Defining Control Strategies for Analysing MicroGrids Islanded Operation

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***Abstract*—The main objective of this paper is to present the development of microsource modelling and the definition of control strategies to be adopted to evaluate the feasibility of operation of a microgrid when it becomes isolated. Normally, the microgrid operates in interconnected mode with the MV network, however scheduled or forced isolation can take place. In such conditions, the microgrid must have the ability to operate stably and autonomously. An evaluation of the need of storage devices and load-shedding strategies is included in the paper.**

***Index Terms*—Power system dynamic stability and control; Renewable energy sources and storage devices; Integration of distributed generation in the main grids.**

I. Introduction

THE need of reducing CO_2 emissions in the electricity generation field, recent technological developments in the microgeneration domain and electricity business restructuring are the main factors responsible for the growing interest in the use of microgeneration. In fact, the connection of small generation units – the microsources (MS), with power ratings less than a few tens of kilowatts – to Low Voltage (LV) networks potentially increases reliability to final consumers, brings additional benefits for global system operation and planning, namely regarding investment reduction for future grid reinforcement and expansion. In this context, a MicroGrid (MG) comprises a LV network (for example covering an urban area, a shopping-centre or even an industrial park), its loads and several small modular generation systems connected to it [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 and different types of fuel-cells, and also storage devices (such as flywheels or batteries).

The MG is intended to operate in two different operating conditions:

- Normal Interconnected Mode – the MG is connected to a main MV network, either being supplied by it or injecting some amount of power into the main system.
- Emergency Mode – the MG operates autonomously, in a similar way to physical islands, when the disconnection from the upstream MV network occurs.

It will not be common to find fully controllable synchronous units in a MG, which are normally responsible for voltage and frequency control in conventional power systems. The majority of MS to be installed in a MG are not suitable for direct connection to the electrical network due to the characteristics of the energy produced (DC power in fuel-cells and PV generators or high frequency AC power in microturbines). Therefore, a power electronic interface (DC/AC or AC/DC/AC) is required. For instance, in [2] a control scheme based on droop concepts to operate inverters feeding a standalone system is presented.

In this paper the droop concept for inverter control is further explored in different modes of operation. Two inverter control schemes are combined in order to demonstrate the feasibility of a seamless transition from Normal Interconnected Mode to Emergency Mode under specific conditions, as well as the possibility of stably operating a MG in islanded conditions. In order to achieve this goal, the potentialities of the *MatLab*® *Simulink*® environment and its libraries (mainly the *SimPowerSystems* toolbox) were employed in order to develop a simulation platform suitable for identifying MG control requirements and evaluating the MG dynamic behaviour under several conditions. Different MS technologies coexist and are operated together in the simulation platform. Controllable and non-controllable sources as well as the disconnection of non-essential loads are used in order to guarantee the continuity of electric supply in a LV area after scheduled or forced loss of the upstream MV network connection.

This research is being developed within the framework of an EU R&D project with the objective of studying the problems that challenge the integration of large amounts of different MS in LV grids and involves several institutions and companies [3].

II. MicroGrid Architecture

The control of the MG is based on a hierarchical control architecture in order to assure a robust operation [3]. Consequently, a MicroGrid Central Controller (MGCC) is installed at the LV side of a MV/LV substation managing in an upper level the MG operation through several crucial

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management functions, both technical and economical. At a second hierarchical level each MS and storage device is locally controlled by a Microsource Controller (MC) and each electrical load or group of loads is 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. A typical MG structure is shown in Fig. 1.

