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WORK PACKAGE D

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Emergency Strategies and Algorithms

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General Introduction

The main objective of WP D is to develop the control strategies that will be adopted in the MicroGrid when the systems becomes isolated or has to deal with a local Black-start situation. When failures occur in the MV or HV system, the distribution network may break into isolated “islands”, each of which must be supplied by itself. With an intelligent distributed approach where the micro controllers (MC and LC) act, in a very fast way, as independent agents with local control strategies and making an efficient use of the local resources, it will be possible to maintain system operation in islanded conditions. Such an islanded operation requires the development of frequency and load-shedding control strategies exploiting the dynamic response characteristics of the different microsources and storage devices.

If a black out takes place, a local black-start will be tried, 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 Black-start functions contribute to assure an important advantage for power system operation in terms of reliability resulting from the presence of a very large amount of dispersed generation.

This deliverable regards the control strategies and algorithms (to be implemented as software blocks in the MGCC) for emergency operation, meaning:

- islanded operation and
- local black-start.

Regarding control there is neither a unique view nor a clear and consensual option for a control scheme to operate a microgrid under islanded operation mode. In the available bibliography, several authors present different approaches and conceive distinct solutions to control microgrid operation in islanded operation mode. Basically, two different control strategies were followed during the course of this task of Work Package D:

- A control strategy based on active power/frequency and reactive power/voltage control of the microsources and particularly of the storage devices with power electronic interfaces. This control strategy is supported by several authors, like in Kundur [8]. This control scheme was used by UMIST and NTUA.

- A control strategy based on inverter control modes at the microsources. This control strategy is supported by several authors like in Barsali [5] and in Engler [7]. This control scheme was used by INESC Porto and ISET (in Work Package B).

Thus, the following document will be divided into three distinct parts: a first part concerning the INESC Porto contribution, a second part concerning the UMIST contribution and a third part concerning the NTUA contribution. Each part will detail the models used for simulation, the control strategies chosen to operate the microgrid, the algorithms developed and the main results that were obtained from simulations that show the feasibility of the developed approaches.

Conclusions will be presented in a single final chapter.

INESC PORTO CONTRIBUTION

Table of Contents

1. Executive Summary

The main objective of this document is to present the development of control strategies and algorithms to be adopted to operate a MicroGrid when the system becomes isolated. This isolation takes place when faults occur in the Medium Voltage network and the microgrid must have the ability to operate stably and autonomously. Using an intelligent distributed approach, local action will be executed in a very fast way, making efficient use of the resources available in order to maintain system operation in islanded conditions.

A summary of the work developed for this deliverable is given in the following lines:

A short introduction giving the context of microgrid operation is made complemented with the description of the main characteristics of this type of operation.

A brief description of the models used is made, as well as of the changes implemented concerning a particular control strategy.

Two basic operation and control modes of inverters are presented alongside with the main implications of each choice. Details are given of the implementation of such schemes.

The emergency strategies developed are also described, presenting algorithms that allow safe islanded operation and operational sequence rules for black-start purposes.

The study case networks used and the simulation platform chosen are introduced and the results of several tests and simulations are subsequently presented.

The main conclusions are detailed and explained giving the characteristics of the operation strategy.

2. Introduction

Following the increasing penetration of Dispersed Generation in Medium Voltage (MV) networks, the connection of microgeneration to Low Voltage (LV) networks starts to be investigated, and in some cases subjected to pilot experiences. In this context, a MicroGrid can be defined as a LV distribution system to which small modular generation systems are to be connected. Generally, a microgrid corresponds to an association of electrical loads and small generation systems through a LV distribution network. This means that loads and sources are physically close.

In terms of the currently available technologies, the microgeneration systems can include several types of devices such as fuel cells, renewable generators such as wind turbines or Photovoltaic (PV) systems as well as microturbines powered by natural gas or biofuels.

Apart from a LV distribution network, microgeneration devices and electrical loads, a microgrid also includes storage equipment (such as batteries, ultracapacitors and flywheels), network control and management systems. The storage devices present will play an important role in this kind of network, mainly in what concerns fast load-following situations.

At the current research status, it is assumed that the microgrid can be operated in two main situations:

- Normal Interconnected Mode – the microgrid will be electrically connected to the main MV network either being supplied by this network (totally or partially, depending on the generation allocation procedures adopted to operate the microsources) or injecting power into the main MV grid (when the relation between the microsources installed capacity and the electrical loads allows this type of operation);
- Emergency Mode – in case there is a failure in the main MV network, the microgrid must have the ability to operate in an isolated mode, that is, to operate in an autonomous way, similar to the power systems of physical islands.

A simulation platform under the *MatLab*® *Simulink*® environment was developed in order to evaluate the dynamic behaviour of several microsources operating together in a LV network under pre-specified conditions including interconnected and autonomous operation of the microgrid.

It is important to state that this study was developed autonomously from the simulation tool developed in Work Package A (described in the report for Deliverable DA2 [2]). However, most of the models used were taken from that same Work Package.

The resulting analysis was intended to promote the understanding of the interaction between different types of microgenerators and storage devices, providing sufficient knowledge to design appropriate decentralized control strategies to be installed in the microgrid.

It is well known that conventional power plants are based on rotating masses with relatively high inertia constants, which are of great importance to provide stability to system operation. However, in microgrids the majority of the sources are connected to the network through interfaces based on non-linear power electronics (*v.g.*, converters), therefore without a direct grid connection to rotating masses. Such a fact requires the adoption of novel control strategies, since the transients that occur in the network will be much faster than in conventional systems.

Several types of disturbances need to be considered and analysed in order to understand microgrid dynamic operation. The most important disturbances that should be considered are: faults in the MV network causing the islanding of the microgrid, sudden connection or disconnection of loads and/or microsources under islanded operation.

During islanded operation microsources should be able to operate in a stable way, according to an adequate control strategy. After islanding, frequency control and voltage control becomes the main concern. So, in these first moments, economic scheduling policies are a secondary issue. They will be considered again later for an economic operation of the islanded microgrid.

The microsources included in the simulation were modelled according to the description provided in Deliverable DA1 [1]. The addition of storage device models involved development and adaptation of specific models. The description of these models is included in this document.

3. Models

This chapter will discuss the models used for the simulation platforms that were developed.

The microsource models used for simulation purposes were the ones detailed in the Deliverable DA1 [1]. These models were later improved and some new ones were created. Still, some devices (such as synchronous and induction machines, loads, breakers, buses and lines) were modelled using the *MatLab*® *Simulink*® Power System Blockset.

The inverter models were developed independently and will be discussed in detail since their development took into consideration the control strategies adopted that will be explained in a later chapter.

However, for example purposes mainly, a description of the model of the Single-shaft microturbine is given. The model of the wind generator is also detailed in this section since it was developed differently from the one in [1].

3.1. Single-Shaft Microturbine

The single-shaft microturbine has a gas combustion turbine engine coupled to an electrical synchronous generator operating at high speed. Electric power is produced at hundreds or thousands of Hertz, is converted to DC voltage and then inverted to AC low frequency voltage (50 Hz). The model of the mechanical part of the microturbine was previously presented (Deliverable DA1 [1]).

When using the inverter type model based on the Instantaneous Power Theory (to be described in the following pages) there is a complete decoupling between the grid and the generator. Therefore, when using the complete model of this type of microgenerator, some limitations had to be overcome through the addition of a virtual resistive load that must be manually adjusted to define the generator output power from the high speed AC side. This problem arises because the *MatLab*® *Simulink*® Power System Blockset model for the synchronous machine must always be connected to an external load. Acting this way, the active power generation of the microsource can be specified.

Due to the need of having the microturbine participating in frequency control and load-following functions, it is necessary to implement a virtual resistive load controller, defined in a way similar to the conventional active power/speed controller.

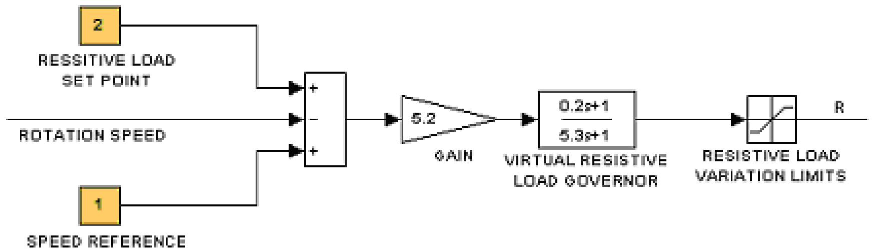

Figure 1: Virtual resistive load control system

The mechanical power of the prime mover is adjusted via another governor and the virtual resistive load control system allows matching the mechanical power of the prime mover to the electrical power absorbed by the virtual resistive load. This electrical power is measured and becomes the active power input to the inverter model, as defined above.

The microturbine is equipped with a permanent magnet synchronous generator, modelled here as a conventional synchronous machine with a constant field voltage. Notice that the speed variations are very high, and the conventional model of the synchronous machine (a voltage source and a subtransient reactance) does not provide results with enough quality.

Figure 2 describes the full model adopted to simulate the operation of the microturbine, including the load/frequency control loops (detailed in a later section).

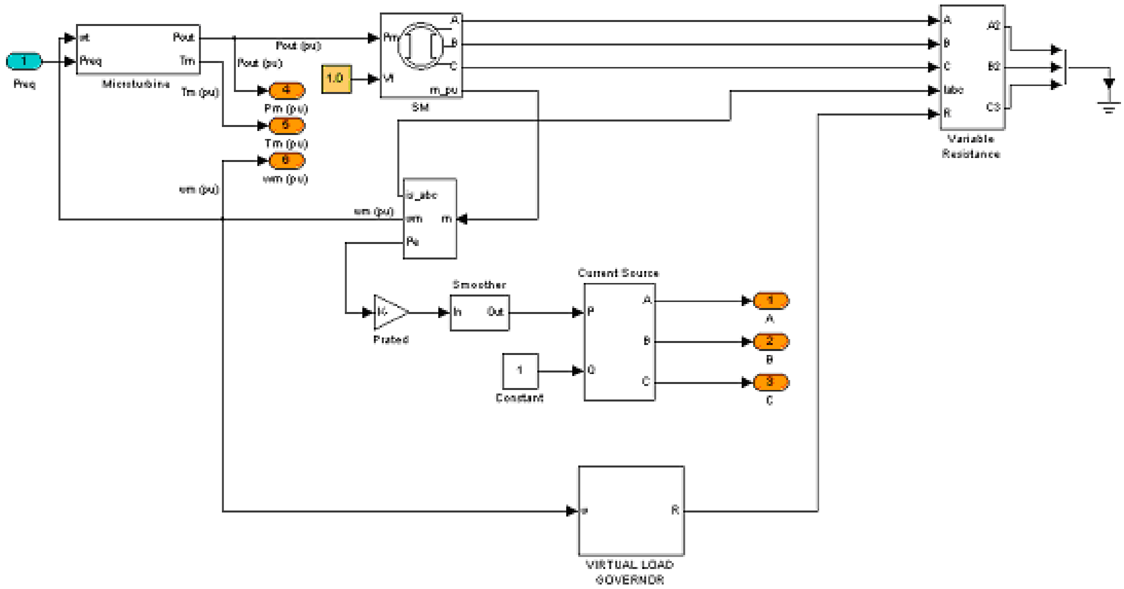

Figure 2: ***MatLab*® *Simulink*® block diagram for the single-shaft microturbine**

3.2. Wind Generator

A small wind generator was included in the study case network. This wind generator uses a squirrel-cage induction generator that is directly connected to the grid. The *Matlab*® *Simulink*® block used to model the asynchronous machine is the one available in the Power Systems Blockset. The Wind Turbine block uses a 2-D Lookup Table to compute the turbine torque output (Tm) as a function of wind speed (w_Wind) and turbine speed (w_Turb), as can be seen in **Figure 3**. A function was developed in order to simulate the wind regime for the wind generator. This function is based on a Rayleigh Distributed Noise Generator Block (available in *Simulink*®) with a specified average value for wind velocity and specified variation limits. This is intended to provide a more faithful representation of the wind behaviour.

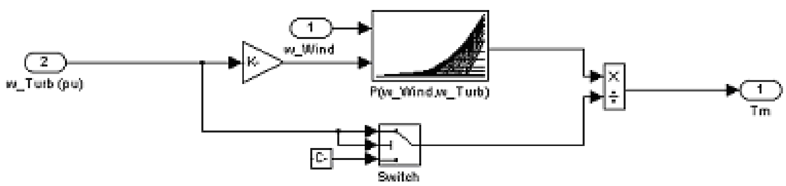

Figure 3: Wind turbine block

The complete model, including both the electrical and mechanical parts is shown in the next figure.

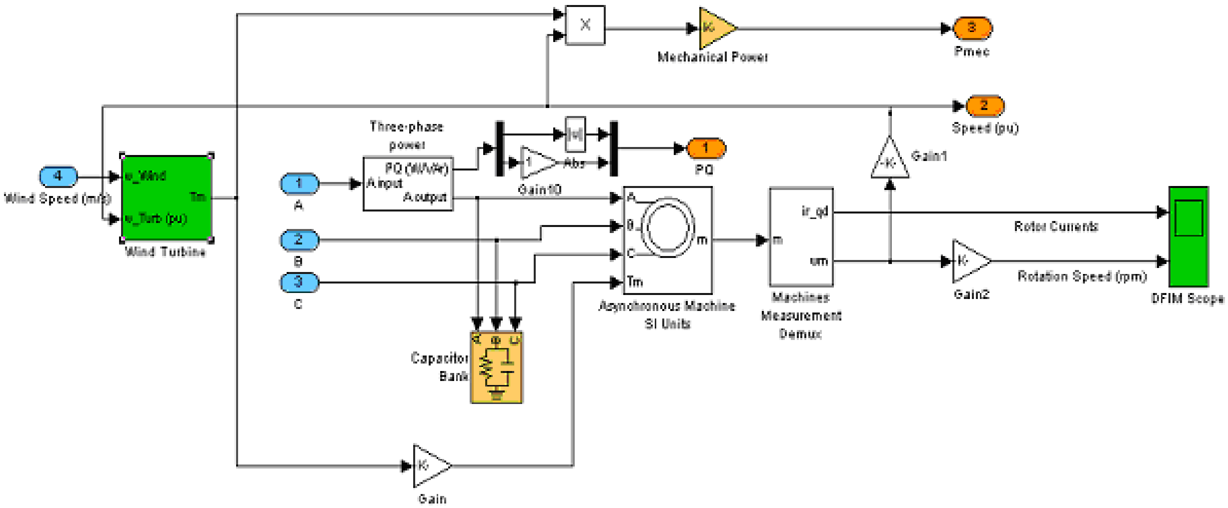

Figure 4: Wind generator model in the *MatLab® Simulink®* environment

3.3. Inverter

Two inverter models were used in different versions of the simulation platform.

The first model is the one proposed by INESC PORTO in the Deliverable DA1 [1] and is based on the Instantaneous Power Theory. This model replaces the behaviour of the inverter electronic converter, namely the fast commutations of its components, by the mathematical concept that power is injected at the AC side without harmonics, distortion, losses or delays. The inverter model behaviour becomes similar to the one of a current source. The voltage of the bus to which the inverter is connected is measured and the current is computed so that the active and reactive power specified in the inverter's inputs can be injected into the AC network (PQ Inverter model). This model requires a frequency and voltage reference in the network that can be given either by a synchronous machine (such as a small diesel unit) or by a Voltage Source Inverter (VSI).

This model expresses the instantaneous voltages and currents as instantaneous space vectors in conventional a-b-c coordinates. These vectors are then transformed into α-β coordinates using the Clark Transformation. This transformation uses the following equations (for a balanced three-phase system):

$$\begin{bmatrix} v_\alpha(t) \\ v_\beta(t) \end{bmatrix} = \sqrt{\frac{2}{3}} \cdot \begin{bmatrix} 1 & -1/2 & -1/2 \\ 0 & \sqrt{3}/2 & -\sqrt{3}/2 \end{bmatrix} \cdot \begin{bmatrix} v_a(t) \\ v_b(t) \\ v_c(t) \end{bmatrix}$$

$$\begin{bmatrix} i_\alpha(t) \\ i_\beta(t) \end{bmatrix} = \sqrt{\frac{2}{3}} \cdot \begin{bmatrix} 1 & -1/2 & -1/2 \\ 0 & \sqrt{3}/2 & -\sqrt{3}/2 \end{bmatrix} \cdot \begin{bmatrix} i_a(t) \\ i_b(t) \\ i_c(t) \end{bmatrix}$$

so that the active and reactive instantaneous powers can be calculated as

$$\begin{bmatrix} p(t) \\ q(t) \end{bmatrix} = \begin{bmatrix} v_\alpha(t) & v_\beta(t) \\ -v_\beta(t) & v_\alpha(t) \end{bmatrix} \cdot \begin{bmatrix} i_\alpha(t) \\ i_\beta(t) \end{bmatrix}$$

Such a general model may be considered adequate for the simulation of islanded operation, if no serious faults are considered so that the voltage reference is kept.
The details of the model may be found in [4].

Concerning the second model of the inverter, the output voltage of a VSI is determined by the output power (both active and reactive). The terminal voltage and output current are continuously measured to compute active and reactive power levels, which are delayed for decoupling purposes. The active power determines the frequency of the output voltage by the active power/frequency droop. Similarly, the reactive power determines the magnitude of the output voltage by the reactive power droop. The control loop is closed by the electrical network and the resulting current and voltage are fed back for the computation of the new values of active and reactive power.

Storage devices are associated with VSI. In this simulation platform it is assumed that for the time interval under analysis the DC link voltage is not significantly affected by a charge or discharge of storage devices. This means that dynamics are therefore not included.

A block diagram of this inverter model is given in the following figure.

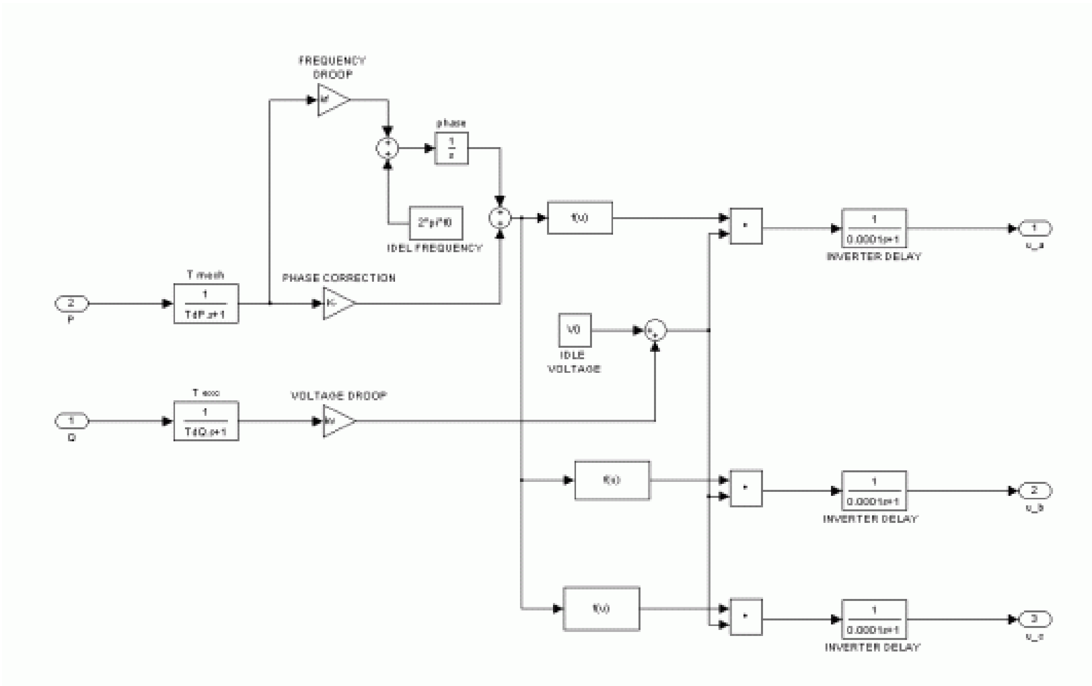

Figure 5: VSI model in the *MatLab*® *Simulink*® environment

4. Operation and Control Modes

This chapter describes the different control modes developed and tested and the strategies chosen that will lead to adequate microgrid performance behaviour.

The new distributed generation technologies (such as microturbines, fuel cells, PV´s) are not very suitable for supplying power directly to the grid: a power electronic interface (inverter) is usually required.

