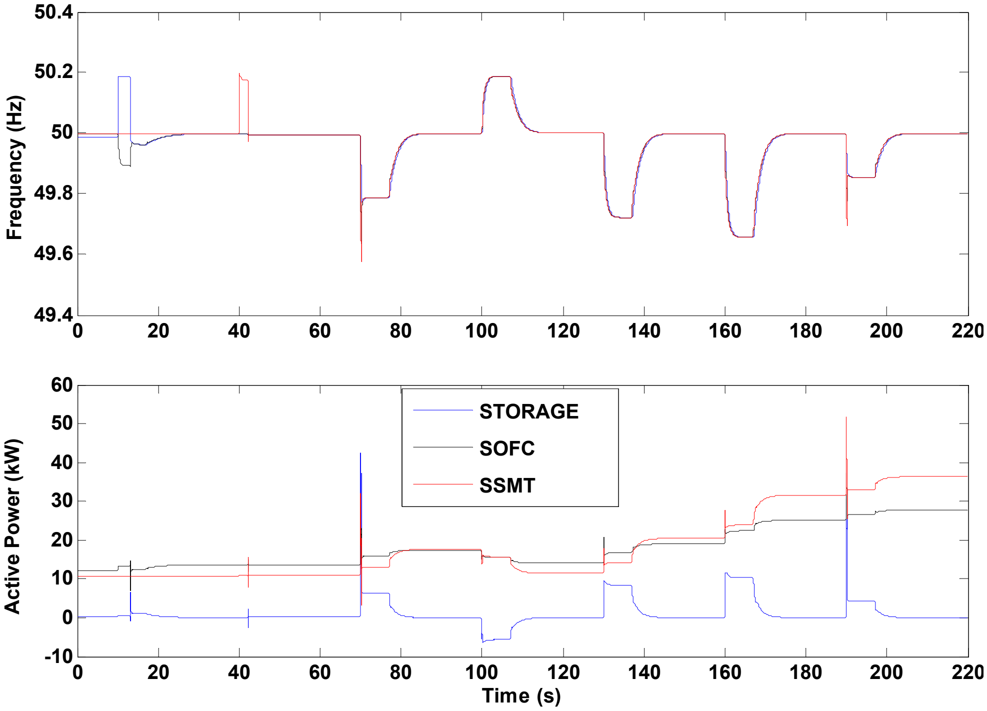

Figure 34: Inverters frequency and active power during the first stages of the BS procedure

For VSI synchronization purposes, the necessary conditions are checked carefully. This requires correcting the voltage magnitude and phase angle (frequency) of the VSI (**Figures 34** and **35**). A detail of storage device and SOFC inverters current during and in the moments subsequent to the connection of the SOFC inverter to the LV grid is shown in **Figure 36**. The transient current resulting from the synchronization is quite reduced and its impact 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 (**Figure 34**). 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=13.2s the storage device idle frequency is set to the nominal value (50 Hz). Therefore active and reactive powers return to the values they had prior to synchronization (**Figures 34** and **35**).