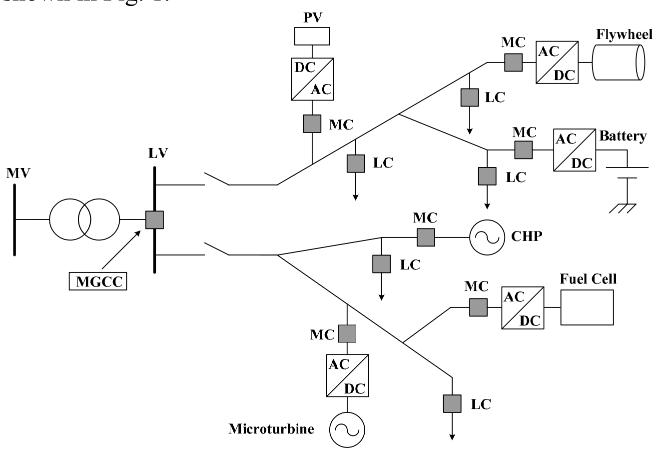

Fig. 1. MG control architecture

The interaction between the control devices is as follows: the MGCC promotes adequate technical and economical management policies and provides set-points to LC and MC. LC will act based on an interruptibility concept and MC are responsible for the control of the MS active and reactive power production levels.

It is important to understand that the amount of data to be exchanged between the several network controllers is small, as it includes mainly messages with set-points to LC and MC, as well as information requests sent by the MGCC to LC and MC about the active and reactive powers and voltage levels. Another important factor that eases the establishment of the communication infrastructure is the small geographical span of the MG.

The communications system can use either Power Line Communication, which presents some interesting characteristics for this type of network, or explore other type of access such as Wireless Communication (a rapid-growing technology).

III. Dynamic Models

The analysis of MG behaviour requires the development of a set of dynamic models able to simulate the response of the MG under several conditions. For this purpose, MS and storage devices, together with control systems, have been modelled.

Inverter modelling is an important issue, especially regarding operation control, thus deserving careful analysis and detailed implementation.

A. Microsource Modelling

The MS models developed within the project include photovoltaic arrays, wind generators, microturbines and a fuel-cells. Concerning storage devices, flywheel systems and batteries have also been modelled [4].

For illustration purposes only details on the dynamic model developed for the Solid Oxide Fuel-Cell (SOFC) are given next. The fuel-cell includes a Fuel Processor that converts the used fuel in Hydrogen, a Power Section, where chemical reactions take place, and a Power Conditioner that converts DC to AC power. The SOFC model adopted assumes several simplifications, such as: fuel gases are considered to be ideal, it is sufficient to define only one single pressure value in the interior of the electrodes, the temperature in the fuel-cell is presumed to be always stable, only ohmic losses are considered, assuming that the working conditions are far away from the upper and lower extreme values of current, and the Nernst equation is assumed to be applicable. The complete model can be seen in the block diagram in Fig. 2.

The state variables used to model the fuel-cell behaviour are the reaction current (I^r_{fc},) the hydrogen input flow (q^{in}_{H2}) and the partial pressure of the reaction components - p_{H2}, p_{O2} and p_{H2O} - respectively hydrogen, oxygen and water.

The full dynamic model description for the adopted SOFC can be found in [5] and [6].

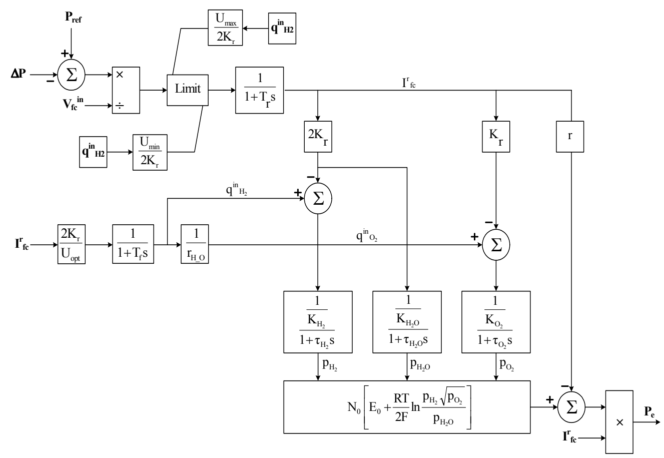

Fig. 2. SOFC block diagram model

A GAST dynamic model was adopted for the microturbines primary unit, since they are small simple-cycle gas turbines, [5]. Both high-speed single-shaft units, with a compressor and turbine mounted on the same shaft as the electrical synchronous machine, and split-shaft units using a power turbine rotating at 3000 rpm and a conventional induction generator connected via a gearbox, were modelled. The single shaft unit requires an AC/DC/AC converter to connect the unit to the grid. The wind generator is considered to be an induction machine directly connected to the network and represented by fifth-order model available in *MatLab® Simulink®*. Concerning the PV generator, it was assumed that the array is always working at its maximum power level for a given temperature and irradiance. It is basically an empirical model based on experimentation results as described in [7].