Usually, two kinds of control strategies can be used to operate an inverter [5]:

- A PQ control: the inverter is used to supply a given active and reactive power set point. This kind of control can be achieved using the model presented in **Section 3.3**. In this case, the inverter output voltage is always synchronized with the grid voltage and the inverter output current is controlled in magnitude and phase to meet the desired set points.
- A Voltage Source control logic: the inverter is controlled to "feed" the load with pre-defined values for voltage and frequency. Depending on the load, the inverter real and reactive power output is defined **Section 3.3**.

If a cluster of microsources is operated within a microgrid and the main power supply (the MV network) is available, all the inverters can be operated in the PQ mode, because a voltage and frequency reference is provided by the main power supply. However no effect can be achieved if the MV network is lost: in that case, all the inverters will shut down because there will not be a voltage reference within the microgrid. It is desirable that a seamless transition from interconnected operation to islanded (autonomous) operation be possible, even under emergency actions (for example load-shedding when the imbalance between local generation and local load is too high). Combining the above mentioned control strategies, one can fulfil this requirement by establishing one of two operation modes for a cluster of microsources connected to an electric grid:

- 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 the reference voltage when the main power supply is lost; all the other inverters can be operated in the PQ mode;
- Multi Master Operation: All inverters are operated as a VSI (no synchronous machine is needed).

5. Single Master Operation

5.1. The Importance of the Local Proportional-Integral Control

It is crucial to understand the importance of the proportional-integral (PI) action directly applied to the primary machine (implemented as shown in the next figure).

During islanded (autonomous) operation, when an imbalance between load and local generation occurs, the grid frequency drifts from its nominal value. Given the features of the storage devices and their control, they would keep injecting power into the network as long as the frequency differed from the nominal value.

A PI controller (being the input of this controller the frequency error) acting directly in the primary machine allows frequency restoration (neglecting economic scheduling policies). After frequency restoration, storage devices will be operating again at the normal operation point (zero active power output).

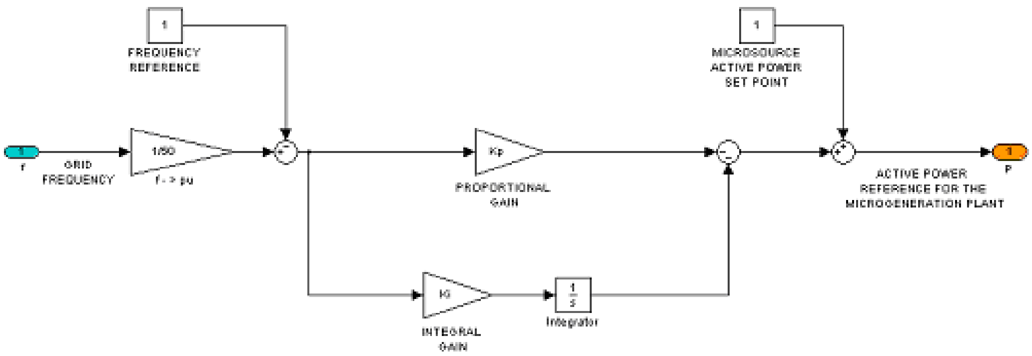

Figure 6: Control of the active power in each microsource

5.2. Single Master Operation with a Synchronous Machine

The single master operation with a synchronous machine was the first approach used to deal with the islanded operation mode. The small Diesel unit of 30 kW supplied the voltage and frequency reference for the PQ inverters serving as interface to some of the microsources (namely the single-shaft microturbine and the SOFC). The use of batteries coupled to the microsources tackled the problem related to the need of storage capacity.

5.2.1. Reactive Power/Voltage Control

The next figure describes the voltage control strategy adopted. Knowing the network characteristics, it is possible to define the maximum voltage droop. To maintain the voltage between acceptable limits, the inverter will adjust the reactive power in the network: it will inject reactive power if the voltage falls below the nominal value and will absorb reactive power if the voltage rises above its nominal value.

Phase to phase voltages are measured in the bus where the inverter is connected. These values are compared with the reference value (for example the nominal value, 400 V). The error voltage is the input of a proportional control (voltage droop control) to obtain the reactive power to be injected in the network, as described in **Figure 7**.

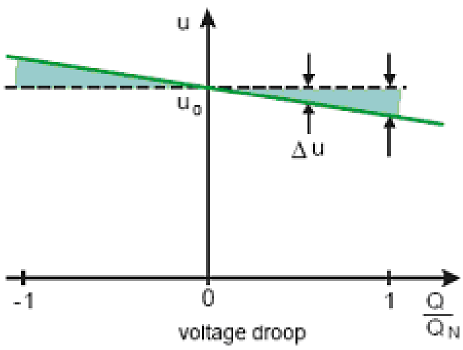

Figure 7: Droop control of the inverter terminal voltage

The *Simulink®* model of this voltage control system is shown in **Figure 8**, as implemented in the fuel cell and in the single-shaft microturbine.

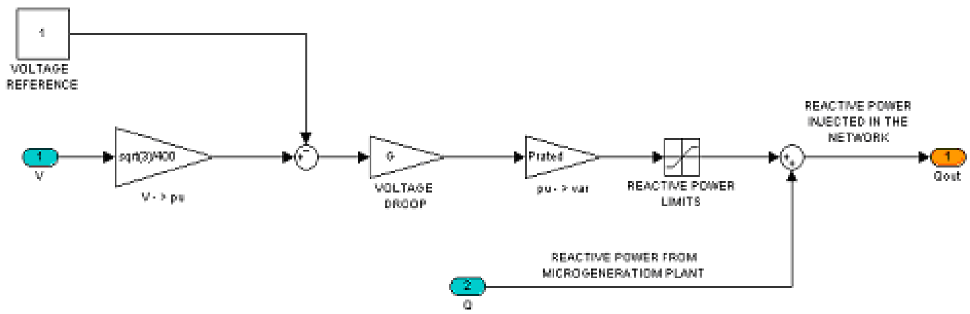

Figure 8: ***MatLab® Simulink®*** **block diagram of the voltage control**

The output of this proportional controller (reactive power to be injected in the grid at the nod where it is implemented) is the "Q" input of the PQ inverter, as described in a previous section.

5.2.2. Active Power/Frequency Control

The transition to islanded operation mode and the operation of the network in islanded mode require microgeneration sources to participate in active power/frequency control, so that the generation can match the load. During this transient period, the participation of the storage devices in system operation is also very important, since the system has very low inertia, and some microsources (microturbines and fuel cells) have a very slow response to the request of an increase in power generation. As already mentioned, the power necessary to provide appropriate load-following is obtained from batteries (in this section they are assumed to be installed in the fuel cell and in the single-shaft microturbine) and by the flywheel.

The output power of the storage devices is added to the output power of microsources, with the result being the input "P" of the PQ inverter previously defined.

5.2.3. Models of Storage Devices

Battery Model

As mentioned before, storage capacity is of major importance to provide fast load-tracking ability. Batteries allow some storage capacity to be installed at the DC link buses of several microsources. The main role of the batteries will be during transient operation periods, which have typical durations of a few seconds. The charging mode was neglected considering that it will only take place during normal operation of the network (for example, after a discharge period, the batteries will only be recharged when a stable point of operation is reached, even in islanded operation mode, if the energy required to this operation is available from the other microsources).

Batteries usually have a big discharge time constant. For a simulated time of just a few minutes, the behaviour of the battery can be represented by a constant voltage source (ideal model).

Concerning the first inverter model, where it is only necessary to specify the active and reactive power in its inputs, the transient response of the network will not be affected by the chemical behaviour of the batteries.

Battery Contributions for Control

Since batteries are energy storage devices, they will provide active power to the grid to compensate for fast load changes. From this point of view, the role of the batteries can be regarded as a finite source of energy. This energy will be injected in the network following a request from an active power/frequency control unit.

If load is larger than generation, the system frequency will decrease. Generation must then be increased to restore frequency to its nominal value. This will be done by acting on the prime power source of each microsource. If the primary machine of the microsource is not able to provide the required power, especially during the initial transient period, batteries can help by providing the remaining power, assuming that such request is below their nominal value. In this case, frequency deviation is considered the control variable of the power that will be delivered by the batteries, as shown in **Figure 9**.

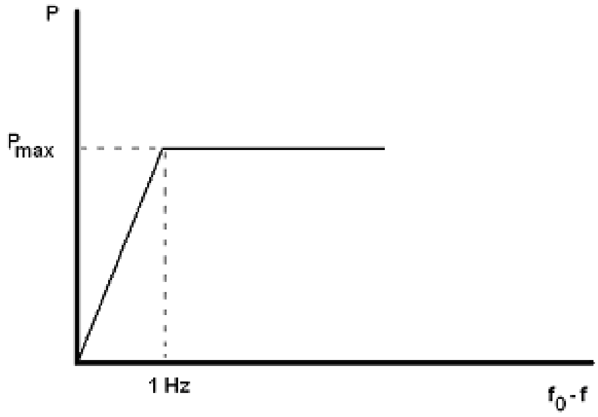

Figure 9: Battery P-f characteristic

The battery response is controlled according to the block diagram of **Figure 10**. It is important to notice that this droop has nothing to do with the PI control described in a previous section.

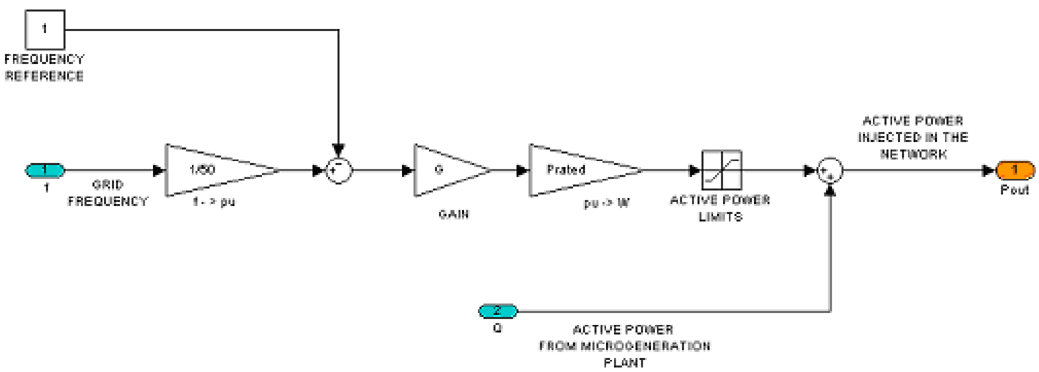

Figure 10: ***MatLab® Simulink®*** **block diagram describing the battery dynamics**

Flywheel Model

Flywheel technology has great advantages over batteries (usually lead acid batteries) because the useful life of the flywheel is almost independent of the depth of discharge. The type of load variations considered is always a risk to the batteries useful life, since fast, in depth discharges significantly reduce their life cycle. The charge of the flywheel is determined by its rotating speed, while the charge of a battery is more difficult to evaluate.

Flywheel systems comprise kinetic energy storage devices (which depend on a rotating mass to store energy), a permanent magnet synchronous machine (fed by a bidirectional IGBT inverter), a DC link and an inverter (ensuring the interconnection with the grid).

UMIST and URENCO Power Technologies presented the first draft version of the flywheel model, as described in [3]. In this model it can be observed that mechanical transients are decoupled from the flywheel's output power. Using convenient control algorithms to control the grid-side inverter, the DC link voltage variations can be compensated and the transient response of the flywheel system has no effect on the microgrid output. Thus, the kinetic energy storage device may be modelled as a constant voltage source-fed VSC (neglecting the DC link voltage variations) for short time intervals (tens of seconds).

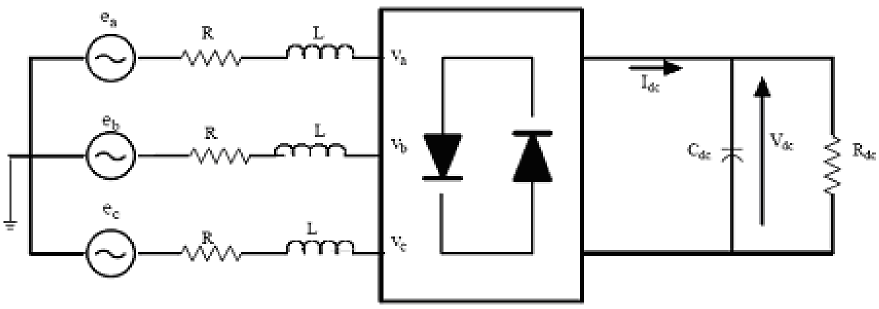

Figure 11: Kinetic energy storage device model

Since the DC link voltage is assumed to be constant, all the elements up to the rectifier bridge of **Figure 11** can be neglected. Under such an assumption, they do not limit the changes in the power flow and therefore are not included in the flywheel model used here.

Flywheel Contributions for Control

A limit was set to the kinetic energy that can be supplied by the flywheel system. As already explained, when power demand increases/decreases in the network, there is an imbalance between load and generation and a frequency deviation from its nominal value can be observed. The frequency deviation is used as the input of a proportional control and an active power value to be injected/absorbed in the microgrid is calculated. The power injected/absorbed in the network is limited by the kinetic energy stored in the flywheel system.

The *Matlab*® *Simulink*® model of the flywheel, with the frequency deviation of the network being the control variable, is presented in the next figure.

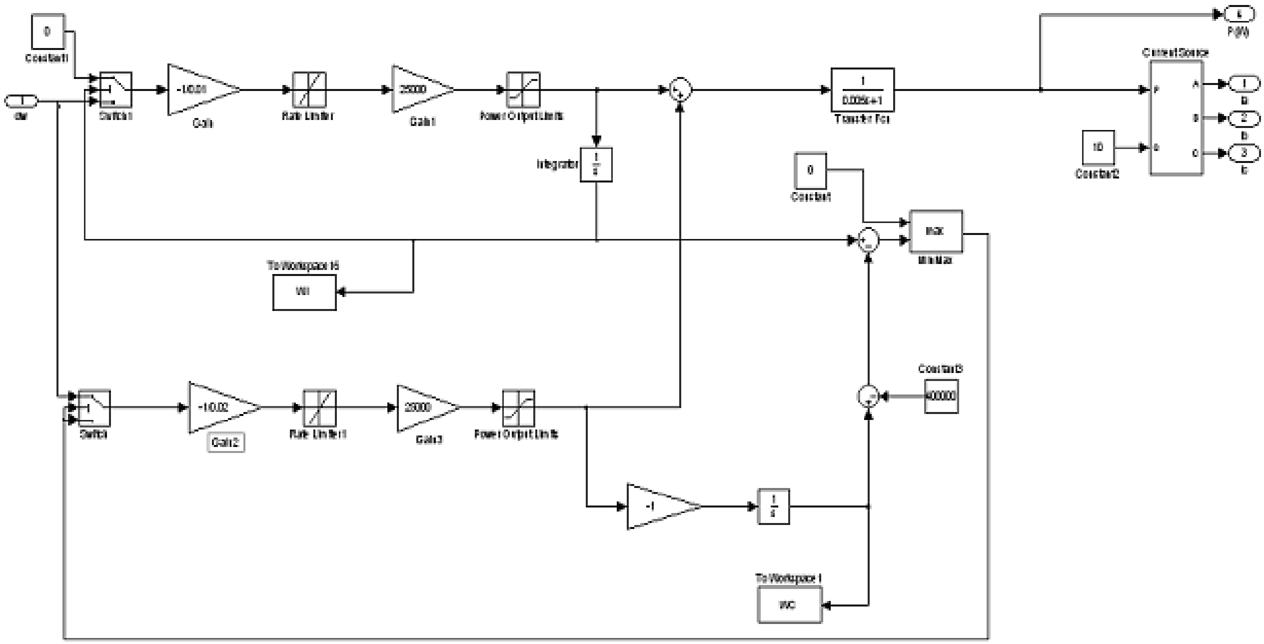

Figure 12: ***MatLab*® *Simulink*® block diagram of the flywheel and its control system**

5.3. Single Master Operation with a VSI

The operation of a microgrid with several PQ inverters and a single VSI inverter is similar to the previous approach. The VSI provides the voltage reference for the operation of the PQ inverters when the microgrid is isolated from the main power supply. By definition, the output of a voltage source depends on the load connected to it. Acting as a voltage source, the VSI requires a significant amount of storage capability in the DC link or a prime power source with a very fast response in order to maintain the DC link voltage constant. In other words, the power requested to a VSI needs to be available almost instantaneously in the DC link. In fact, this type of behaviour actually models the action of the flywheel system.

Using the communication capabilities of the microgrid and the MicroGrid Central Controller (MGCC), each PQ inverter set point will be updated in order to achieve an optimal operation scenario regarding voltage levels, frequency and reactive power flows. The VSI is responsible for fast load-tracking during transients (natural variation of load and consumption, as well as during the islanding transient) and for voltage control (only at one point of the network). During normal operation conditions (stable frequency at the nominal value), the output active power of the VSI is zero; only reactive power is injected in the grid for voltage control.

In the simulation platform, the PV panel, the SOFC and the single-shaft microturbine are associated with a PQ inverter type. As the inverter control is quite fast and precise, it is possible to neglect the DC link voltage fluctuations; if losses are also neglected, the output active power of a PQ inverter is equal to the output power of the associated microsource. The output reactive power can be specified via the MGCC.

6. Multi Master Operation

The operation of an isolated network with several VSI "feeders" is similar to the one of a conventional power system, with synchronous generators controlling active power/frequency and reactive power/voltage. These functions are usually performed by conventional voltage and speed governors, which are now replaced by the droop characteristics: the frequency/active power and voltage/reactive power droops.

Considering the interconnected operation mode, the frequency of the LV grid is set by the conventional power system. Each inverter is operating with a pre-defined frequency/active power characteristic. The idle frequency (f_0) (the frequency at which the output active power is zero) can be modified in order to define the desired value of the active power injected by the VSI. As the grid frequency fluctuations are usually very small, the idle frequency can be used to dispatch generation. This function can be performed by the MGCC, using the communications infrastructure. A periodic actualization of several setting parameters is required, depending on market conditions.

If a fault causes the transition from the interconnected to the islanded mode, it is not necessary to change the control strategies of each microsource. When the main power supply is disconnected, the overall system moves to a new operation point (in voltage and frequency), depending on the local load. Then, a secondary control strategy can be made to act on the inverter in order to get the primary machine to restore the nominal value of the frequency. This can be done by changing the idle frequency value of each inverter, while keeping the output power constant.

As VSI are associated with storage devices, it was assumed that the voltage variations are not very significant during the time interval used for the dynamic simulations. In this case, the dynamic model of the microsource was not included in the simulation platform since it would not be reflected in the dynamics of the grid.

7. Emergency Strategies and Algorithms

7.1. Islanded Operation

This chapter presents the operational strategies that were found adequate for microgrid operation islanding involving the presence of storage devices and of load-shedding mechanisms.

7.1.1. General Concept

The main control strategy involves the passage to islanded operation of the microgrid in case of a fault in the upstream MV network or in other special operating conditions. Contrary to the classical belief in not allowing islanded operation except in cases of physical impositions, a new strategy is being followed that implies "normal" operation under these conditions. The islanding procedure is therefore regarded as intentional and it corresponds to a careful planning of the system's conditions in respect to load, DG production levels, existence of faults, etc.

7.1.2. The Importance of Storage Devices

Storage devices such as batteries and flywheels are of the utmost importance to microgrid operation, especially concerning the passage to islanded operation mode. These devices have the ability to perform fast load-following either resulting from the passage to islanded operation itself or from load/production variations in islanded operating conditions.

Details concerning these devices have been given in a previous section.

7.1.3. The Importance of the Load-Shedding (Controllable Load)

The controllable loads concept plays an important role under some operating conditions of the microgrid, namely those concerning the imbalance between load and generation (load larger than generation).

In order to deal with this problem, a load-shedding scheme was implemented to aid frequency restoration to its nominal value after the islanding of the microgrid. The philosophy adopted was based on the amplitude of the frequency deviation, but it would also be possible to include the rate of frequency change in the load-shedding. However, at present, only the frequency deviation was considered as the control variable to the load-shedding.

Load-shedding is used as a remedy against long and strong frequency excursions. Basically, the dynamic behaviour of the system is improved if some percentage of the load is temporarily lost, allowing the generators with frequency regulation functions to react to the frequency deviation. The benefits derived from such a scheme are well known, particularly in what concerns a rapid reaction following a large frequency deviation leading to a faster stabilization of the system and to the restoration of the frequency to its nominal value.