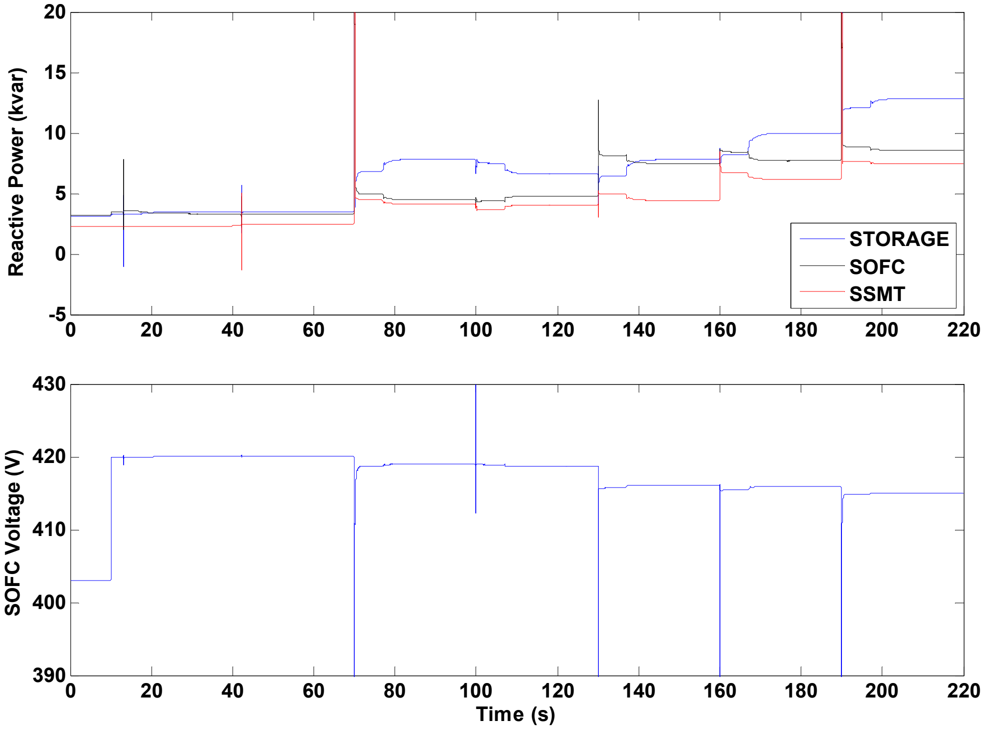

Figure 35: Inverters reactive power and SOFC node voltage during the first stages of the BS procedure

A detail of the impact resulting from the start-up of a 10 kW motor load can be observed in **Figure 37** in terms of inverters terminal voltages and output currents. Although starting-up from the stall position, the effect on the system is not a critical issue due to the inverter voltage control strategy. Comparing with the MG behaviour during and subsequent to the islanding process after a fault in the MV network, the effect is much less pronounced because the motor is starting-up using a MMO scheme, which has several advantages on voltage control. As can be observed, motor load acceleration is processed without significant impact on the MG voltage.

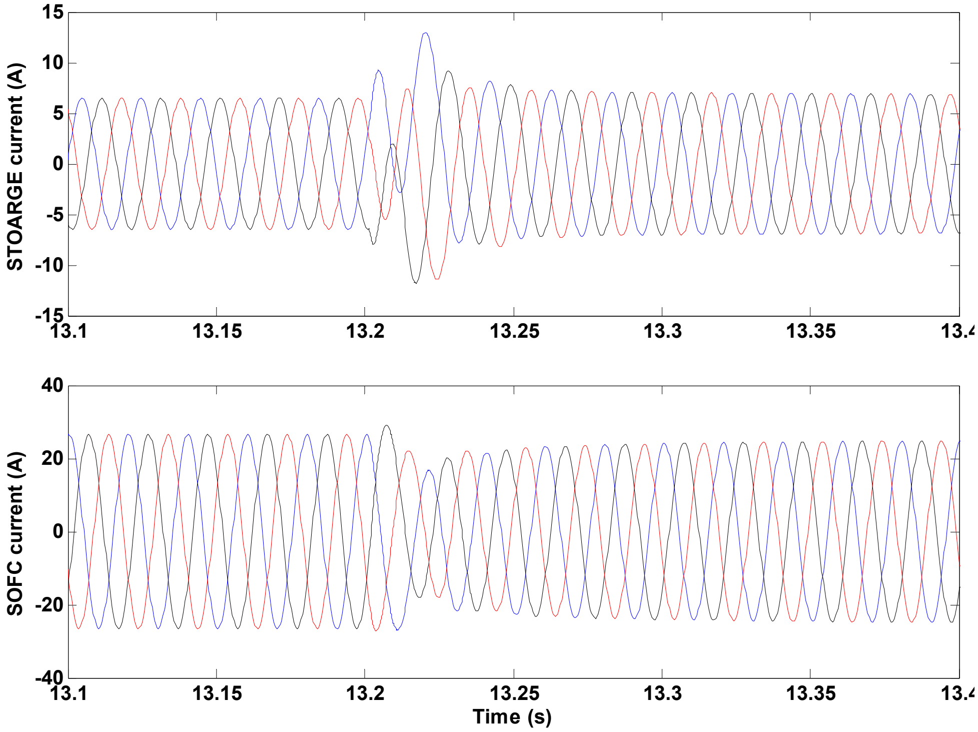

Figure 36: Storage and SOFC Inverter current during the synchronization procedure