B. Storage Devices Modelling

Storage devices like flywheels and batteries are modelled as constant DC voltage sources (taking into account the time span under analysis) to be coupled with the electrical network by means of power electronic interfaces. They 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.

Grid interface of the storage devices is done using AC/DC/AC converters for flywheels and DC/AC inverters for batteries. Usually, the active power is injected into the MG using a proportional to frequency deviation control approach (with a specified droop), with the energy delivered to grid evaluated through the time integral of the active power injected by the storage device during the simulation time [4]. Due to the large time constants found in the responses of several MS, such as fuel-cells and microturbines, storage devices have to provide the amount of power required to balance the system.

C. Inverter Modelling

Usually, two kinds of control strategies may be used to operate an inverter. According to the control strategy followed, the corresponding model is derived. More details on these strategies can be found in [8]:

- 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.

It is also important to mention that when analyzing the 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.

1) PQ Inverter Control

This kind of control can be achieved using an inverter control scheme based on a current-controlled voltage source.

In [9] a method for computing single-phase active and reactive powers is presented. This method was adapted in this work 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 limited in the interval [-1, 1].

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 (Set Point = 0 in Fig. 3) or receive a set-point (locally or from a central controller) for the output reactive power.

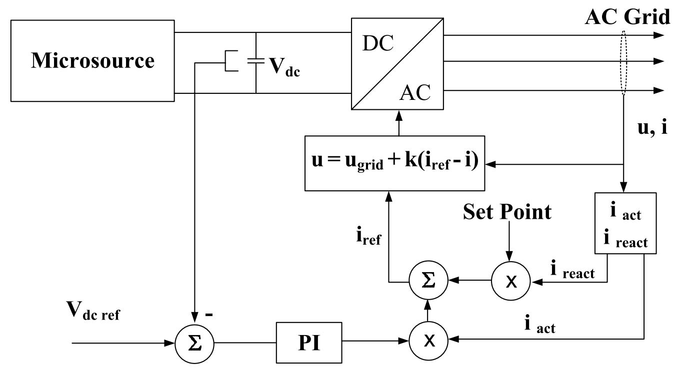

Fig. 3. PQ inverter control system

2) Voltage Source Inverter Control

In this case the frequency and voltage control concept used in a synchronous machine is transposed for the VSI control.

When a VSI is operating in parallel with a stiff AC system with angular frequency ω_{grid} (Fig. 4), the output power of the VSI is defined from the droop equation derived. In order to change the output power of the inverter, a change in the idle frequency (ω_0) is required. 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 [9]. Similar considerations can be made for the voltage/reactive power control.

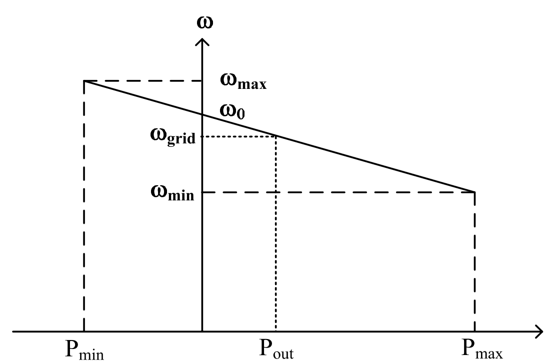

Fig. 4. Frequency / active power droop characteristic

A three-phase balanced model of a VSI including the droop concepts was derived from a single-phase version presented in [9] and is shown in Fig. 5.

VSI voltage and current are measured in order to calculate active and reactive powers, which are delayed for decoupling purposes and in order to emulate the behaviour of a synchronous machine. Frequency is determined by the delayed active power through the frequency/active power droop. Similarly, the voltage magnitude is determined by the delayed reactive power by using the reactive power/voltage droop. This control scheme allows the computation of the voltage reference signals to control the VSI switching sequence using a PWM technique.