The implementation adopted uses four steps of load-shedding, each one corresponding to a certain deviation in the system's frequency and a load reconnection implemented in small steps. **Table 1** shows the maximum frequency deviation that corresponds to a specific percentage of load-shedding (relative to the load total):

Frequency Deviation (Hz)	Percentage of Load-Shedding (% of total load)
0.25	30
0.50	30
0.75	20
1.00	20

Table 1: Load-shedding parameters

To avoid the load-shedding action when the frequency deviation has very short duration, a delay was implemented in order to allow the load-shedding only if the frequency deviation is sustained for a time interval larger than Δt (which can be controlled). The identification of these steps was defined, in this case, after a trial and error off-line approach.

The load reconnection strategy is now described. To avoid large frequency deviations during the load reconnection, it was assumed that it is possible to define a certain number of steps for load reconnection. This number of steps is variable and depends on the percentage of load-shedding. For example, if the overall percentage of the load-shedding is 30 %, (one step of the load-shedding was activated), the load reconnection procedure occurs in two steps of 15 % of the total load (with a controlled time interval in between); if the percentage of the load-shedding is 60% (two steps of the load-shedding were activated), the load reconnection procedure occurs in four steps of 15 % of the total load. **Table 2** shows the full details of the implementation.

Steps Activated in Load-shedding	Load Reconnection
1	2 steps of 15 % of the total load, with a time interval of 10 seconds
2	4 steps of 15 % of the total load, with a time interval of 10 seconds
3	6 steps of 13.33 % of the total load, with a time interval of 10 seconds
4	8 steps of 12.5 % of the total load, with a time interval of 10 seconds

Table 2: Load reconnection parameters

7.1.4. A Load-Shedding Algorithm

A central load-shedding dispatching algorithm was also developed to minimize load shedding amounts, using the MGCC that defines new operation set points for load shedding (changed according to operation conditions). This requires the load controllers to adapt the shedding settings, following a set point received from the MGCC.

The steps of this algorithm are next presented.

Initialization

1. Definition of the frequency deviation steps (such as 0.25, 0.5, 0.75, 1 Hz…);
2. Definition of the load-shedding percentage corresponding to the frequency deviation steps (as a percentage of the total load of the microgrid, such as 5, 10, 15, 15 %...);

Note: These first two steps are performed off-line. The following ones are part of an on-line operation.

Cycle

3. For a specified time interval (for example, every five minutes):
    i. The loads that are available for load-shedding offer their services to the MGCC;
    ii. The MGCC gathers all the offers and organizes the proposals of availability for load-shedding services from the smallest load value to the highest one for each of the frequency deviation steps;
    iii. The MGCC programmes the set-points for each load for the load-shedding services and dispatches to the corresponding under-frequency relay present at each load;

Acting this way, if a disturbance occurs, leading to a specific frequency deviation, the relays act according to their activated set-point, shedding the percentage of load corresponding to the deviation occurred. This algorithm is also suitable for market operation, providing an ancillary reserve service (as already happens with secondary reserve, reactive energy supply, etc.). It is important to mention that the parameters such as the frequency deviation steps and the percentage of load to be shedded in each step must be analysed case by case, including numerous simulations for the validation of the parameters. The value of the parameters presented should be considered exemplificative.

In pseudo-code this could be implemented as presented next.

A vector of frequency deviation steps and a vector of the load-shedding percentage corresponding to the frequency deviation steps are built as shown below.

$$\begin{bmatrix} P_{ls1} \\ P_{ls2} \\ \ldots \\ P_{lsm} \end{bmatrix} \quad , \quad \begin{bmatrix} \Delta f_1 \\ \Delta f_2 \\ \ldots \\ \Delta f_m \end{bmatrix}$$

A vector with all the loads available for load-shedding and a vector with the corresponding bus number are created.

$$\begin{bmatrix} P_{L1} \\ P_{L2} \\ \ldots \\ P_{Ln} \end{bmatrix} \quad , \quad \begin{bmatrix} 1 \\ 2 \\ \ldots \\ n \end{bmatrix}$$

The vectors described above are sorted from the smallest load value to the highest one.

$$\text{Sort} \quad \begin{bmatrix} P_{L1} & 1 \\ P_{L2} & 2 \\ \ldots & \ldots \\ P_{Ln} & n \end{bmatrix}$$

The following cycle must be executed periodically (on a 5 minute basis, *p e*)

```
Plsi = 0 ;
for i = 1 to m
        do while PLj < Plsj
                Plsj =  Plsj + PLj
                increment j
        end ;
end ;
```

7.2. Black-Start Operation

This chapter presents the operational strategies that were found adequate to the restoring procedure for the microgrid and for black-start operation.

The restoration process for any power system is a very complicated process. The related restoration tasks are usually carried out manually, according to predefined guidelines. They have to be completed fast in a real time basis under extreme stressed conditions. In a microgrid, the whole procedure is much more simple because there are not many loads, switches and large, difficult to control production units. In addition, the power electronic interfaces of the distributed resources and loads offer considerable flexibility. Thus, the idea of creating a totally automatic system for restoration is quite realistic.

7.2.1. Black-Start of a Medium Size Isolated Network

In this section an example of restoration procedure actually used in the field when the network has to deal with a general blackout is presented. This procedure is used in French island networks [9], as described in the technical report delivered by EDF.

7.2.1.1 Definitions

Dispatcher – The HV and MV networks are under the responsibility of the **dispatcher**. His role is in particular to enforce general and special instructions related to network operation, established by the utility, in order to provide a good quality of service.

Gas Turbine operator – In a normal situation no operator stays permanently at the Gas Turbine site. But, when a failure occurs, a **Gas Turbine operator** goes on site in order to switch on the network (under the authority of the **dispatcher**).

Power system – the **power system** consists of electricity generators, overhead lines and cables, transformers and circuit-breakers, and all customers' installations. This system is managed by the **control centre**, via the **dispatcher**. The term **system** will also be used in this section and will refer to the **power system** described above.

7.2.1.2 Electric Plan of the Network

The procedure described is based on a network similar to the one shown below:

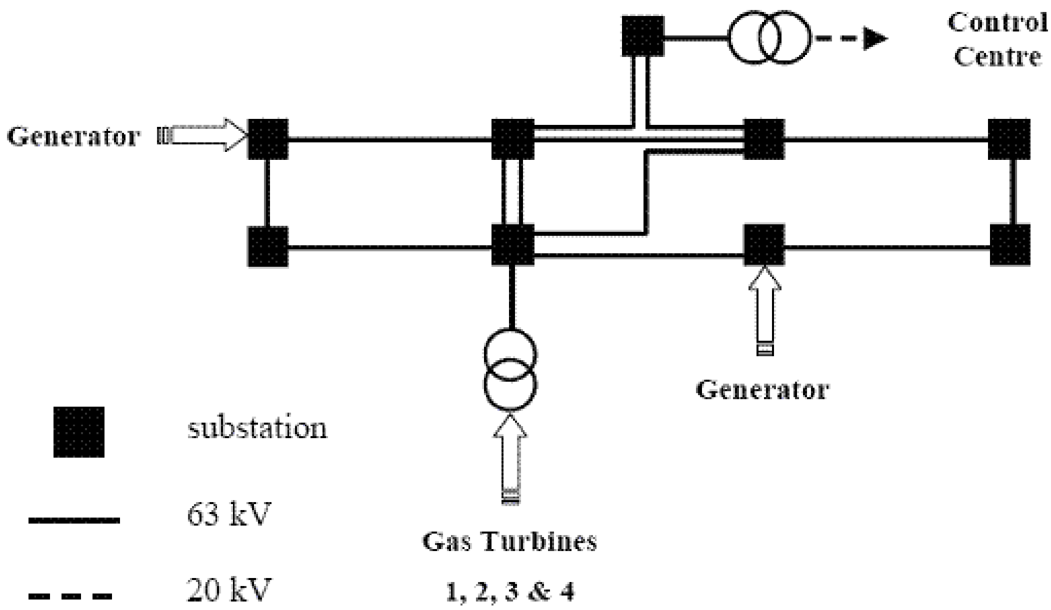

Figure 13: Electrical plan of the network

7.2.1.3 Usual Procedure

Stage 1: Verification of the state of the power system and request for the Gas Turbine operator

Before any operation, the **dispatcher** verifies the state of all generators (Generators, Gas Turbines and Standby Power Supply) and asks **the Gas Turbine (GT) operator** to go on GT site in order to release alarms on GT 4.

Stage 2: Rescue of the control centre

For the restoration of the network, under the responsibility of the **control centre**, it is essential to have an independent source of power at its disposal. This is the reason why it is equipped with a Standby Power Supply to cope with the case of a generalized failure.

In the context of the rescue of the control centre, the **dispatcher** verifies the start up of this Standby Power Supply and switches the control centre on "**safe supply**" position.

Stage 3: Preparation of the network to be supplied

The dispatcher:

• Switches off all 63 kV switchgears of the 63/20 kV transformers of the primary substations,
• Switches off all switchgears of the 20 kV feeders.

These operations consist of removing all loads existing in the network in order to limit the load to feed when the network is actually switched on

Stage 4: Supply the network by Gas Turbine (GT) 4

The **GT operator** confirms that faults are overcome in GT 4 and authorises the start up in "BLACK START".

As soon as the **dispatcher** sees the "IN BLACK START"screen on his computer, he is free to communicate with the GT 4 and to give the order "PREPARE TO SWITCH ON".

The **GT 4** receives the order and confirms to the dispatcher "GT READY TO SWITCH ON".

The dispatcher then gives the order "SWITCH ON" and verifies that the 63 kV network is live.

At this stage of the procedure, the entire 63 kV network is live.

Stage 5: Start up of other Gas Turbines

The **dispatcher** asks the **GT operator** to start the other GTs (1, 2 & 3).

Stage 6: Restoration of the network

When the 63 kV network is live and when all GT are started, the **dispatcher** carries out the operations necessary to supply the control centre from the main network, so as to follow the frequency during the restoration of the network.

These operations consist of:

• Switching on the 20 kV feeder which supplies the control centre,
• Switching the control centre from the standby power supply to the main network so as to follow the frequency,
• Connecting the available generators to the network,
• Switching on the 20 kV feeders one by one relating to the load coupled on the network.

7.2.1.4 Emergency Procedure

The usual procedure is used in priority. But an emergency procedure can be used according to the generators available on the network. Sometimes, it is possible to appeal to a private generator. In this case, a **particular command** is issued which contains the limits of the responsibilities and access conditions to private and public installations. In all cases, operations are **under the responsibility of the utility** (dispatcher).

7.2.1.5 Key Points of the Procedure

The procedure described in this section reflects the reality of the field. It is not only theoretical, it has already been tested, in particular after a blackout in 2001 in a French island.

The key points of this procedure can be summarized as follows:

1. A **usual procedure** used in priority,
2. An **emergency procedure** in case of problem with traditional generators,
3. The possibility to appeal to a **private generator** under the previously mentioned conditions,
4. The existence of **generators able to start without any external voltage source** (not all generators need to have this functionality),
5. A **Standby Power Supply** for the control centre, responsible for the restoration of the network,
6. No particular communication plant used in this case: only **telephones**, **mobiles** and **radios**.

7.2.2. Black-Start of a Microgrid

The restoration procedure on a microgrid can have some similarities with the approach adopted on a medium sized power system [9], namely: need for several sources with black-start capability and standby power supply and a monitoring and control scheme (defined through a dispatching or an MGCC). Other points should also be considered:

- **Communication facilities:** in the procedure described in the previous section, only usual means are used (telephone, radio…), and a person is required to go on site to start the turbines. In the case of a microgrid, an advanced communication system will be available. It should be checked that this communication system will be supplied in any situation. Moreover, the operation rules and the contracts should describe precisely the responsibility of producer (microsource controllers, MC) and MGCC, concerning the availability of the black-start function at its direct activation by the MGCC or after an acknowledgement.
- **Load disconnection and network separation:** in the procedure described, loads and HV/MV transformers are disconnected from the HV network through existing switchgears, so that the restoration can begin by making the no-load HV network live. In a microgrid, this same concept should be transposed and adapted. First, if there are controllable loads, switching them off during the restoration will help. Second, it should be studied how to deal with the significant frequency and voltage variations at non disconnected loads during the restoration: if they risk damaging the loads, switching devices should be added, that would be controlled by the MGCC.

INESC Porto and NTUA developed procedures handle microgrid black-start. Although the general concepts used by INESC Porto and NTUA for the development of the black-start functionalities are very similar, a different implementation was adopted by the two partners. INESC Porto proposes a set of rules identified in advance and embedded in the MGCC, while NTUA uses a Multi Agent System (MAS) approach. An important issue is that both procedures have a common rational due to the specific nature of the microsources and to the dimension of the microgrid. **Section 9.2** describes the results from the black-start sequences after simulations in *EMTP-RV*® and *MatLab*® *Simulink*® platforms.

7.2.2.1 Sequence of actions during Microgrids Black-Start

In this section, the key-lines of the blackstart procedure developed at INESC Porto are presented.

Two types of black-start functions are needed: local black-start of the microgrid after a general system blackout and grid reconnection during black-start. The strategies to be followed use the hierarchical control system of the microgrid, namely load controllers (LC), MC and the MGCC. The electrical problems to be dealt with include building the LV network, connecting microgenerators, controlling voltage, controlling frequency and connecting controllable loads. During the restoration of the LV network, load-tracking problems will arise, since some microgenerators (fuel-cells, microturbines) have slow responses and are inertia-less. Such a system requires some form of storage to ensure a fast energy balance between local generation and consumption.

For this purpose, the simulation platform under the *MatLab® Simulink®* environment was adapted in order to include black-start functionalities that will be described in the next section. According to the protection guidelines presented in [10] the microgrid would not lose the source earth at the distribution transformer in any event. In this case the microsources do not require to be earthed. Thus, when building the LV network it is necessary to energize the distribution transformer as soon as possible. This situation was simulated using *EMTP-RV®* using a detailed representation of the power electronics interfaces. After building the LV network, the other events were analyzed using the *MatLab® Simulink®* simulation platform and assuming a three-phase balanced operation.

Due to the small number of elements participating in system restoration in a microgrid (microsources, loads, breakers, etc) the procedure to be followed is quite straightforward. Because of this less complicated task, advanced optimization searching techniques that could be used to identify optimum restoration sequences (minimizing restoration time and energy non delivered) were not used. Such techniques can be adopted in larger dimension and more complex microgrids.

The main actions to be taken are based on the following assumptions: the MGCC periodically gets information from LC and MC about consumption and electric production respectively and stores this information in a database. It also has information about black-start capability of each microgenerator, or in a more detailed way, about the capabilities and services that it can offer, as well as its technical characteristics such as active and reactive power limits. In this way, the MGCC has a mapping of the available resources and limitations.

After a blackout, the MGCC will try to restore the last MG load scenario. The black-start procedure is in this case a sequence of events controlled by a set of rules stored in the MGCC and activated by local information about voltage and frequency.

If a general blackout is detected, the following actions will be commanded by the MGCC:

1. Disconnect all loads and sectionalize MG so that some microgenerators may feed its own loads.

After a general blackout, all loads should be disconnected in order to avoid large frequency and voltage deviations when energizing the network. The MG should also be sectionalized so that each microsource with black-start capability is started up and feeds its own (protected) loads. These actions lead to the creation of small islands inside the microgrid that will all be synchronized later.

2. Start energizing the LV cables and the distribution transformer using one of the microsources

MGCC will decide which microsource energizes the LV network and the distribution transformer based on information such as its rated power, load percentage or other market conditions.

3. Synchronize the other microsources with the LV network

The microsources previously started are synchronized with the LV network. With this action the power production in each microsource should not be significantly affected. Synchronization conditions (phase sequence, frequency and voltage differences) should be verified in order to avoid large transient currents.

If there are any microsources without black-start capability, they can now be synchronized with the LV network.

4. Connect controllable loads taking into account the available storage capability

If the microsources running in the LV network are not at full load and are intended to operate under market conditions, some controllable loads may be connected to the network. The amount of power to be connected should take into account the available storage capability in order to avoid large frequency and voltage deviations during load connection.

5. Connect non-controllable generators

At this stage the system has microsources and loads capable of smoothing voltage and frequency variations due to power fluctuations in non-controllable microsources like PV and wind generators. Thus they can now be connected.

6. Connect as much load as possible taking into account local production capability

All the microsources are running and can be operated under a market environment according to the MGCC instructions. Depending on production capability, loads can be connected in order to feed as much load as possible.

7. Synchronize the MG with the MV network when it becomes available

When the MV network becomes available, synchronization conditions (phase sequence, frequency and voltage differences) should be verified to avoid large transient currents during reconnection.

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 would not be possible to connect all the local loads. In this case, the remaining load can now be restored.

More developments on black-start operation will be given in a future deliverable.

7.2.2.2 Black-Start Operation of Microgrids Based on Multi Agent Systems.

In this section a MAS for the automatic restoration of a Microgrid is presented. This approach is under development in the Power System Laboratory of NTUA. The general idea is that the agents will execute all the necessary actions without human interference. Furthermore some actions are decided in advance, if possible. This approach has two main advantages. The first advantage is that the computational demand during the critical event is limited and this is very important if we consider that the time limits are very strict and the processors that will be used in a future Microgrid are not powerful supercomputers, as in large centralized power systems. The second advantage lies in the fact that during the black out there are several communication problems. Therefore the data exchange should be even more limited. The ideal situation is the one were no communication is needed (all the actions are decided in advance).

The main actions are in chronological order:

1. Identification that the system is in black out state.

The obvious solution is to measure the voltage of the grid, however there are some technical difficulties: for example since most of the voltage meters/transducers are fed by

the grid, in the black out state they will be off so the agent should have the intelligence to understand that this is due to the black out and not due to a failure of the equipment.
One critical point that has not been solved yet is how the system will identify that the black out is caused by a local fault inside the Microgrid. In this case the black start will fail but the problem is that the system might try again.

2. **Identification of which production units have start up capabilities as well as the controllable loads**

For example PV units or Wind Generators cannot start a system alone. On the contrary a battery bank or a diesel generator has this kind of capabilities. During the start up of the MAS (not the microgrid), every agent declares its capabilities and services that can it offer. This function provides to the system a mapping of the available resources and limitations. For example if the only available unit for black start is a battery bank with a 2kW inverter then the system knows how much load it could energize.

3. **Making all the necessary switching actions to prepare the network for start up.**

Before launching the units for black start some actions should be performed.

- Disconnection from the Grid. If the Microgrid is still connected to the Main Grid then the black start will fail because the grid will absorb a high value current.
- Shut down all the loads. This operation ensures that the system will not fail again because of increased demand and transient currents.

4. **Launch the black start units.**

The system starts the black start units. This operation is successful if the tracking agent (described later) will detect voltage inside the microgrid. In this case it is assumed that at least one unit has successfully started.

5. Start the loads.

The system starts one by one the loads starting from the critical loads. Avoiding to start the agents all together serves two causes:

- Avoiding overload of the system. For example the total start up current of induction machines will be reduced if they start up at different times.
- The system provides time to the non-black start units to connect to the system and to provide a smoother transition to the isolated mode by having more available power.

The system was implemented and developed in the power system laboratory of NTUA. There are two agents that are mainly involved in this task.

The first agent is the tracking agent shown in **Figure 14**. This agent is responsible for monitoring the network and detecting any black out. If a black out is detected then it sends a message to the MGCC for further actions.

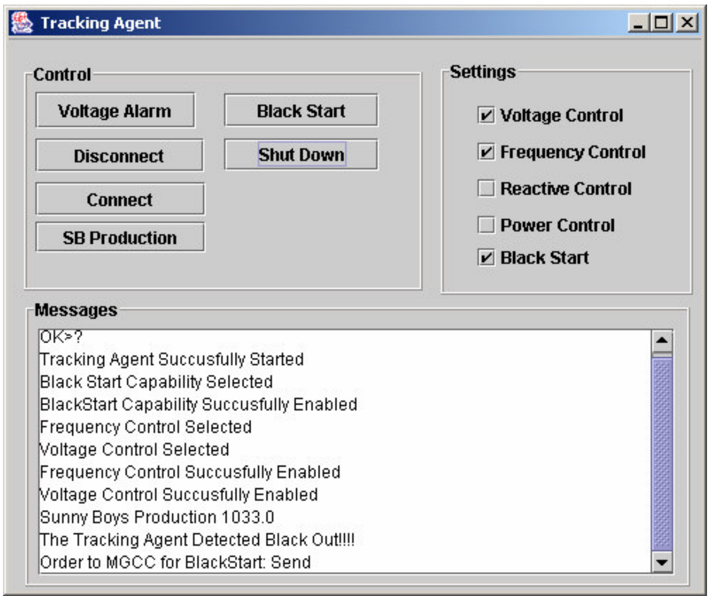

Figure 14: The screen of the tracking agent

The main form of the MGCC agent is shown in **Figure 15**. This agent is responsible for sending the start up message to the black start units as well to shut down the loads. After the start up of the units the MGCC decides which loads will open for safe operation.