The MG long term dynamic behaviour was studied using a voltage droop control scheme in all MS with BS capability. Only small adjustments in the idle voltage of inverters are performed in order to minimize the errors in the voltage magnitude before the synchronization. The results show 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 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 VSI overload may occur.

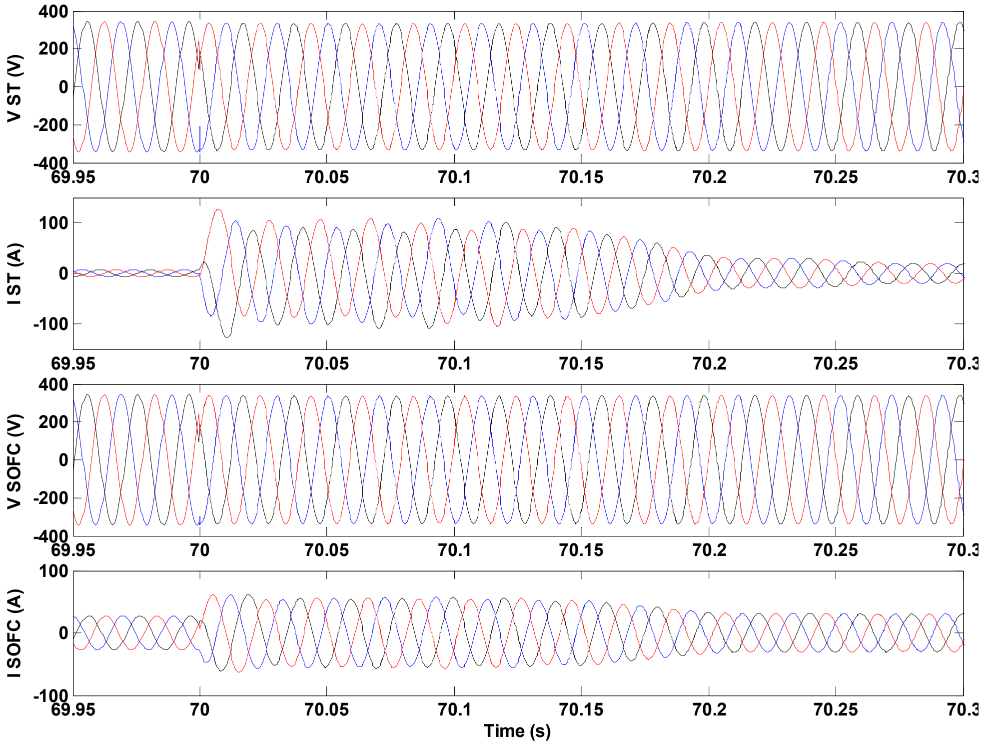

Figure 37: Impact of a motor load start-up in the storage device and SOFC inverters