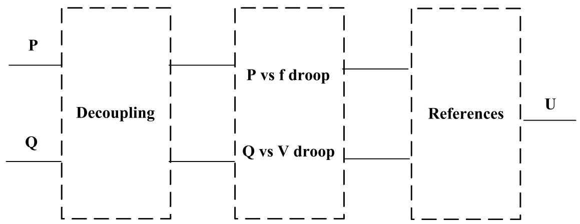

Fig. 5. VSI control system

3) *Inverter Behaviour During Short-Circuit Conditions*

Conventional power plants comprising synchronous machines directly connected to the network are able to provide large short-circuit currents, which are very helpful for a 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. According to the protection guidelines for a MG presented in [10], a protection scheme based on current (over current protection) will be a great concern due to the low short-circuit to load current ratios, during islanded operation. Power electronic 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. Based on these considerations, the short-circuit handling capability of a power electronic interface can be increased only by increasing its power rating.

Accordingly, the following considerations are made:

- The VSI was selected to be up-rated in order to provided a suitable contribution for short-circuit currents (ranging from 3 to 5 p.u.)
- PQ inverters can provide only a small amount of short circuit current (around 1.5 p.u.)

The PQ inverter control scheme permits the control over the output inverter current during short-circuit conditions. In case of a short-circuit, the voltage drop at the inverter terminals leads to a reduction of the active power output. As a consequence, the DC link voltage increases and the PI controller tries to increase the active output current of the inverter. 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 experimented.

Being a voltage source, the output current of a VSI tends to be very high (similarly to what happens in conventions synchronous machine). In order to limit its output current a control technique like the one presented in Fig. 3 is used. The main difference is that in this case the current reference has a maximum peak value dependent on switching devices characteristics and its frequency is imposed by inverter frequency/active power droop. The output current is continuously monitored, and if its value overcomes the maximum value, the control scheme is switched accordingly. When the fault is removed, the VSI returns to Voltage Control.

D. *Load Modelling*

The dynamic behaviour of MG 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, the 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, with the amount of load to be shed defined from the amplitude of the grid frequency deviation.

IV. Operation and Control of the MicroGrid

A MG is an inverter dominated network, where the power electronic interfaces are responsible for controlling frequency. Also, a voltage control strategy is required; otherwise the MG can experience voltage and/or reactive power oscillations [11].

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, two main control strategies are possible:

- Single Master Operation: 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: More than one inverter is operated as a VSI, corresponding to a scenario with dispersed storage devices; other PQ inverters may also coexist.

As already mentioned, the VSI has the ability to emulate the behaviour of a conventional synchronous generator. It reacts to power system disturbances (for example, load-following situations or wind fluctuations) based only on information available locally at the inverter's terminals (voltage and current measurements) [2]. In order to promote adequate secondary control with the aim of restoring frequency to the nominal value after a disturbance, two main strategies can be followed: local secondary control, by using a local PI controller at each MS, or centralized secondary control mastered by the MGCC, both defining target values for active power outputs of the primary energy sources [12].

A. *Single Master Operation*

In this case, a VSI (acting as "master") is connected to the network; the other MS are connected to the grid through an inverter with a PQ control scheme ("slaves"). Droop settings of the VSI can be modified by the MGCC according to the operating conditions and in order to avoid large frequency excursions.

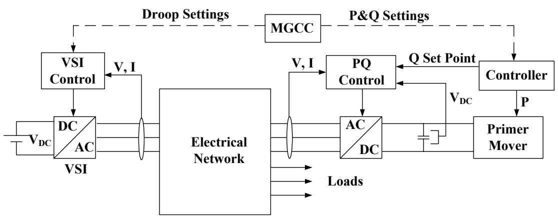

Fig. 6. Control scheme for single master operation

Assuring a zero frequency deviation during any islanded operating conditions should be considered the key objective for any control strategy. This is especially important since storage devices have limited capacity and it is necessary to avoid them from keep injecting (or absorbing) active power whenever the frequency deviation differs from zero.

B. Multi Master Operation

In a multi master approach, several inverters are operating as VSIs with pre-defined frequency/active power and voltage/reactive power characteristics. Eventually, other PQ-controlled inverters may also coexist.