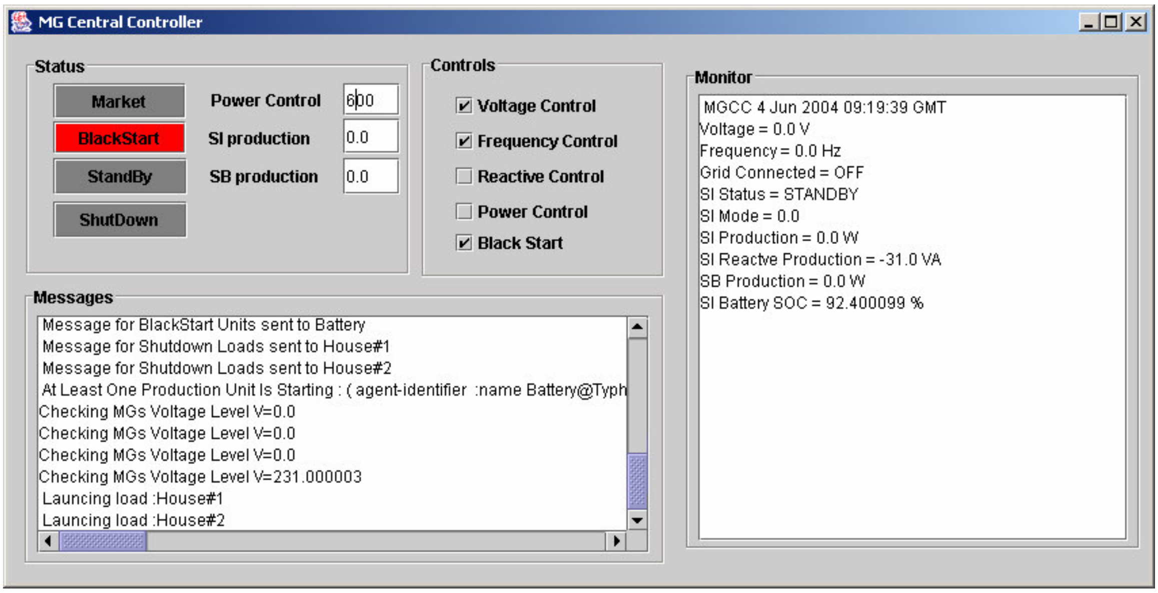

Figure 15: The screen of the MGCC agent

8. Study Case LV Networks

This chapter introduces the LV networks that were used for simulation purposes considered in this document.

The study case LV network defined by NTUA was the base for the simulation platform that was developed, with some modifications that were later introduced. A basic scheme of this network can be seen in **Figure 16**.

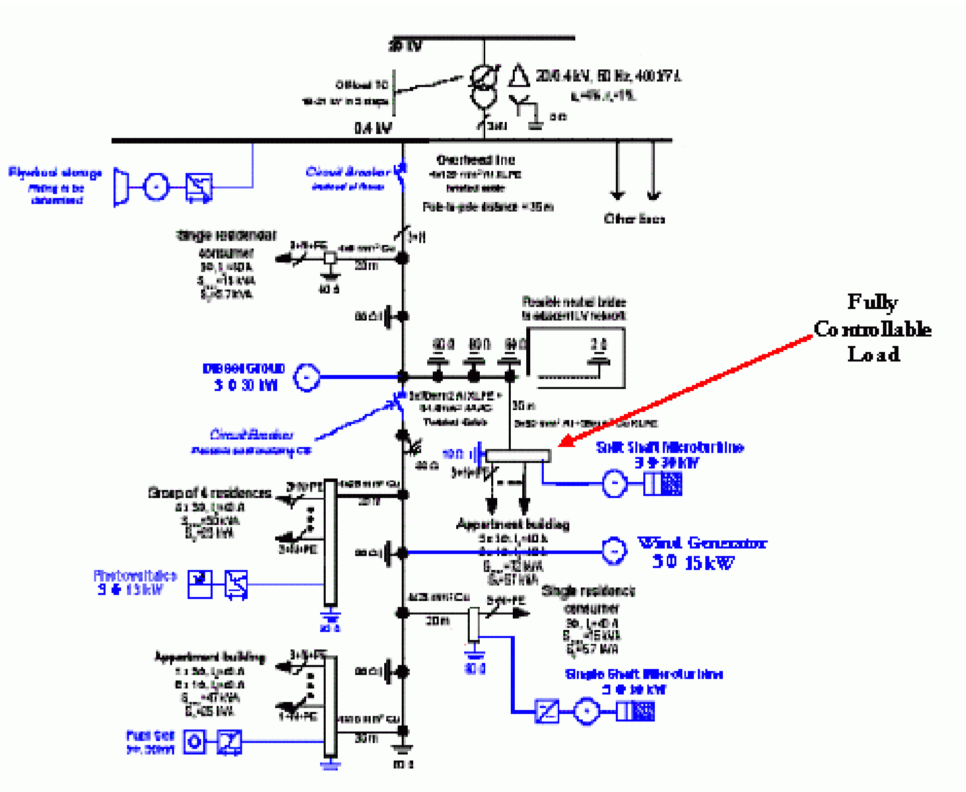

Figure 16: The NTUA LV network for the *MatLab® Simulink®* simulation platform

Two versions of the simulation platform were considered, both based on the LV NTUA network. These two versions differ in the control scheme implemented: the first considers Single Master Operation with a Synchronous Machine (**Figure 17**) and the second one considers Single Master Operation with a VSI (**Figure 18**).

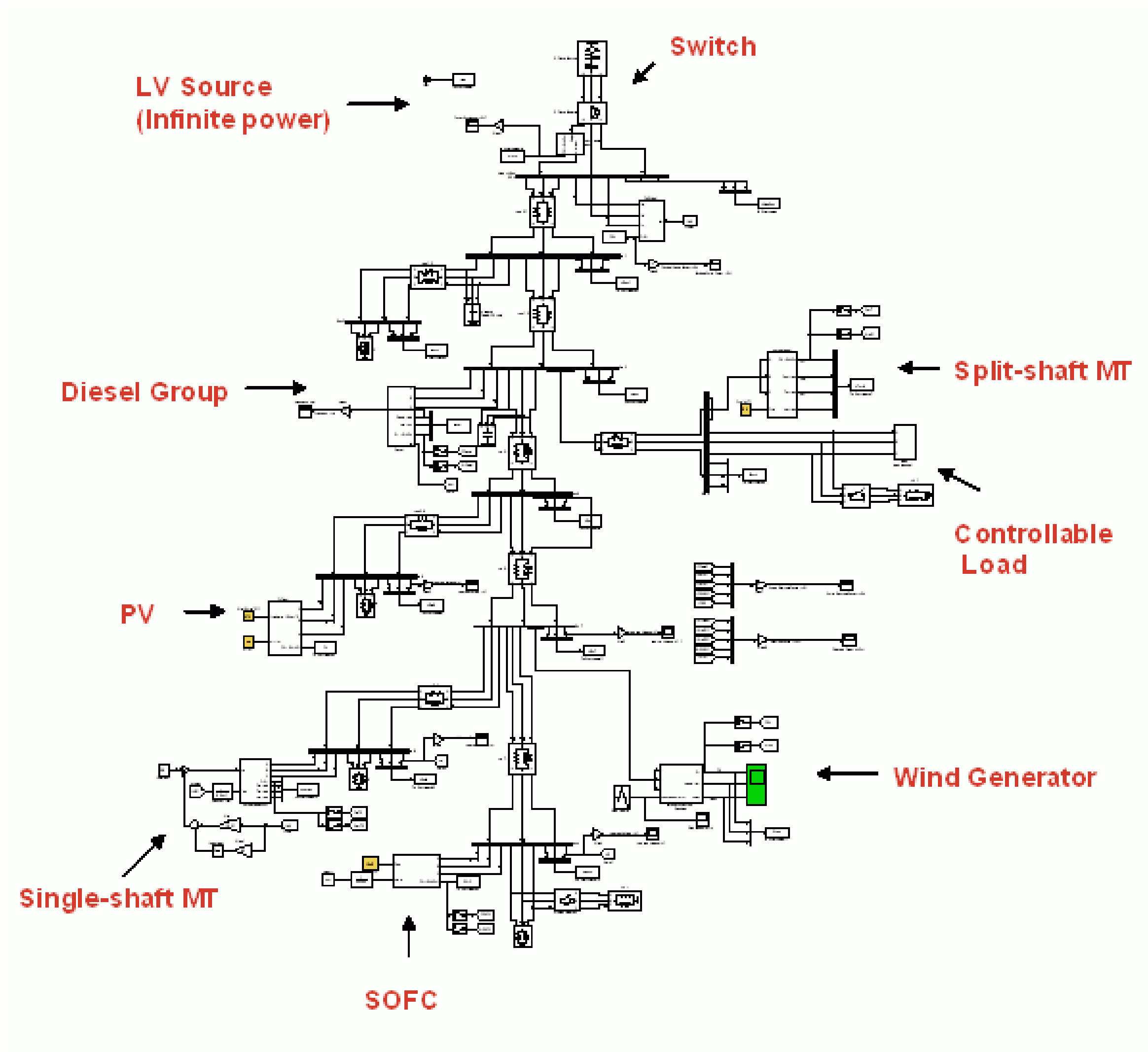

Figure 17: First version of the LV network for the *MatLab® Simulink®* simulation platform

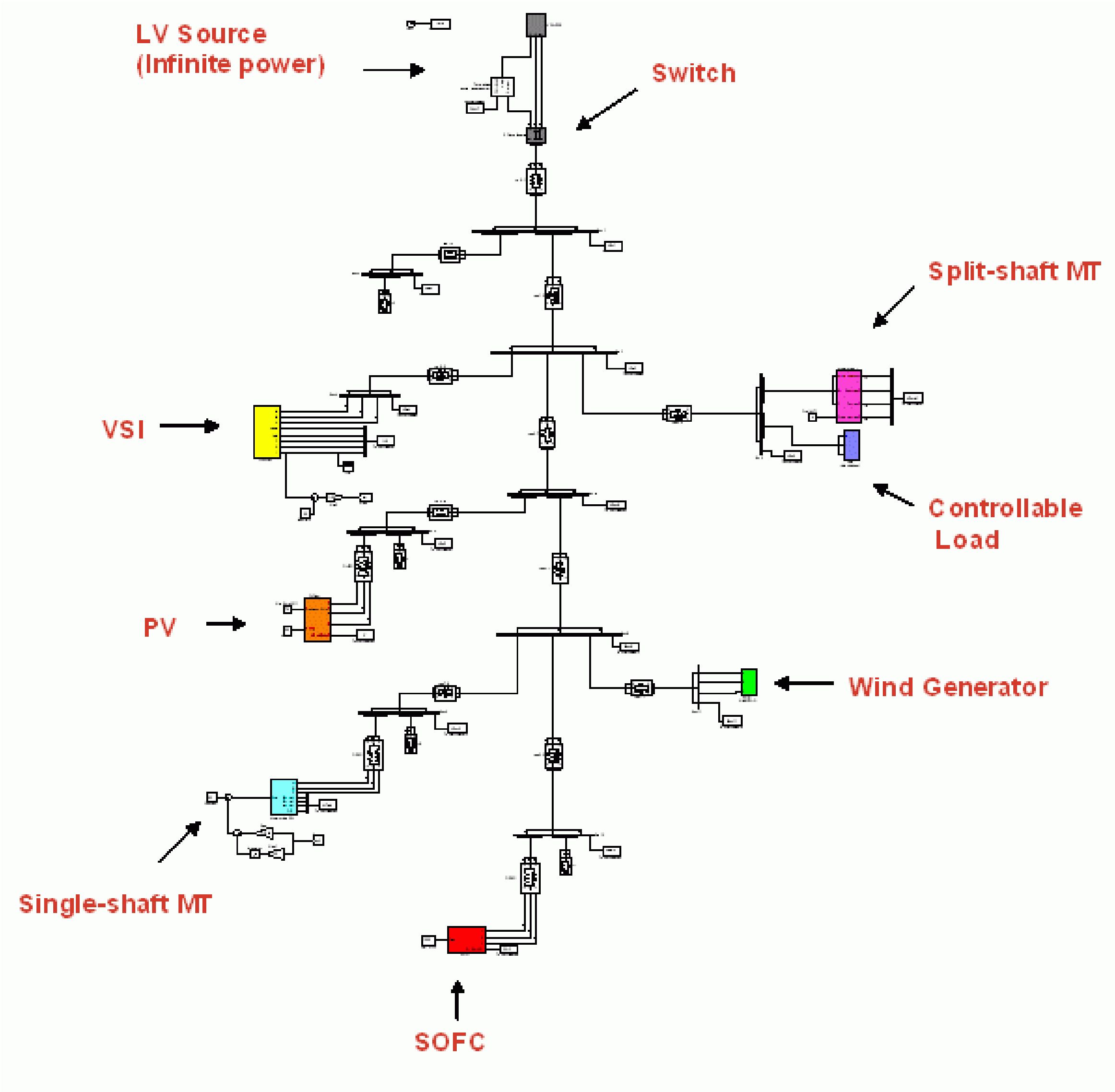

Figure 18: Second version of the LV network for the *MatLab® Simulink®* simulation platform

The simulation platform developed for the Multi Master Operation is a totally new and different network and is presented in **Figure 19**.

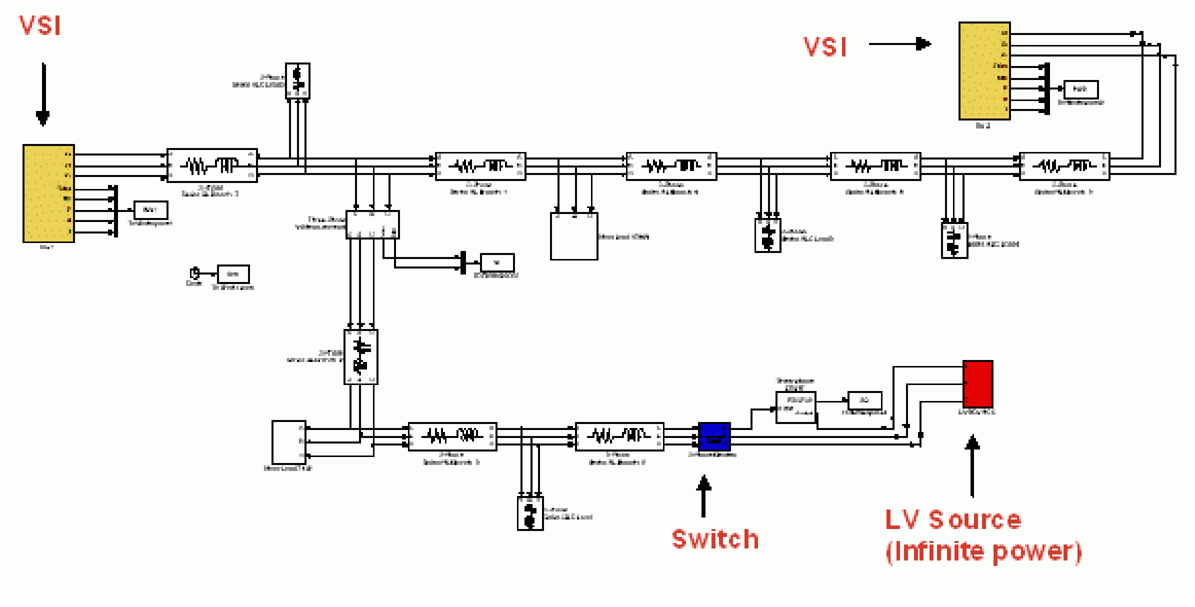

Figure 19: New LV network for the *MatLab*® *Simulink*® simulation platform

The NTUA study case LV network was also implemented in *EMTP-RV*® environment in order to perform the first steps of black start studies. Some modifications were introduced as can be seen in **Figure 20**.

It is important to notice that the simulation platforms used only consider three-phase balanced operation of the network, meaning that no one-phase loads have been contemplated.

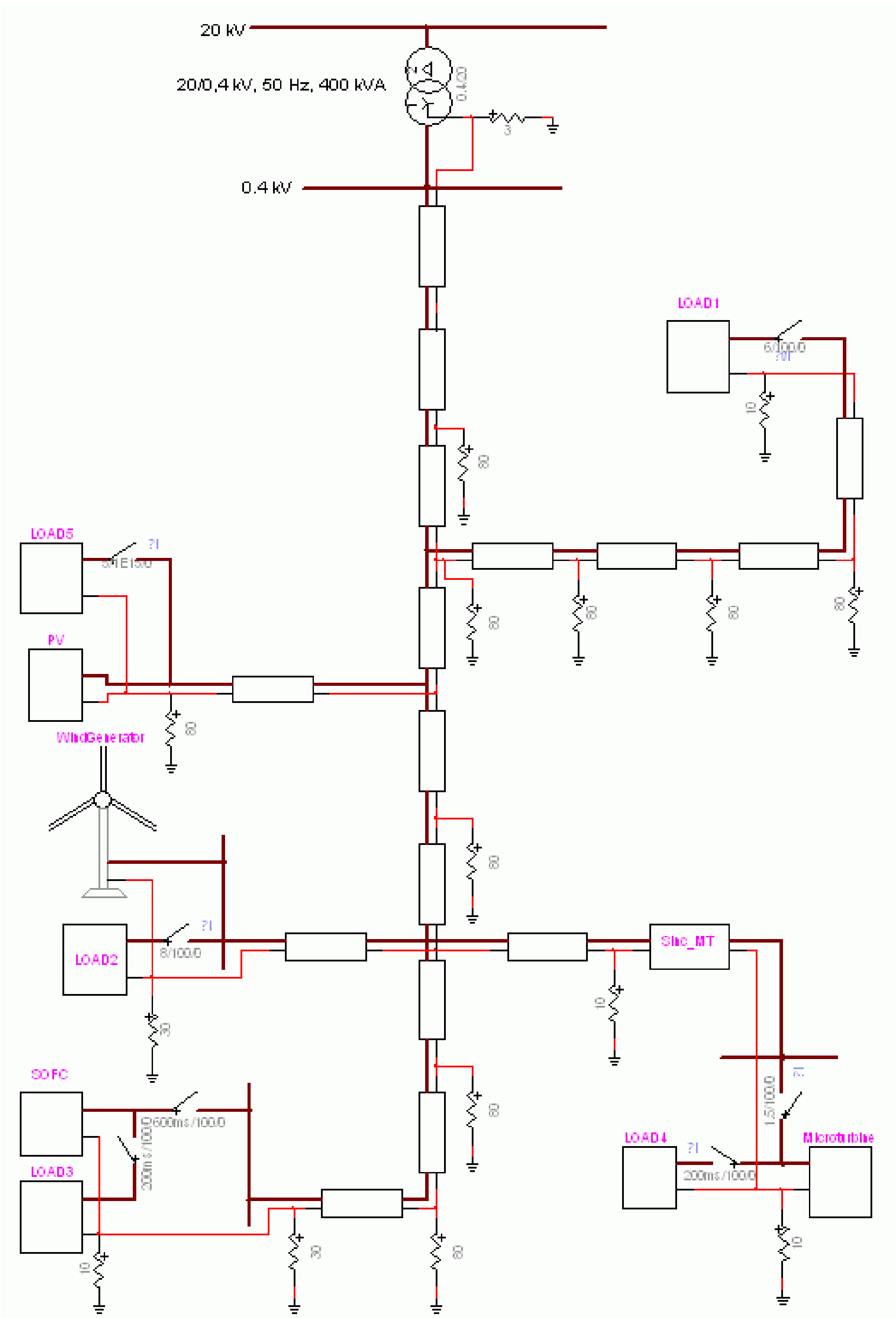

Figure 20: LV network for the *EMTP-RV®* simulation platform

9. Results from Simulations

This chapter introduces the most interesting results obtained from a large number of simulations that were performed. The main quantities will be presented and a critical analysis of the results will be made.