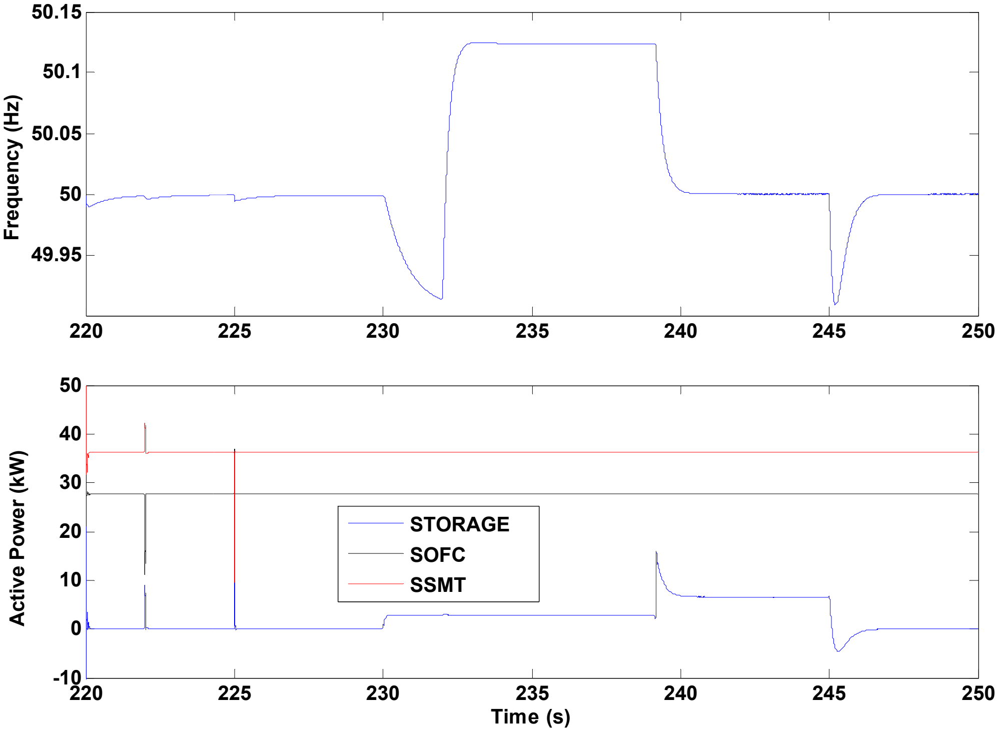

Figure 38: MG frequency and MS active power in the final stages of the BS procedure

After connecting the most important loads, the control scheme of the SSMT and SOFC inverters is changed from VSI to PQ, as explained in section 5. It is possible to observe in **Figures 38** and **39** that changing the control mode has no significant impact on the output power of each MS, since the power levels in the MS are maintained (the control mode of the SOFC and SSMT inverters are changed at t=222s and t=225s, respectively).

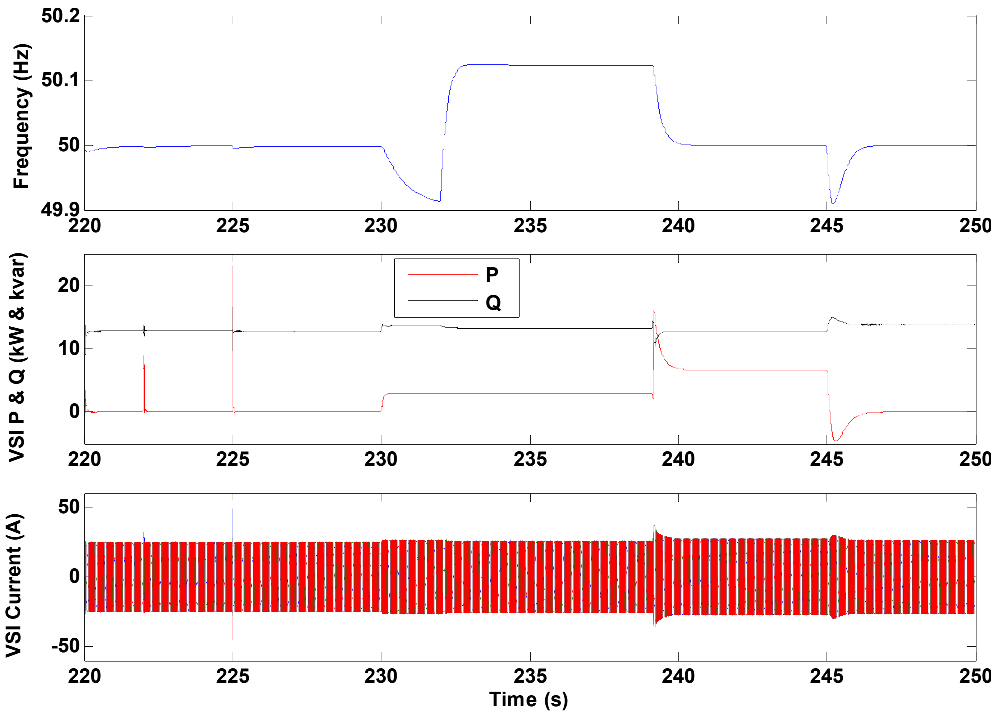

Figure 39: VSI frequency, active and reactive powers in the final stages of the BS procedure