The correction of frequency deviations can be performed by changing the idle frequency value as used in proportional/integral frequency governors of synchronous generators. The change in the idle frequency can also be performed centrally by the MGCC, a sort of centralized secondary control, using the communications infrastructure. In this control strategy the aim of obtaining zero frequency deviation is also a driving concern, as in the single master approach and for the same reasons.

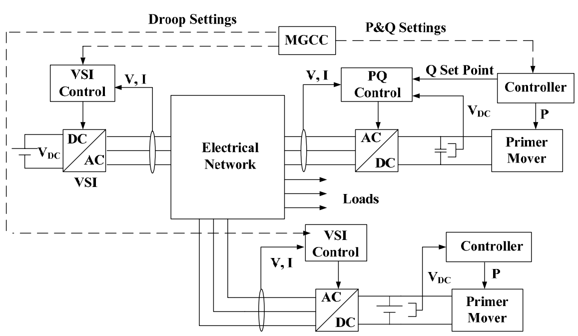

Fig. 7. Control scheme for multi master operation

V. Description of the Simulation Platform

A simulation platform under the *MatLab® Simulink®* environment was developed in order to evaluate the dynamic behaviour of several MS operating together in a LV network under pre-specified conditions including interconnected and autonomous operation of the MG. At this stage only three-phase balanced operation of the network is considered.

A LV test system, defined by NTUA [13], was used to test the approaches developed. Fig. 8 shows a single-line diagram with the different types of MS operated in this MG.

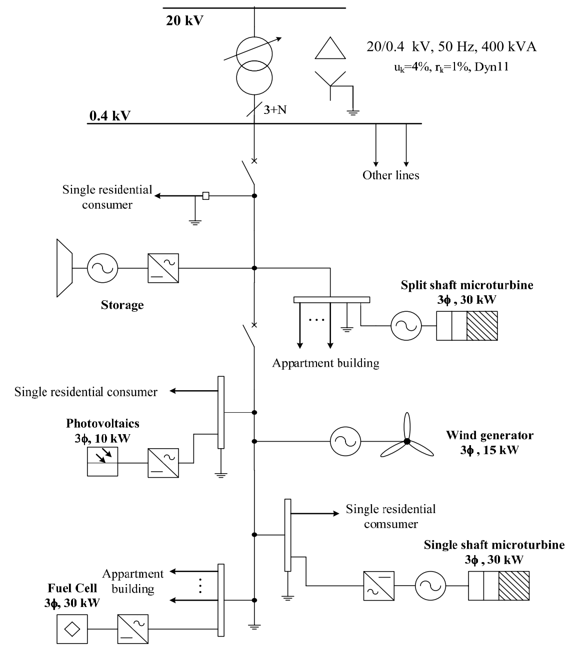

Fig. 8. LV network test system

Fig. 9 illustrates the LV simulation platform developed for the dynamic simulation studies. It includes models and controls for microturbines (single-shaft and split-shaft), fuel-cells, small asynchronous wind generators, PV panels and storage devices (flywheels and batteries) as well as controllable loads (available for load-shedding).