9.1. Islanded Operation

A set of simulation scenarios was defined for the several simulation platforms used in order to evaluate the dynamic behaviour of the microgrid. These scenarios are characterized by different load and generation levels, as well as the inclusion of different control strategies. The main objective of this strategy is to have a thorough analysis of the system's behaviour under specified conditions in order to allow comparison of the impact of different decisions in the control of the system.

To understand the dynamic behaviour of the microgrid, the disturbances that were analysed included disconnection from the upstream MV network and load-following in islanded operation.

Several scenarios were simulated; however, only the most important results will be presented.

The results are structured according to the three control strategies previously described.

9.1.1. Results from Single Master Operation with a Synchronous Machine

The number of successful dynamic simulations performed to develop an on-line security assessment function for the MGCC [6] proves the robustness of the control parameters chosen. What really influence the dynamic behaviour of the microgrid are the control parameters of the storage devices used.

The disconnection of the upstream MV network was simulated for t=10 seconds and the simulation results are presented for the main electrical quantities.

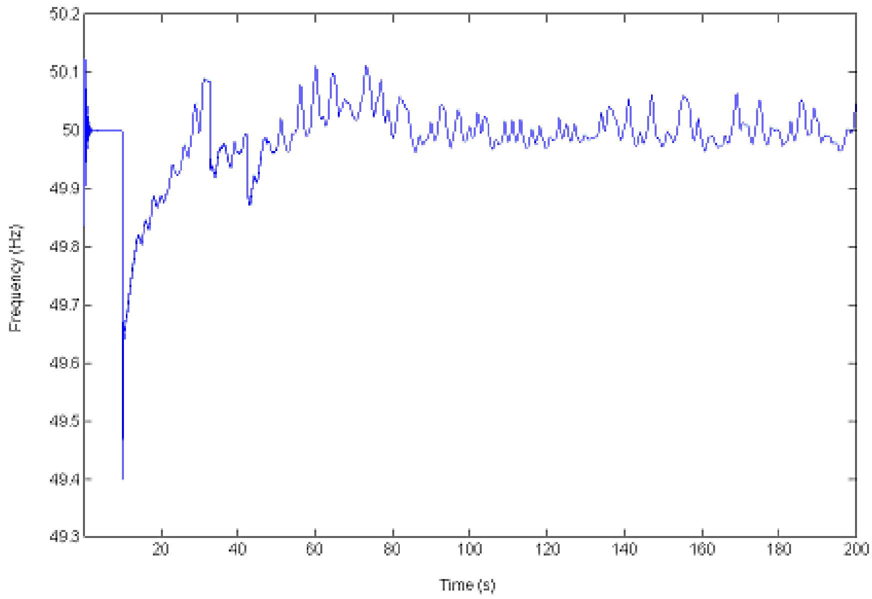

Figure 21: System frequency

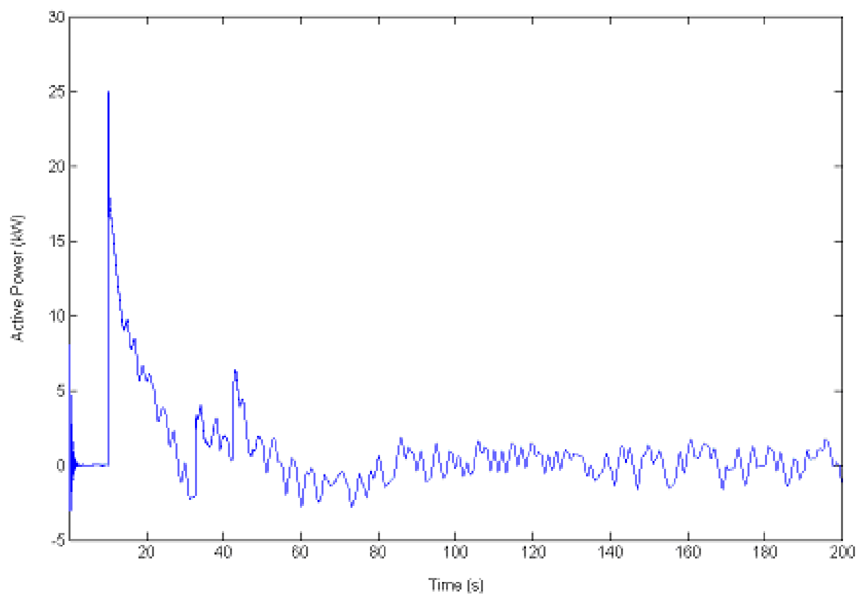

Figure 22: Active electrical power in the flywheel

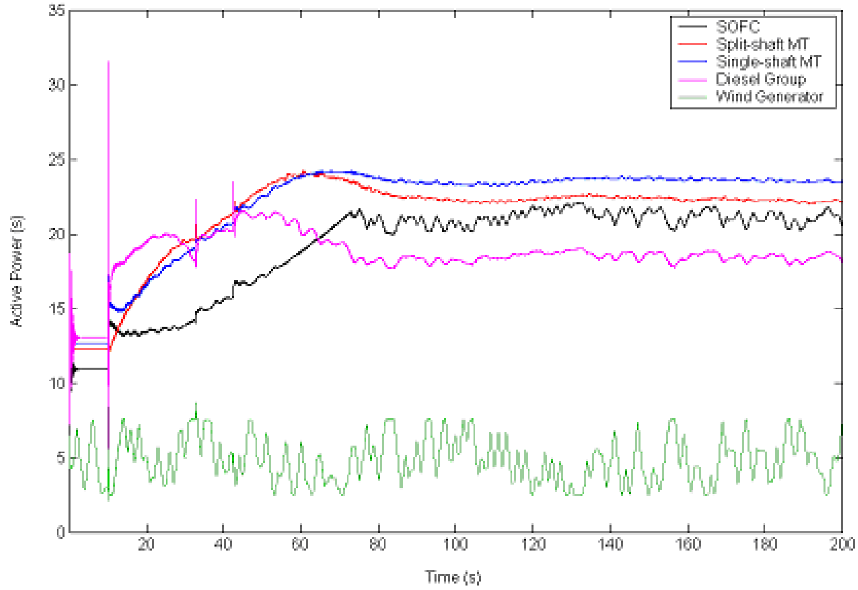

Figure 23: Active electrical power in several microsources

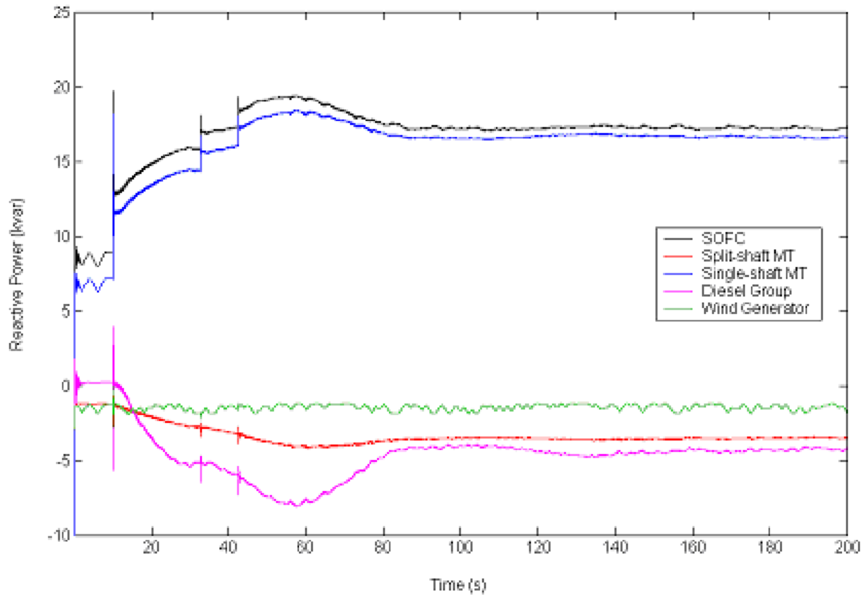

Figure 24: Reactive electrical power in several microsources

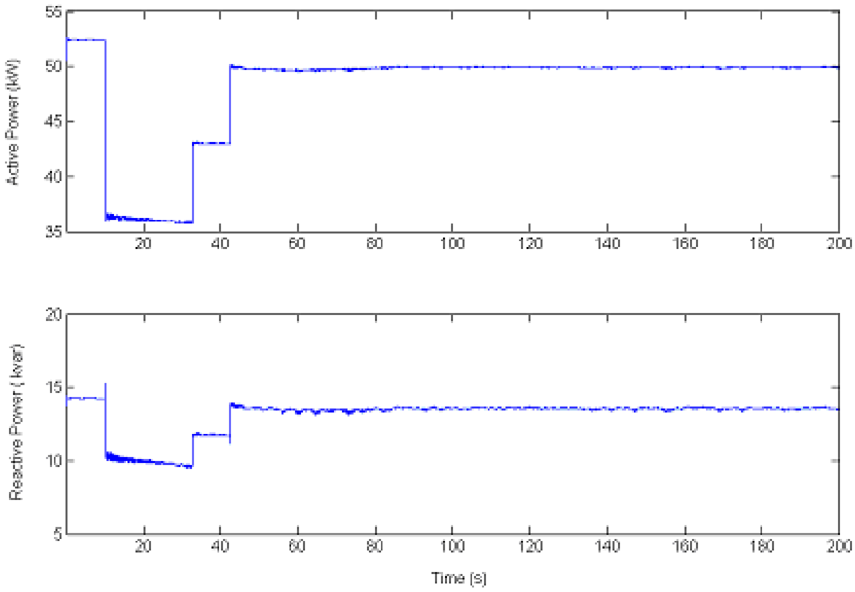

Figure 25: Active and reactive power in the fully controllable load

If the time interval assumed as the minimum time in which the frequency is smaller than a pre-defined value to allow the activation of the load-shedding is reduced, a smaller frequency deviation would be expected. On the other hand, the time interval in which the frequency is lower than 49.7 Hz is very short. Bearing these options in mind, a choice was made, trying to minimize the load put out of service.

After a controlled time interval, the load is reconnected to the system in steps, as it can be observed in **Figure 25**.

Special mention should be made to the irregular wave form of frequency, and both active and reactive powers, which is due to the presence of the wind generator fed by inconstant wind velocity.

9.1.2. Results from Single Master Operation with a VSI

After finding suitable control parameters for the VSI, it was verified that the set of parameters is robust enough to provide a large number of simulations. It was also verified that the local PI control parameters implemented in the single-shaft microturbine and in the SOFC for frequency restoration are not of major importance to define the dynamic behaviour of the overall system.

The disconnection of the upstream MV network was simulated for t=10 seconds and the simulation results are presented for the main electrical quantities.

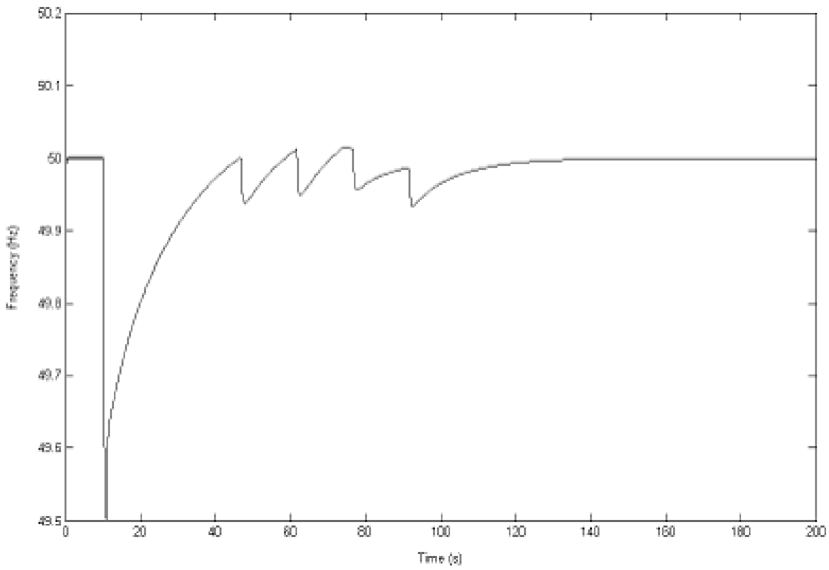

Figure 26: System frequency

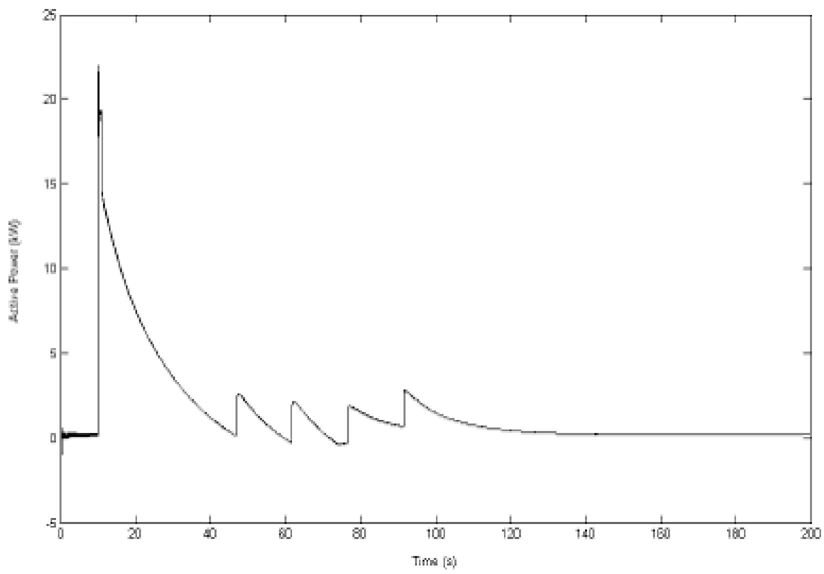

Figure 27: VSI active electrical power

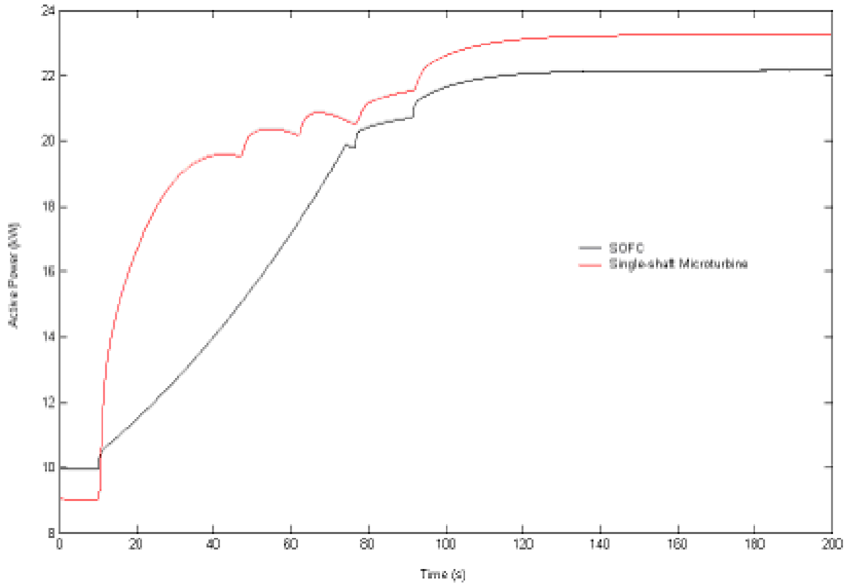

Figure 28: SOFC and single-shaft microturbine active electrical powers

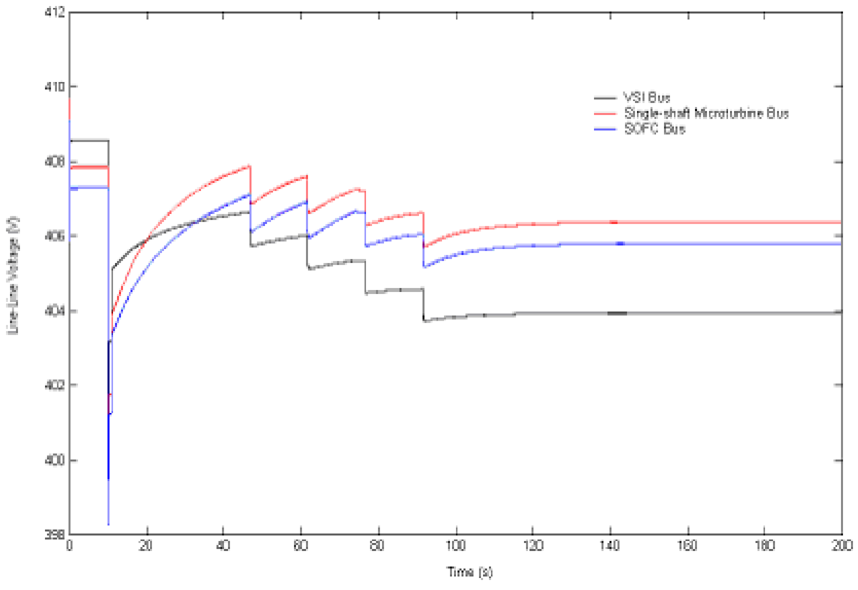

Figure 29: VSI, single-shaft microturbine and SOFC voltages

The four load reconnection steps are clearly shown in **Figure 26** and **Figure 27** and it can also be seen that the load-shedding strategy implemented seems to have good results given that stability is quickly restored to the system.

9.1.3. Results from Multi Master Operation

The microgrid operation using the multi master concept was tested using a different LV network where it is possible to identify impedance and motor loads (with constant torque load).

As already stated, the VSI model used in the multi master operation assumes that a high storage capacity in the DC link is available; as a consequence, the dynamics of the microsource were neglected.

Load-shedding was not implemented in this simulation platform. However it is convenient to notice that this emergency strategy must be evaluated in close coordination with the investment required to obtain a certain level of storage capacity in a LV network: a smaller amount of storage capacity requires higher load-shedding levels.

A set of typical parameters was used to control each VSI. In order to investigate the robustness of the control parameters, 800 scenarios were simulated (each scenario corresponding to different levels of load and local microgeneration). From the results obtained it was possible to make sure that the control parameters are robust enough to deal with the stability problem. Due to this conclusion, further research modes to find other control parameters were kept unexplored. However, a problem was identified: in some scenarios, it was necessary to adjust the idle voltage set point (V_0) in order to avoid large reactive power flows. This is a reactive power dispatch functionality that can be controlled by the MGCC depending on the microgrid load and local microgeneration.

The disconnection of the main power supply was simulated for t=5 seconds; the simulation results are presented for the main electrical quantities.