When the MV network becomes available, the MGCC will initiate the sequence of actions to connect the MV network. The storage device inverter will be responsible for introducing slight changes in MG frequency and voltage in order to check the synchronizations conditions. **Figures 38** and **39** show the details of the impact of synchronization on the VSI At t=230s, a voltage control action is applied to the VSI (voltage increase) in order to match voltage magnitudes in the MG and in the main power supply. At t=232s a slight frequency change is imposed and the synchronization conditions start to be checked. As can be observed in **Figure 39**, no significant changes occur in the power output of the inverter. However, the slight changes on voltage and frequency cause small active and reactive power variations in the inverters as can be observed in **Figure 39** at t=230s. This is mostly due to the effect of loads represented as constant impedances (where power consumption is dependent on both voltage and frequency).

The synchronization with the main power supply occurs at about t=239.2s and a transient current can be observed. At t=245s, the idle frequency of the VSI is restored to the value it had before this procedure started. Otherwise, the dispatch inside the MG would be significantly modified and active power would be injected by the storage device into the MV network. When synchronizing two VSI, the transient current observed (**Figure 36**) is damped quickly because of droop control implemented in both inverters. When synchronizing the MG with the MV network, the VSI is being synchronized with a fixed frequency voltage source, which has slow damping effects in the inverter output current (**Figure 39**).

8. Conclusions

The work carried out in for this task focused on the validation of the control strategies for MG islanded operation considering several operating conditions and disturbances, mainly when the MG becomes isolated after a fault in the MV network. Models for static converters were adjusted, which helped on the feasibility analysis of the proposed control strategies in fault conditions in a MG.

The proposed control strategies were tested in several scenarios, which proves the feasibility of MG intentional or forced islanding under different power importing and exporting conditions. The test systems and the different scenarios analysed do not reveal instability problems. However the results obtained highlight three key issues for MicroGrid islanded operation:

- The presence of storage devices coupled with static converters emulating the behaviour of a synchronous machine in order to provide primary load-frequency and voltage control in the islanded MG.
- The implementation of load-shedding mechanisms in order to avoid large frequency excursions and overload of storage devices, which have no significant thermal overload capabilities; these mechanisms are of great importance, especially in situations where there are few units providing regulation, in order not to use up all storage capacity available.
- The use of a convenient secondary load-frequency control to be installed in controllable MS, combined with load-shedding and a convenient storage device capacity is required in order to maintain the MG frequency within tight limits around 50 Hz during islanded operation.

The sizing of storage devices should be performed according to the specificities of the MG: several factors like the load shedding strategies, the availability of fully controllable MS for load following situations (secondary load-frequency control) need to be considered. These issues highlight the fundamental differences that can be found between the urban and the rural LV test systems analysed in this work. In urban LV distribution systems it is expected a high penetration of MS such as fuel cells and microturbines, which can be used for load- frequency control during islanded operation. Rural LV distribution systems will face high penetration levels of renewable sources without load-following capabilities, and high storage capabilities and more demanding load shedding strategies must be used to allow islanding in this kind of systems.

The inclusion of motor loads when studying the effectiveness of the control strategies after a fault in the MV network revealed the need of fast fault clearance; otherwise motor loads and induction generators may compromise the transition to islanded operation. The current carrying capabilities of VSI are a key issue to avoid losing a high percentage of induction generators in the MG and should be carefully evaluated. Under voltage load-shedding of large motor loads and induction generators could be an emergency solution to be used in some situations, namely those where direct motor restart after fault clearance is not possible.

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. In the initial stages of the restoration procedure, the MG was operated under a multi master approach and the results obtained prove the feasibility of this solution.

9. References

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