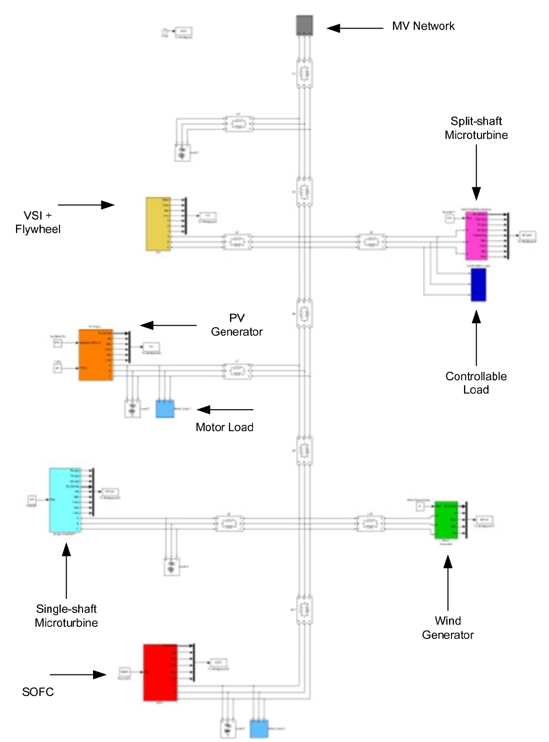

Fig. 9. LV network for the *Matlab® Simulink®* simulation platform

In order to illustrate how MS are represented under the *MatLab® Simulink®* environment, the model of the SOFC is shown in Fig. 10. This representation corresponds to the transposition of the model described in Fig. 2. All MS have been implemented here in the same way. Using the "look under mask" and the "block parameters" options it is possible to change parameters of the MS and its controls.

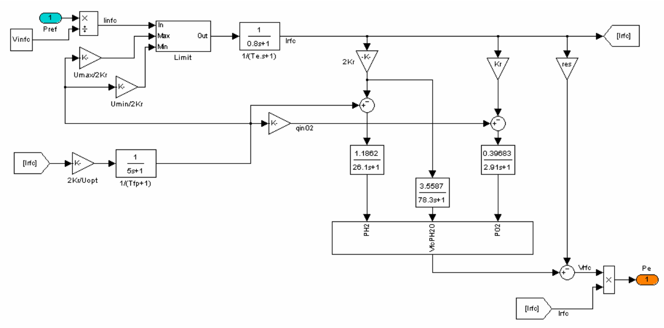

Fig. 10. SOFC model for the *Matlab® Simulink®* simulation platform

VI. Simulation Results

Disconnection from the upstream MV network and load-following in islanded operation was simulated in order to understand the dynamic behaviour of the MG and to evaluate the effectiveness of the developed control approaches. The islanding of the MG was investigated for two different situations: the scheduled islanding and the forced islanding (in case of a fault in the MV grid). Scenarios using the single master operation strategy with a VSI and multi master operation were tested. Due to space limitations, only the results for forced islanding for single master operation and for scheduled islanding for multi master operation are presented.

A. *Single Master Operation*

The short-circuit occurred at t=10 seconds and was eliminated after 100 milliseconds with the islanding of the MG.

The initial total load of the MG was around 70 kW and the microsource generation, prior to the islanding, was around 45 kW. In face of the large initial frequency deviation an amount of load was automatically shedded in order to aid frequency restoration. This load was reconnected later in small load steps allowing also the evaluation of the MG behaviour in load-following conditions.

It is possible to observe from the frequency behaviour that MG stability is not lost when facing the short-circuit at the MV grid side.

In order to preserve MG stability it was necessary to shed the motor loads since the rotation speed would drop too much and cause the whole system to collapse. Asynchronous generators (single-shaft microturbine and wind generator) were not disconnected in order not to loose generation. After fault elimination, there is a transient period for restoring normal operation of these generators, which has a strong impact on inverter current and voltage, as it can be observed in Fig. 12 after t=10.1 seconds.

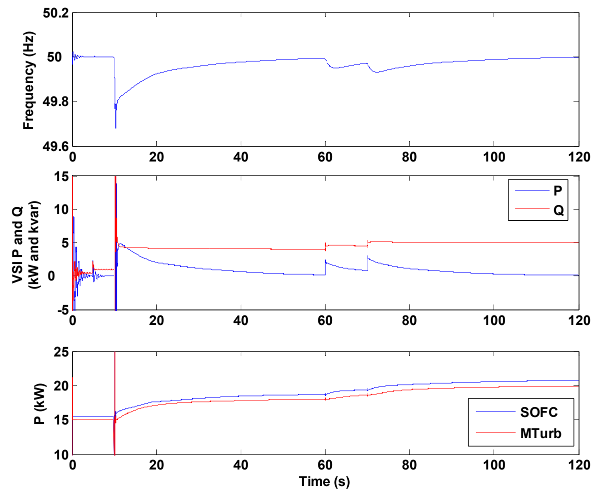

Fig. 11. MG Frequency, VSI active and reactive power and SOFC and single-shaft microturbine active power