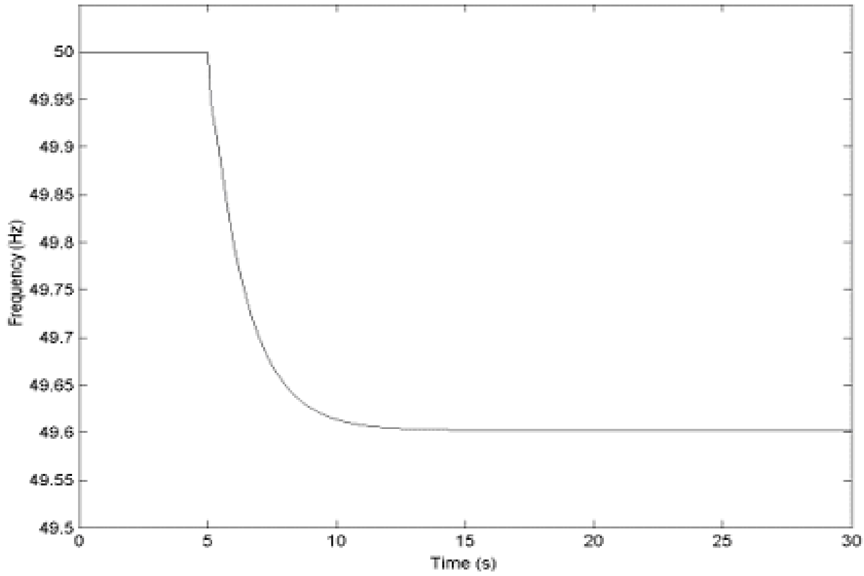

Figure 30: System frequency

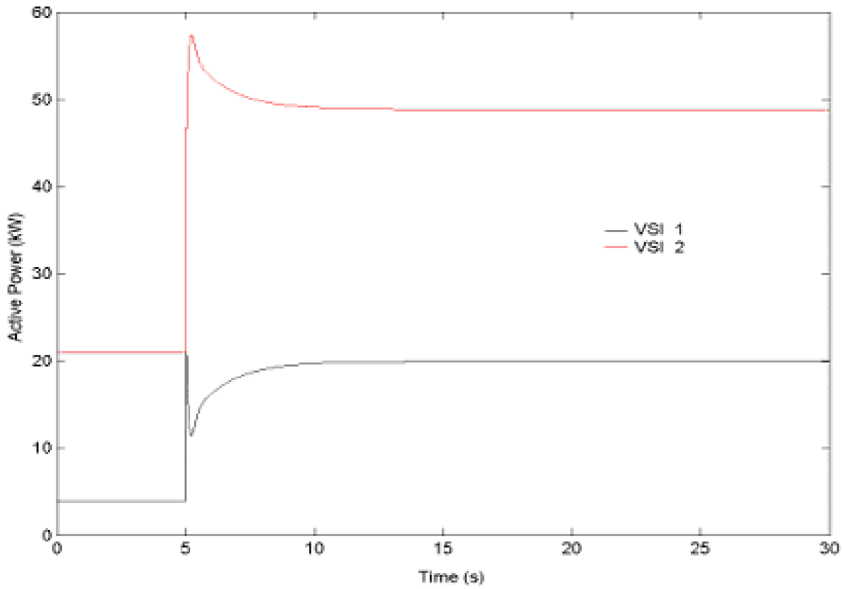

Figure 31: Active electrical power in each VSI

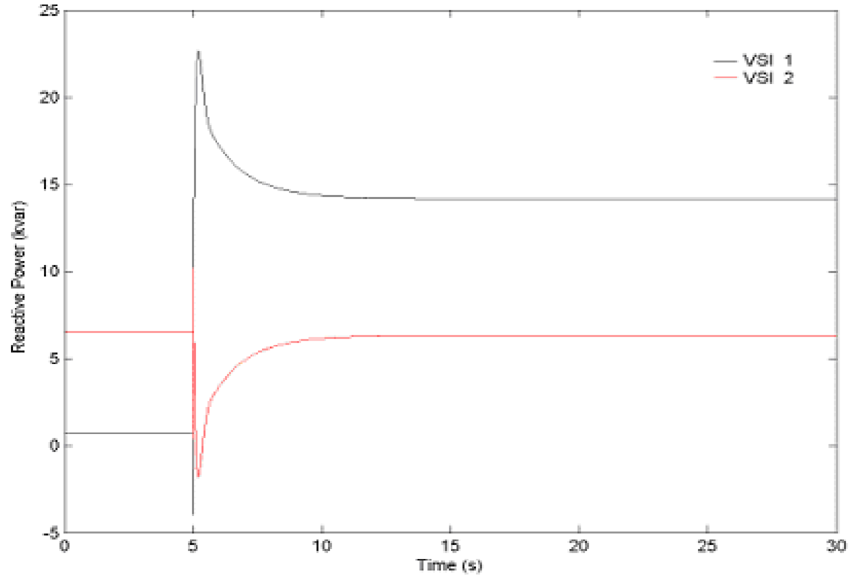

Figure 32: Reactive power in each VSI

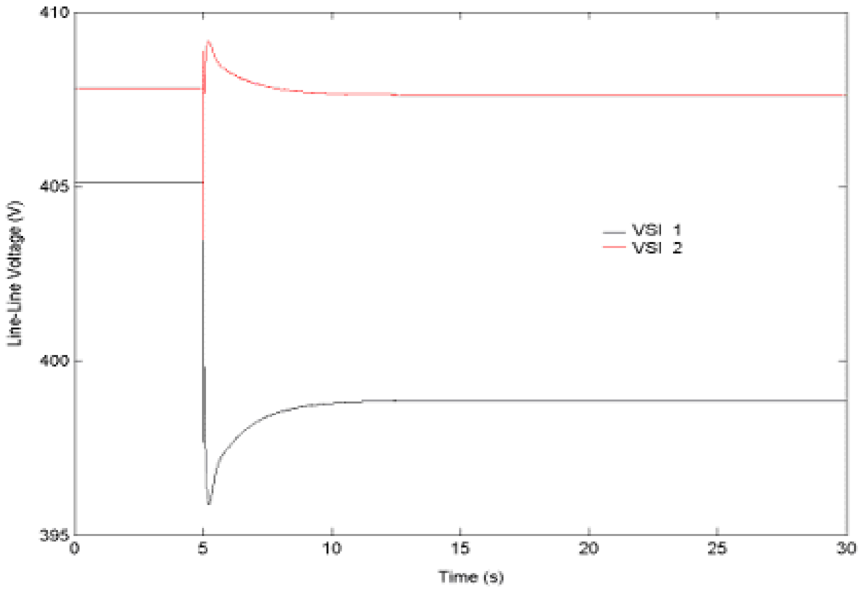

Figure 33: VSI voltage

It should be noticed that the frequency has an offset in steady-state since the PI control (which would restore the frequency to the nominal value of 50 Hz) was not implemented.

9.2. Black-Start Operation

As previously mentioned, two different simulation platforms were used in order to simulate the event sequence of microgrid black-start procedure. The first steps of restoration procedure were implemented in *EMTP-RV®* environment in order to simulate the transient behaviour of starting to energize the LV cables and the distribution transformer, taking into consideration the inverter switching details. Due to the heavy computational burden when using *EMTP-RV®*, the subsequent steps of the black-start procedure were simulated in *MatLab® Simulink®*.

The restoration procedure is carried out with the aim of supplying the consumers as soon as possible. To do this, the production must first be restarted and then the network must be strengthened in order to maintain secure and stable operation while providing good quality power to the consumers.

It was assumed that microsources with black start capability (single-shaft microturbine and SOFC) have storage devices and their power electronic interfaces are operated as VSI's as described in **Section 6**. The wind generator has no black-start capability and is directly connected to the network during the process. The PV´s are connected to the network using a PQ inverter as mentioned in **Section 5**.

9.2.1. Building the LV Network

In this section, it was assumed that the microsources with black-start capability had already received a start-up command from the MGCC and are running and feeding their own protected loads.

Several simulations were performed using *EMTP-RV®* in order to find the most suitable way to energize the distribution transformer. When energizing from the LV side, a very high inrush current (a peak of 1200 A) can be observed if the impedance between the microsource that energizes the LV network and the transformer is small. This behaviour is not desirable due to the physical limitations of the switching devices used in the VSI. For this purpose, the SOFC was selected to energize the LV cables as well as the distribution transformer. Thus, the cable resistance limits the inrush current and duration of this transient period because the time constant (L/R) is decreased.

The distribution transformer is energized at t=600 milliseconds. These results are presented in **Figure 34**.

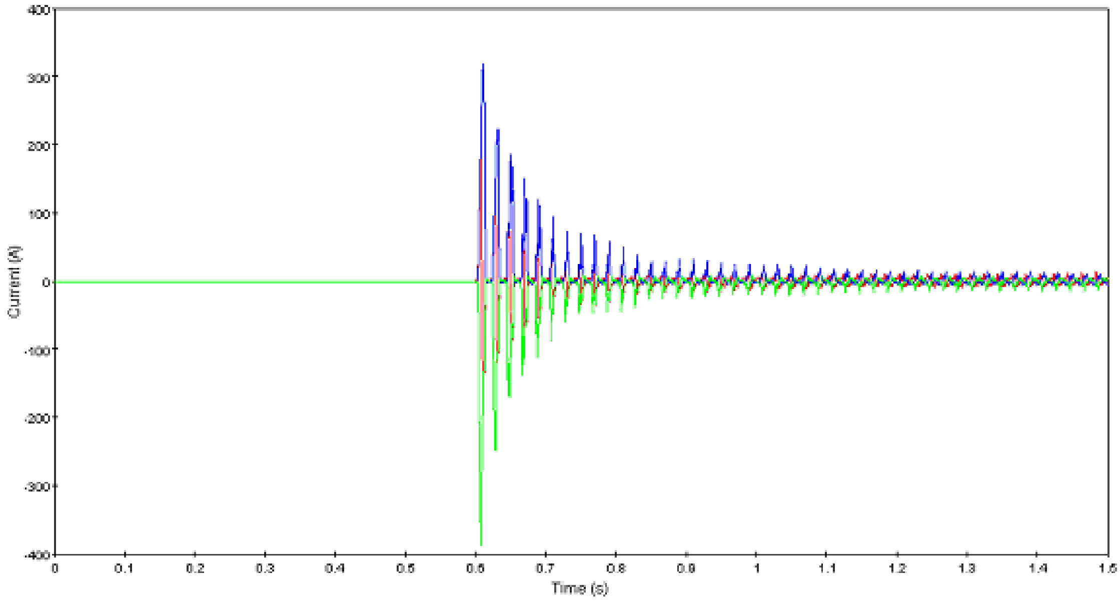

Figure 34: Distribution transformer inrush current

As proposed in **Section 7.2.2.1**, the next step is the synchronization of the two microsources operating in stand-alone. To do this, it is necessary to check the basic conditions for synchronizing three-phase systems: the phase sequence of the two systems should be the same and the phase and voltage difference should be less then a pre-defined error to avoid large synchronizing currents and power exchanges. To check these conditions, the MGCC changes the frequency of SOFC (0.15 Hz) for a small time period and also adjusts the voltage magnitude of the two VSI so that, when the synchronization occurs, the voltage difference between them is less then 5 V. The microturbine synchronization was simulated in *EMTP-RV®*.

At t=200 milliseconds the SOFC and the microturbine own loads are connected. The microturbine synchronizes at about t=3.8 seconds and some load is connected at t=6 seconds. The results are shown in the next figures.

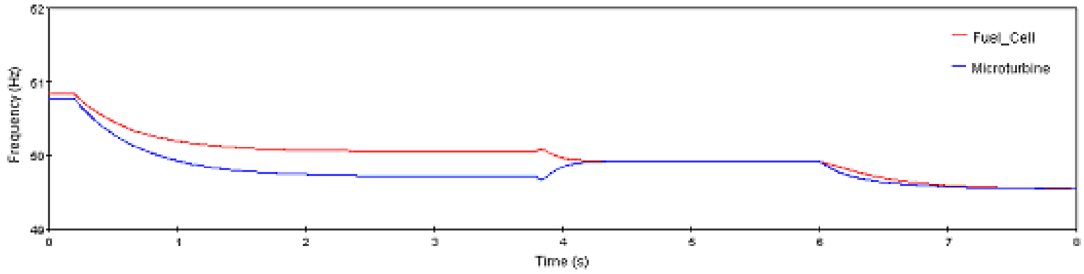

Figure 35: Frequency in each VSI

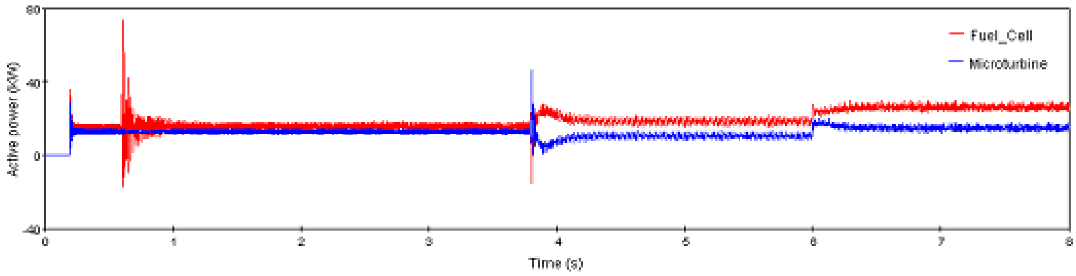

Figure 36: Active power in each VSI

The plot of active powers in **Figure 36** shows oscillations. As mentioned in [11] these oscillations are the result of 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 [11]. One effective mean of damping these oscillations is the introduction of a series active filter between the capacitor and the AC system bus [12]. This filter presents low resistance to the fundamental wave form and high resistance to higher order harmonics, therefore effectively limiting the harmonic current injection into the AC system. The introduction of a series active filter was explored in *EMTP-RV®* environment and in fact the active power oscillations were damped.

9.2.2. Loads and Non-Controllable Microsources Connection

In the previous section, the procedure to build the LV network and some simulation results were presented. In this section, the procedure presented was also tested in *MatLab® Simulink®*, although using the simplified model for VSIs. Assuming that the SOFC and single-shaft microturbine can produce more power to supply a higher amount of load than its own protected loads, it is possible to connect more loads, taking into consideration the storage capability of the system. Non-controllable microsources (PV´s and wind generator) will be connected as soon as possible. The connection of this kind of microsources should be done when the network has loads and controllable microsources capable of smoothing voltage and frequency variations due to wind or solar power fluctuations.

Due to the load connection, special attention should be given to frequency deviations. To avoid large frequency deviations, a local secondary control was implemented for frequency restoration if the frequency deviation is maintained for a large time interval. In what concerns the voltage and reactive power control, it can be easily performed by adjusting the droop settings of each VSI or the reactive set-point of PQ inverters.

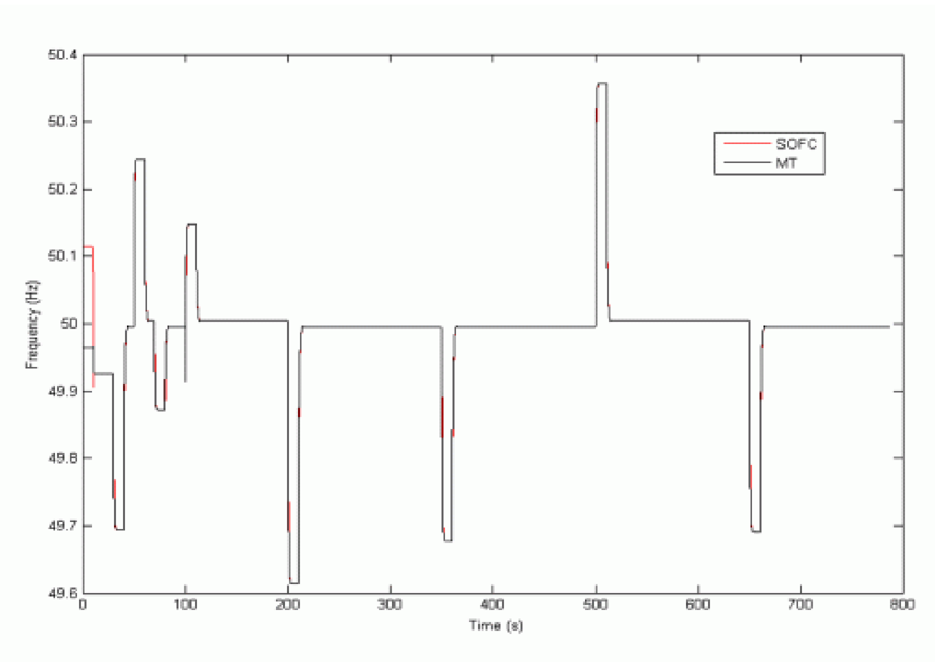

Figure 37: Frequency in each VSI

The sequence of events simulated is presented next:

At t=0 seconds the frequency of the SOFC's VSI is changed

At t=10.5 seconds the ideal conditions for synchronization of the two microsources are verified and the network switches are closed

At t=30 seconds, a load is connected near the SOFC bus; as a consequence the frequency decreases and 10 seconds later the secondary control starts acting to correct it; the secondary control acts when frequency deviations are higher than 0.1 Hz for a time period larger then 10 seconds

At t=50 seconds the PV panel is connected (at constant output power)

At t=70 seconds a new load is connected

At t=100 seconds the wind generator is connected (with constant wind speed)

At t=200 seconds a new load is connected

At t=350 seconds a new load is connected

At t=500 seconds the wind speed feeding the wind generator is increased

At t=650 seconds a new load is connected

The output power of each VSI is shown in the next figure:

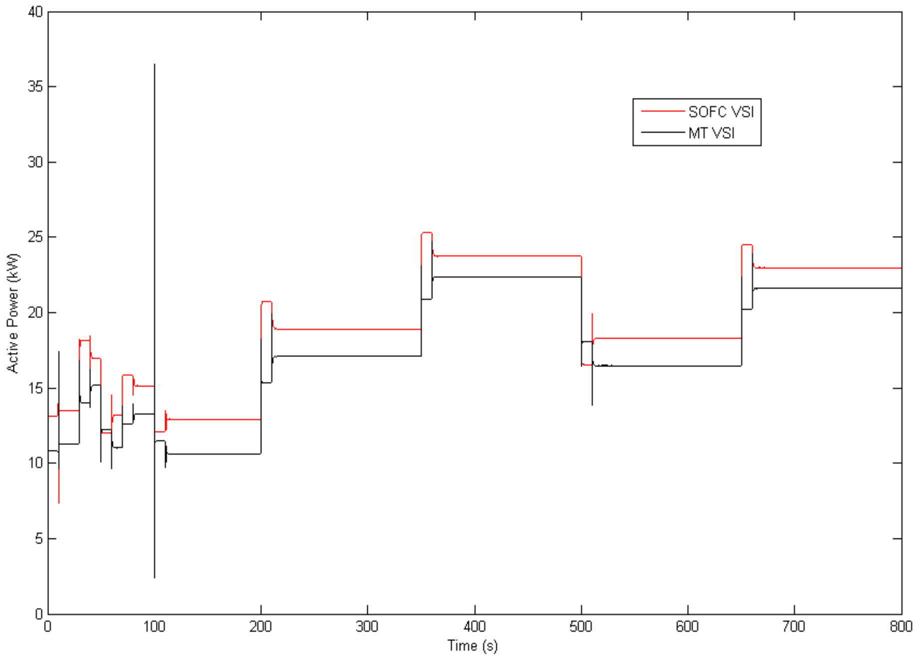

Figure 38: Active power in each VSI

The primary sources (SOFC and microturbine) are linked to the VSI via a large storage device. The output power of each primary source is shown in the next figure:

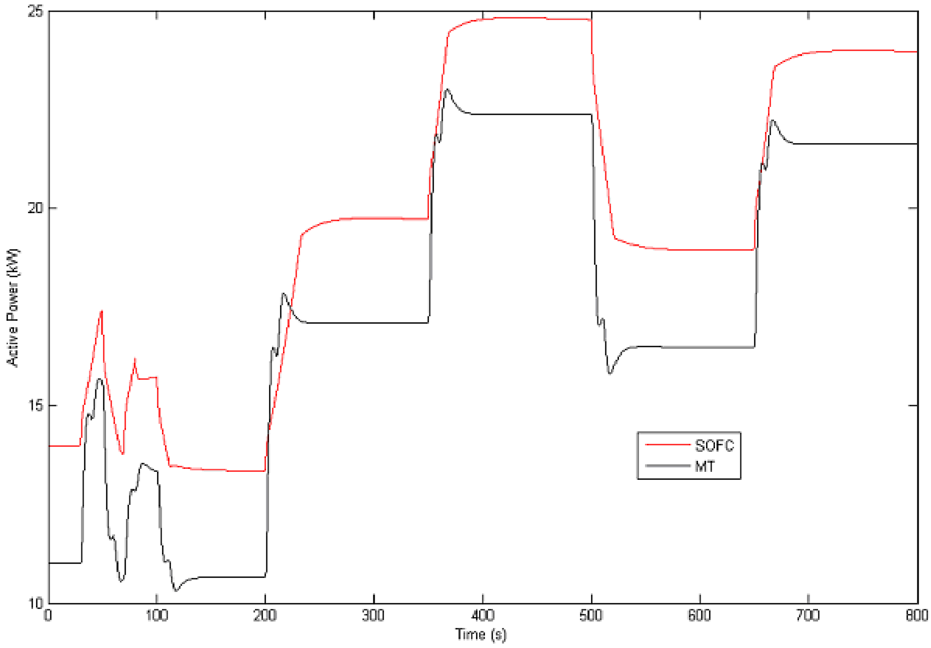

Figure 39: Active power in the primary sources

Voltage control is another issue that must be addressed. The droop control of VSI is able to maintain the network voltage within acceptable limits.

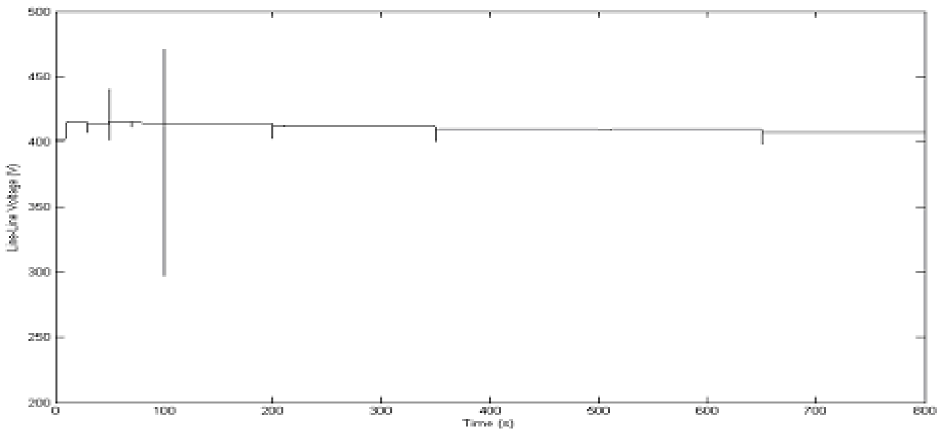

Figure 40: Line-Line Voltage at the MT Bus

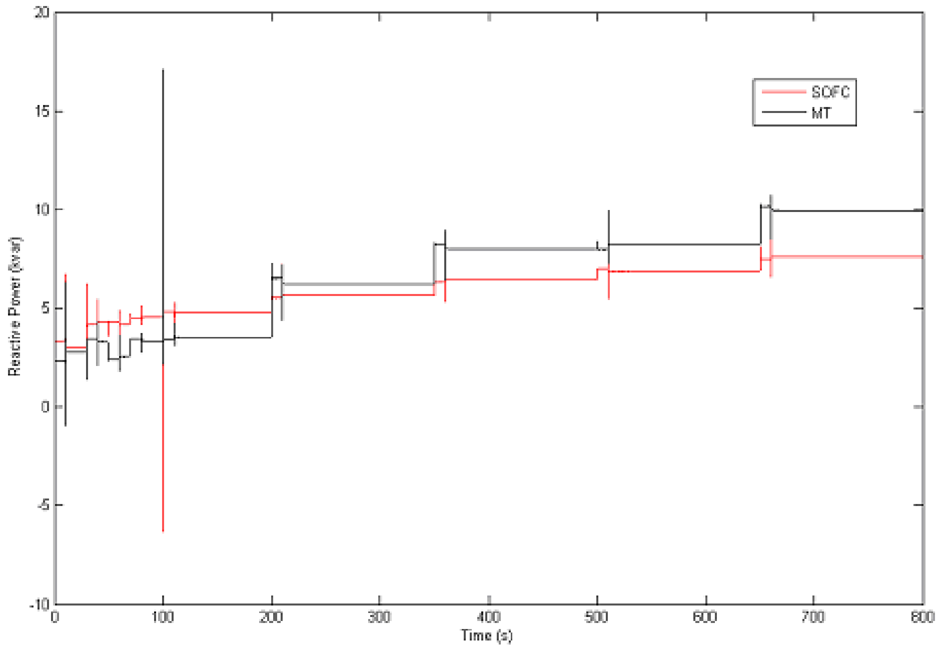

Figure 41: Reactive power in each VSI

9.2.3. Synchronizing the Microgrid with the Upstream MV Network

In order to check the synchronization conditions, the frequency and voltage of each source inverter are slightly changed. At t=1.5 seconds, the frequency of each VSI is changed; at t=9.1 seconds, the necessary conditions for the synchronization are verified and the MV switch is closed. At t=12.5 seconds, the VSI's idle frequencies are set to the initial values in order to maintain the same levels of active power injection to the microgrid.

The results of the synchronization of the microgrid with the upstream MV network are presented in **Figure 42**.

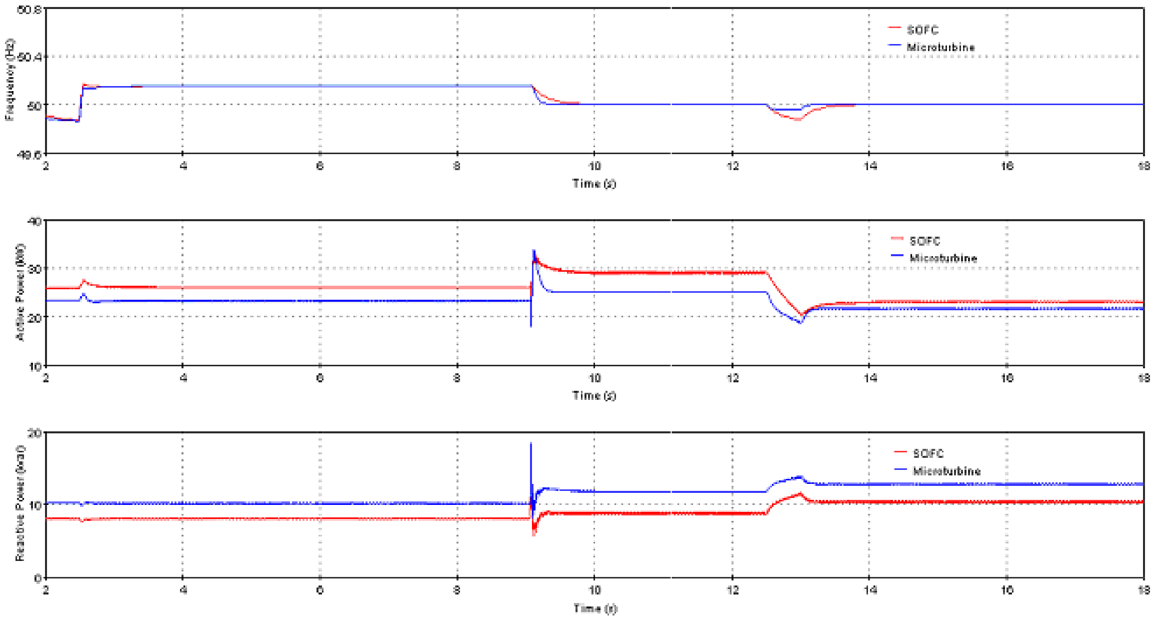

Figure 42: Synchronization of the microgrid with the MV network

The current in the LV side of the distribution transformer during the synchronization process can be observed in the following figure:

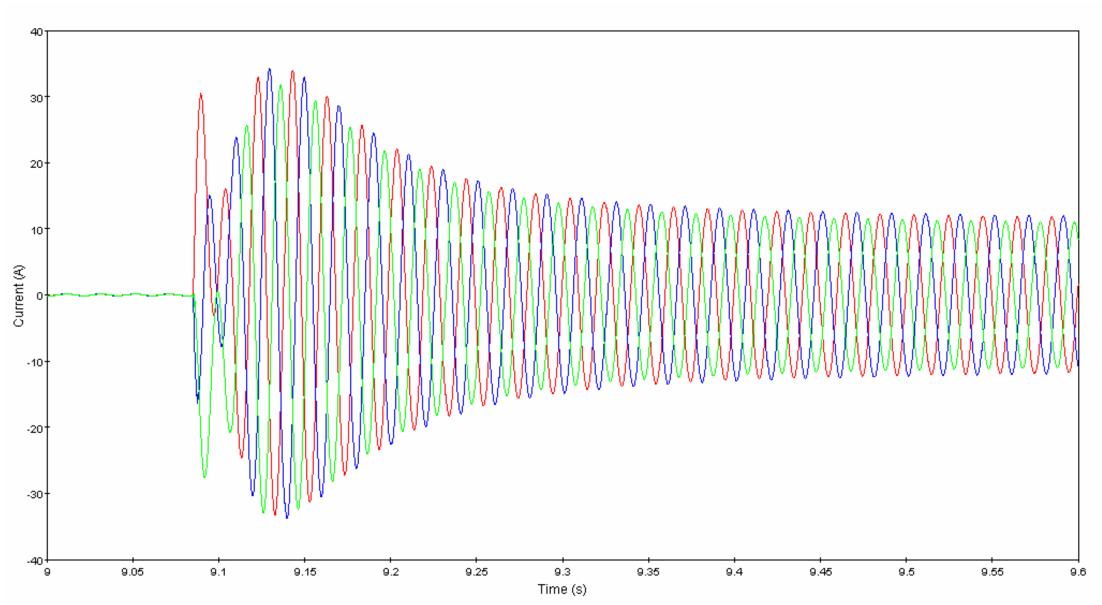

Figure 43: Synchronization current in the LV side of the distribution transformer

10. References

[1] Kariniotakis, G.; et al, *DA1 – Digital Models for Microsources*, MicroGrids project deliverable of task DA1, 2003

[2] Kariniotakis, G.; et al, *DA2 – Analytical Tools for MicroGrids Analysis*, MicroGrids project deliverable of task DA2, 2004

[3] Barnes, M.; Goodwin, A.; Jayawarna, N., *Flywheel Modelling*, UMIST/URENCO draft report, 2002

[4] Akagi, H.; Kanazawa, Y.; Nabae, A., *Instantaneous Reactive Power Compensators Comprising Switching Devices without Energy Storage Components*, IEEE Transactions on Industry Applications, 1984

[5] Barsali, S.; Ceraolo, M.; Pelacchi, P., *Control techniques of Dispersed Generators to improve the continuity of electricity supply*, IEEE, 2002

[6] Hatziargyriou, N.; et al, *DC1 – MicroGrid Central Controller strategies and algorithms*, MicroGrids project deliverable of task DC1, 2004

[7] Engler, A.; et al, *DB1 – Local Micro Source controller strategies and algorithms*, MicroGrids project deliverable of task DB1, 2004

[8] Kundur, P., *Power System Stability and Control*, McGraw-Hill, 1993

[9] Duvauchelle, C.; *Procedure of restoration of an island power system after a complete blackout*, MicroGrids technical report of task DD3, 2003

[10] Jayawarna N., et al, *Review of Earthing in a Microgrid,* DRAFT Issue No 1, MicroGrids project deliverable of WP E, 2004

[11] Chandorkar M., et al, *Control of Parallel Connected Inverters in Standalone ac Supply Systems*, IEEE Transactions on Industry Applications, VOL 29, No 1, 1993

[12] Bhattacharya, S., et al, *Synchronous frame harmonic isolator using active series filter*, Proc. 4th Euro. Conf. Power Electron. Applications (Florence, Italy), VOL 3, 1991.

UMIST CONTRIBUTION

Contents

1. Introduction

Micro-scale distributed generators (DGs), or micro sources, are being applied increasingly to provide electricity for the expanding energy demands in the network. The development of micro DGs also helps to reduce greenhouse gas emissions and increase energy efficiency.

The MicroGrid usually consists of a cluster of micro DGs, energy storage systems (e.g. flywheel) and loads, operating as a single controllable system. The voltage level of the MicroGrid at the load is about 400 Volts or less. The architecture of the MicroGrid is formed to be radial with a few feeders. It often provides both electricity and heat to the local area. It can be operated in both grid-connected mode and islanded mode

The micro DGs existing in the distribution network mainly use rotating machines. They are directly connected to the grid to supply electric power. However, the new technologies (e.g. micro gas turbine, fuel cells, photovoltaic system and several kinds of wind turbines) proposed to be used in MicroGrid are not suitable for supplying energy to the grid directly [Barsali, 2002]. They have to be interfaced with the grid through an inverter stage. Thus, the use of power electronic interfaces in the MicroGrid leads to a series of challenges in the design and operation of the MicroGrid. One of the main challenges is local frequency control of the MicroGrid operated in islanded mode.

It is well known that frequency has a strong coupling with active power in the network [Kundur, 1994]. The value of the frequency is a function of the difference between generation and demand plus network losses. If demand increases, the frequency will fall unless there is a matching increase in generation. If generation increases, the frequency will rise unless there is a matching increase in demand. The rate of change of frequency depends on the inertia of the system. The larger the inertia, the smaller the rate of change. During a disturbance, the frequency of the MicroGrid may change rapidly due to the low inertia (or zero inertia) present in the MicroGrid. In grid-connected mode, the frequency of the MicroGrid is maintained within a tight range (50±0.2Hz) by the main network. However, in islanded mode, with relatively few micro sources, the local frequency control of the MicroGrid is not straightforward.

Obviously, the control of the micro sources and the flywheel is very important to maintain the frequency of the MicroGrid during islanded operation. The controllers of the micro sources and flywheel inverters respond in milliseconds. For basic operation of the MicroGrid, the controllers should use only local information to control the flywheel and micro sources. Communication between the micro sources and flywheel is unnecessary. For a micro source, the inverter should have plug and play capabilities [Lasseter, 2002]. Plug and play implies that a micro source can be added to the MicroGrid without any changes to the control of the units, which are already a part of the network. For the flywheel, the inverter should be able to respond to the change of load in a predetermined manner automatically.

Possible control strategies of the micro sources and the flywheel may be: (a) PQ control (fixed power control), (b) Droop control and (c) Frequency/Voltage control. PQ control is adopted so that the micro sources and the flywheel run on constant power output. The electricity, generated by the micro source, may be constant because of the need of the associated thermal load. In addition, the power output of the flywheel may be fixed at zero when the MicroGrid is operated in grid-connected mode. However, as PQ control delivers a fixed power output, it makes no contribution to local frequency control of the MicroGrid.

Therefore, the control scheme of the flywheel has to be changed from PQ control to Droop control or Frequency/Voltage control during islanded operation. Droop control is similar to the function of Primary frequency control in a conventional synchronous generator. The frequency of the MicroGrid can be restored to a steady state value determined by the droop characteristic. Frequency/Voltage control is similar to the function of Secondary frequency control in the conventional synchronous generator. The frequency and voltage of the MicroGrid can be brought back to the normal values (e.g. f = 50Hz and V = 1.0 p.u.) after a disturbance.

In this report, three control strategies (PQ control, Droop control and Frequency/Voltage control) for the local frequency control of the MicroGrid are proposed. Based on two MicroGrid models (synchronous generator representation and STATic Synchronous Shunt COMpensator with battery energy storage, STATCOM-BES, representation) in PSCAD/EMTDC, these control schemes are implemented and tested. Simulations are demonstrated and discussed with supporting PSCAD/EMTDC results.

2. Local frequency control of the MicroGrid

The unique nature of the MicroGrid determines that the local frequency control of the MicroGrid may be: (a) PQ control (fixed active and reactive power control), (b) Droop control and (c) Frequency/Voltage control. In modelling of the MicroGrid, the micro sources and flywheel could be represented by the synchronous generators or STATCOM-BES. Thus, for different representation of the MicroGrid, the implementation of the control schemes may be different.

1.1 (1) MicroGrid represented by the synchronous generator

In this representation, the micro sources and flywheel of the MicroGrid are represented by synchronous generators. The local frequency control scheme of the MicroGrid is as follows:

1.1.1 (a) PQ control

Using this control, the outputs of the micro sources and the flywheel are fixed at their constant values (settings). The PQ control consists of a P controller and a Q controller.

The P controller adjusts the frequency-droop characteristic of the generator up or down to maintain the active power output of the generator at a constant value (Pdes, desired active power) when the frequency is changed. Figure 1 shows the effect of frequency-droop characteristic adjustment.

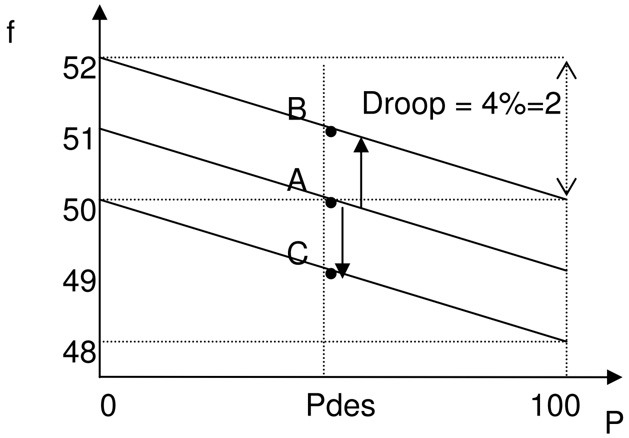

Figure 1 Effect of the frequency-droop characteristic adjustment

At output Pdes, characteristic A corresponds to 50Hz frequency of the grid, characteristic B corresponds to 51Hz frequency of the grid and characteristic C corresponds to 49Hz frequency of the grid. For a frequency change, the power output of the generator can be maintained at the desired value by moving the droop characteristic up or down. A typical droop of the frequency characteristic is about 4% [Kundur, 1994].

The function of a P controller is similar to the speed control of a synchronous generator with a supplementary control loop, as shown in Figure 2.

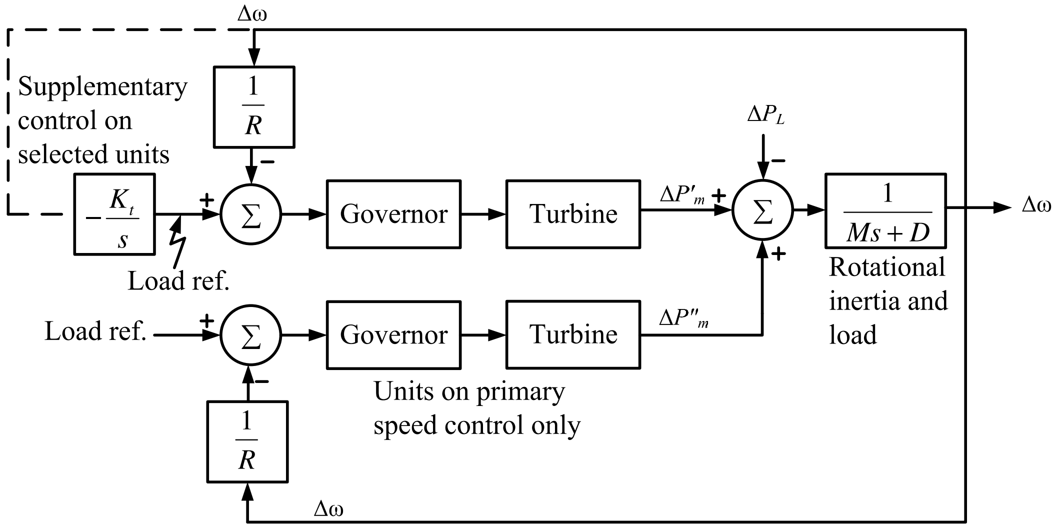

Figure 2 Speed control of synchronous generator with a supplementary control loop [Kundur, 1994]

The movement of the characteristic is achieved through adding an integral control loop, which acts on the load reference settings, to the speed droop control of the generator. The integral control action ensures that the output power of the generator is fixed at a constant value (setting).

Figure 3 shows the configuration of P controller for a synchronous generator representation of the MicroGrid.

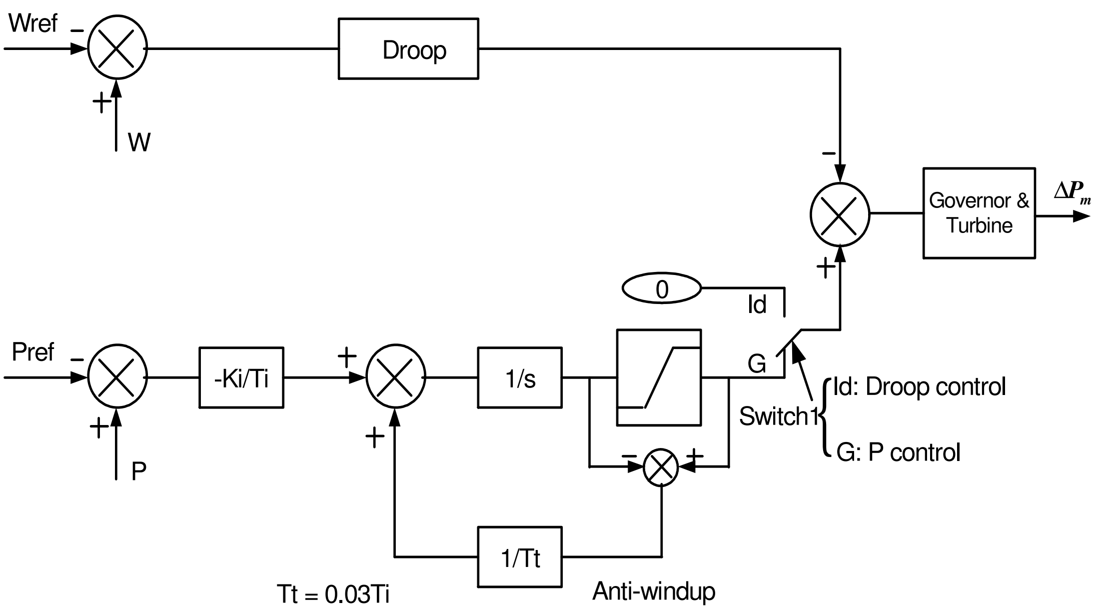

Figure 3 Configuration of P controller for a synchronous generator representation

Similarly, the Q controller adjusts the voltage-droop characteristic of the generator by moving the droop lines upon or down to maintain the reactive power output of the generator at a constant value (Qdes, desired reactive power) when the voltage is changed. Figure 4 shows the effect of voltage-droop characteristic adjustment.