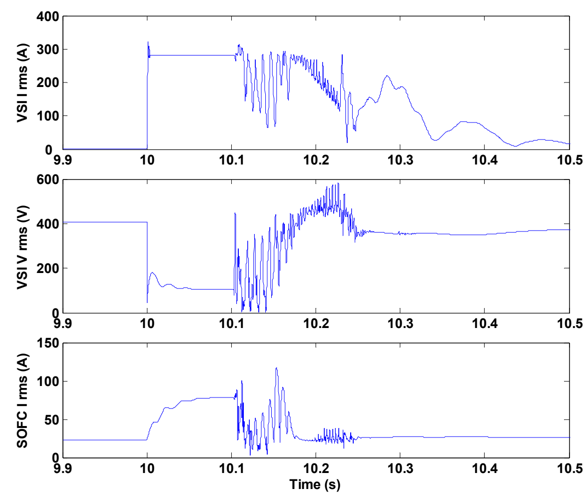

Fig. 12. VSI current and voltage and SOFC current (rms values)

B. *Multi Master Operation*

In order to analyze the dynamic behaviour of a MG under a multi master approach, the dynamics of the primary energy sources (single-shaft microturbine and fuel-cell) were neglected due to the high storage capacity assumed to be installed at their DC link [8]. The considered scenario is similar to the previous one. The disconnection of the upstream MV network was simulated for t=10 seconds.

After the islanding, active power is shared amongst several inverters according to droop settings. At t=20 seconds a local secondary control (based on an integral frequency control deviation approach) is applied to correct the steady state frequency deviation after islanding. It is also possible to observe that voltage variations are very small. In this case voltage control through droops is sufficient to maintain voltage levels within acceptable limits.

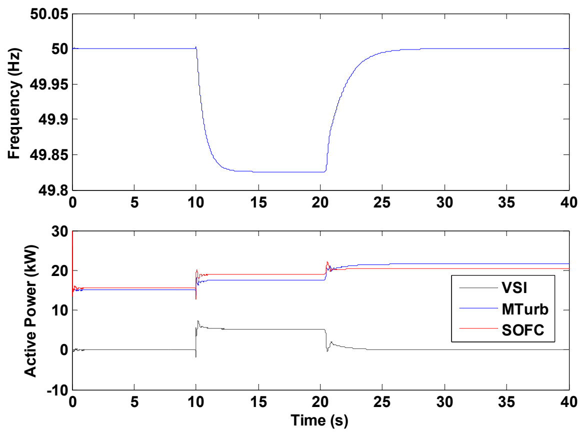

Fig. 13. MG frequency and active power in microsources

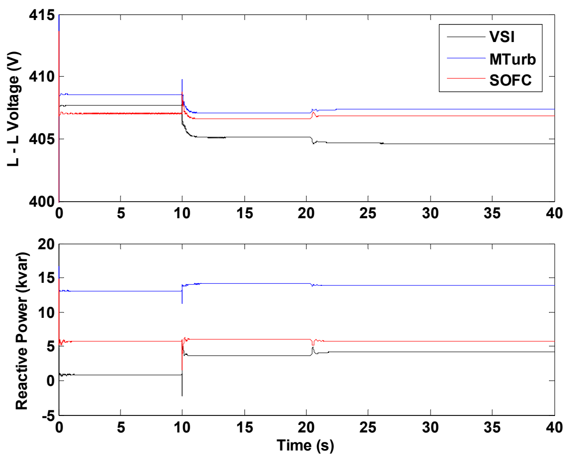

Fig. 14. Microsources voltages (rms values) and reactive powers

VII. Conclusions

From the analysis performed the following main conclusions can be drawn regarding the dynamic behaviour of the MG, given the control strategies presented:

- Simulation results indicate that the islanding of the MG, both scheduled and forced, can be performed safely in several different importing and exporting conditions.
- Simulation results also indicate that both control strategies tested – the single master and the multi master approach – are effective and assure efficient MG operation.
- Also, the results obtained suggest that storage devices are absolutely essential to implement good control strategies for MG operation in islanded mode and the load-shedding procedure is also of very high importance to sustain fast and long frequency deviations.

VIII. Acknowledgments

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X. Biographies

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