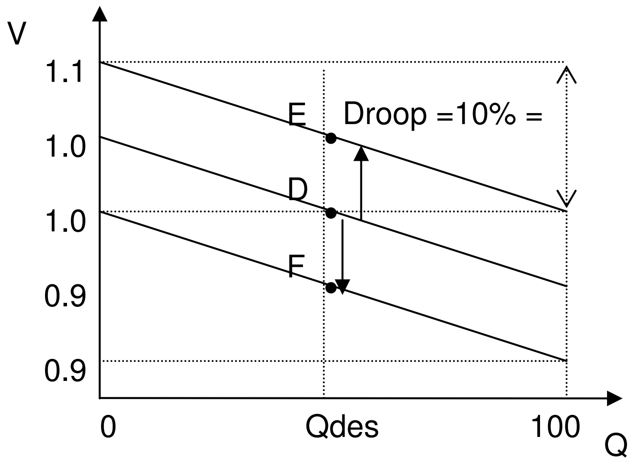

Figure 4 Effect of the voltage-droop characteristic adjustment

At output Qdes, characteristic D corresponds to 1.00 voltage of the network, characteristic E corresponds to 1.05 voltage of the grid and characteristic F corresponds to 0.95 voltage of the grid. For a voltage change, the reactive power output of the generator is maintained at the desired value Qdes by shifting the voltage-droop characteristic up or down. A typical droop of voltage characteristic is about 10% [Kundur, 1994].

Figure 5 shows the implementation of Q controller for a synchronous generator representation.

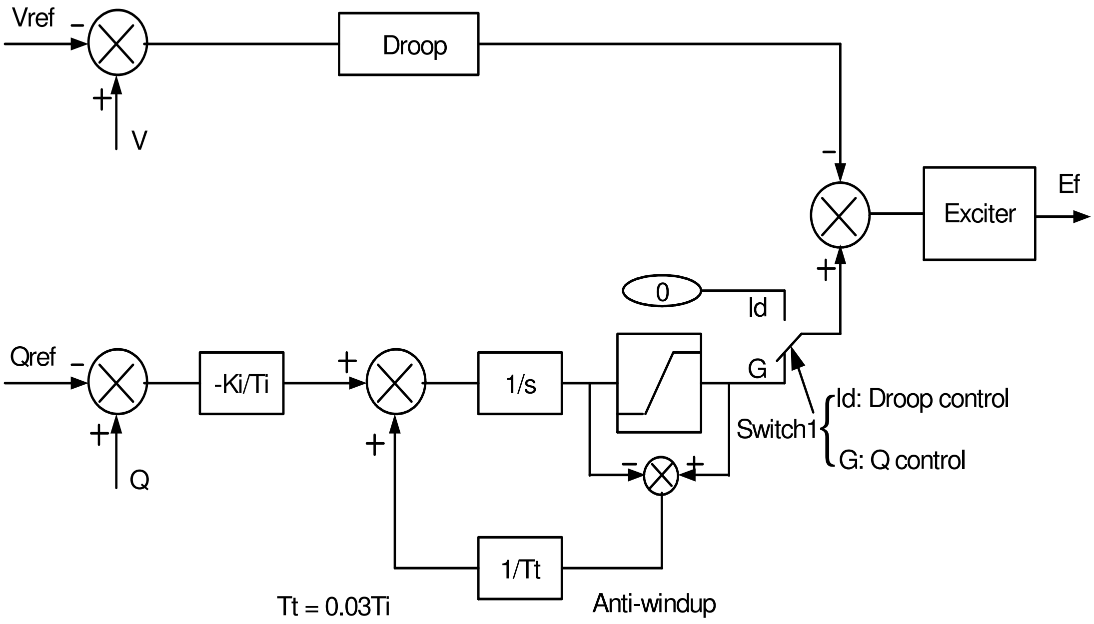

Figure 5 Implementation of Q controller for a synchronous generator representation

1.1.2 (b) Droop control

When the MicroGrid is operated in islanded mode, the control scheme of the micro sources is still PQ control. However, the control scheme of the flywheel should be changed to enable local frequency control. The flywheel may use Droop control. The power output of the flywheel is regulated according to the predetermined droop characteristics. Droop control consists of a frequency-droop controller and a voltage-droop controller.

Figure 6 shows a frequency-droop characteristic, which would be used in frequency-droop controller.

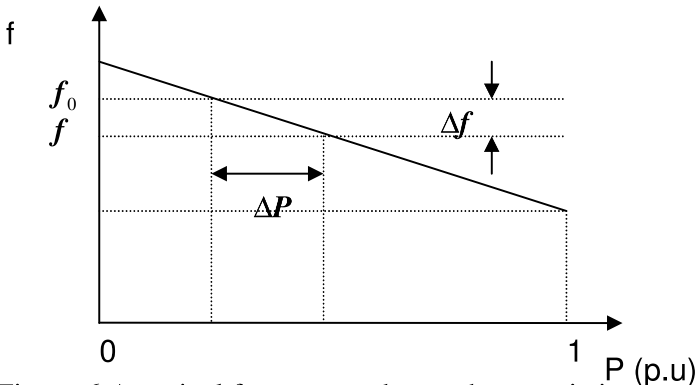

Figure 6 A typical frequency -droop characteristic

The value of droop R_f is a ratio of frequency deviation Δf to change in active power output ΔP. It can be expressed in percentage as equation (1).

$$R_f = \frac{\Delta f(p.u)}{\Delta P(p.u)} \times 100\% \quad (1)$$

Figure 7 also shows a typical voltage-droop characteristic used in the voltage-droop controller.

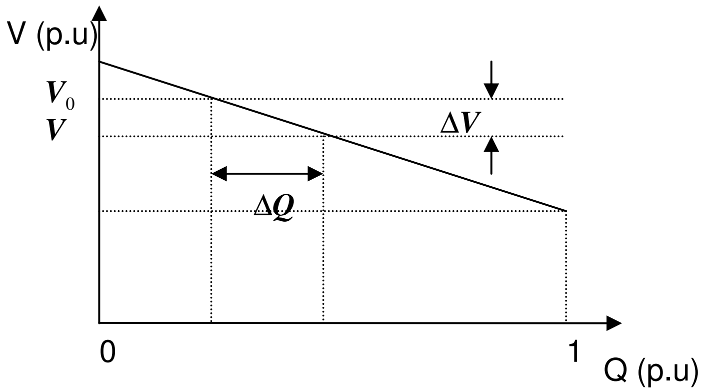

Figure 7 A typical voltage -droop characteristic

The value of droop R_V is a ratio of voltage deviation ΔV to change in reactive power output ΔQ. It can be expressed in percentage as equation (2).

$$R_V = \frac{\Delta V(p.u)}{\Delta Q(p.u)} \times 100\% \quad (2)$$

The implementation of Droop control can be achieved by changing Switch1 from G to Id in Figures 3 and 5.

1.1.3 (c) Frequency/Voltage control

With droop control action, a load change in the MicroGrid will result in steady-state frequency and voltage deviations, depending on the droop characteristics and

Frequency/Voltage sensitivity of the load. The flywheel will contribute to the overall change in generation. Restoration of the Frequency/Voltage of the MicroGrid to their normal values requires a supplementary action to adjust the output of the flywheel. The basic means of the local frequency control of the MicroGrid is through regulating the output of the flywheel. As the load of the MicroGrid changes continually, it is necessary to automatically change the output of the flywheel.

The objective of the frequency control is to restore the frequency to its normal value. This is accomplished by moving the frequency-droop characteristic left or right to maintain the frequency at a constant value. The frequency control adjusts the output of the flywheel to restore the frequency of the MicroGrid to normal (e.g. 50Hz). Figure 8 shows the effect of this adjustment.

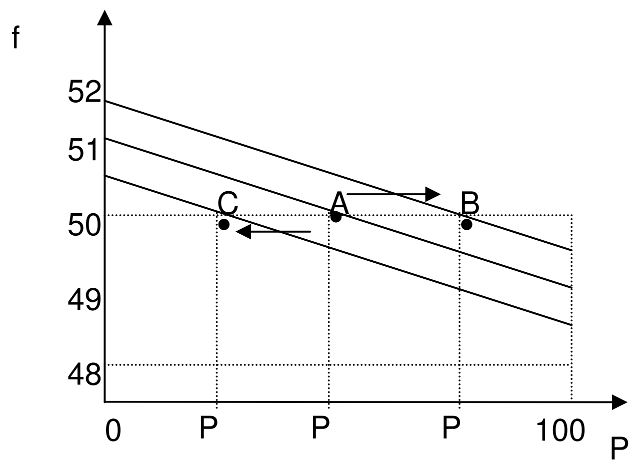

Figure 8 Effect of the adjustment on the frequency-droop characteristic

At 50Hz, characteristic A corresponds to P1 active power output of the flywheel, characteristic B corresponds to P2 active power output and characteristic C corresponds to P3 active power output. The frequency of the MicroGrid is fixed at a constant value (50Hz) by moving the frequency-droop characteristic left or right.

The implementation of Frequency control is similar to P control in Figure 3. But, the connection of the supplementary control loop needs to be changed from Gp of Switch2 to

If and from Id of Switch1 to G. Figure 9 shows the layout of Frequency control for a synchronous generator representation.

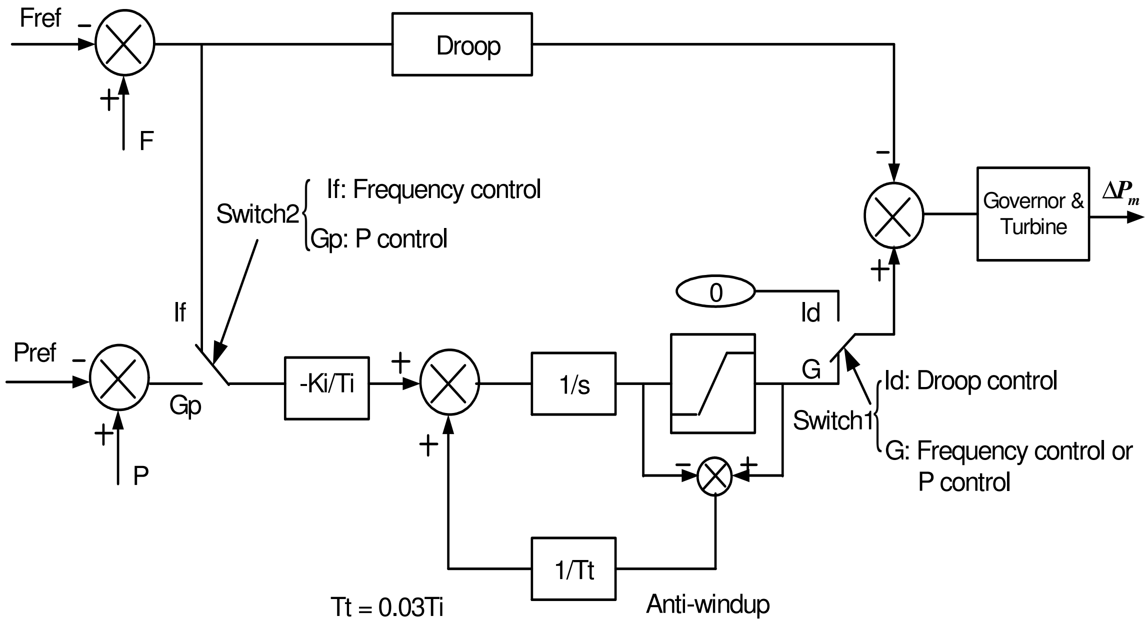

Figure 9 Layout of Frequency control for a synchronous generator representation

Similarly, the voltage control adjusts the voltage-droop characteristic left or right to maintain a constant voltage when the voltage of the MicroGrid is changed. Thus, the voltage of the MicroGrid is fixed at a desired value (e.g. 1.0p.u). The effect of this adjustment is shown in Figure 10.

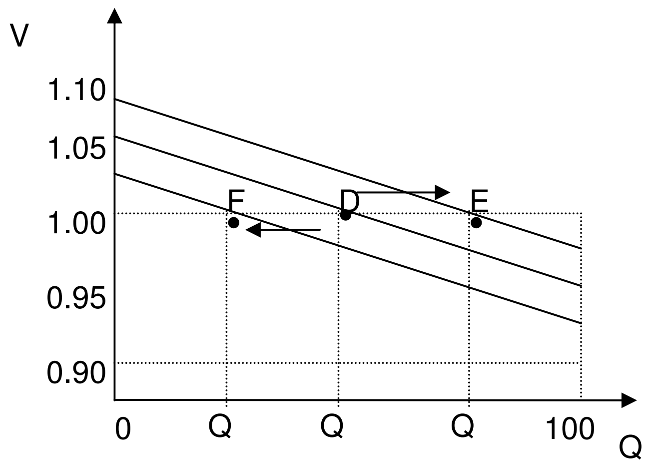

Figure 10 Effect of the adjustment on the voltage-droop characteristic

At 1.0 p.u voltage, characteristic D corresponds to Q1 reactive power output of the flywheel, characteristic E corresponds to Q2 reactive power output and characteristic F corresponds to Q3 reactive power output. The voltage of the MicroGrid is fixed at a constant value (1.0 p.u) by moving the voltage-droop characteristic left or right. Figure 11 shows the implementation of Voltage control for a synchronous generator representation.

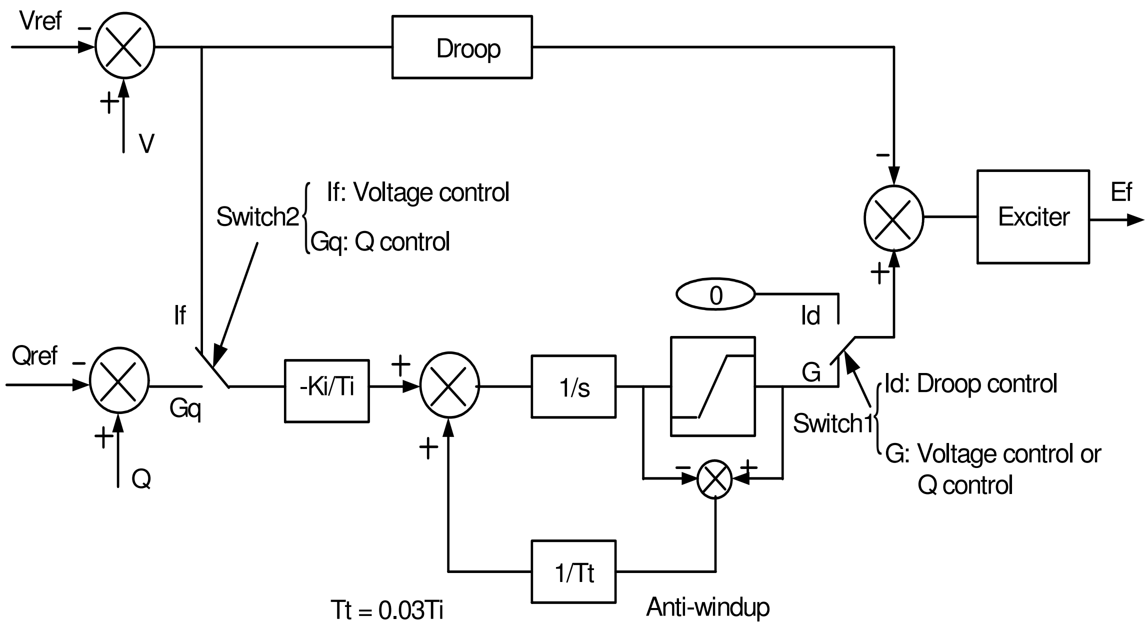

Figure 11 Implementation of Voltage control for a synchronous generator representation

1.2 (2) MicroGrid represented by the STATCOM-BES

In this representation, the micro sources and flywheel of the MicroGrid are represented by the STATCOM-BES. The local frequency control schemes of the MicroGrid are PQ control, Droop control and Frequency/Voltage. Figure 12 shows the implementation of these control strategies of the flywheel in a STATCOM-BES.

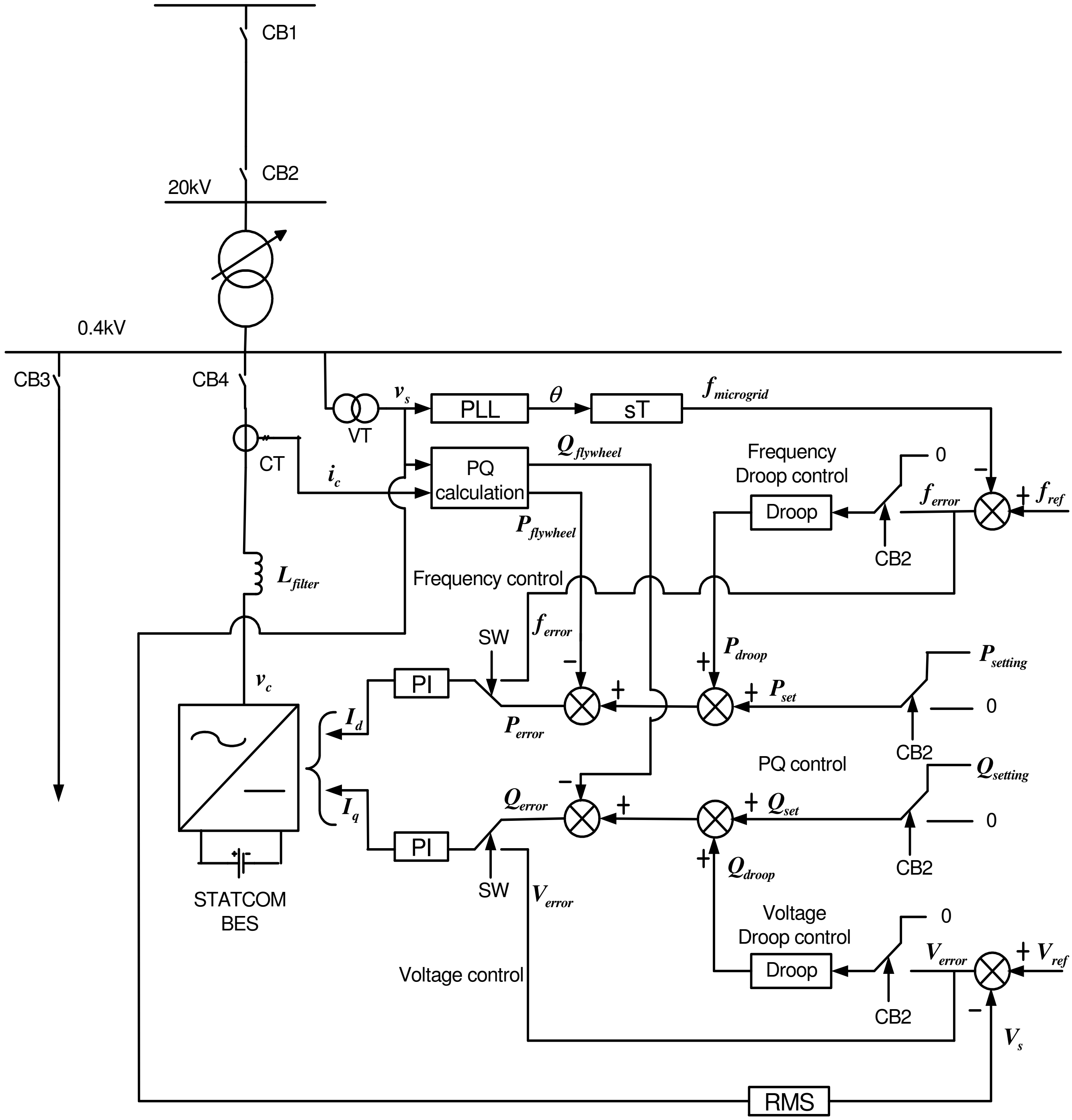

Figure 12 Control schemes of the flywheel represented by a STATCOM-BES

During grid-connected mode, the state of circuit breaker CB2 is closed. The control schemes of the micro source and flywheel are PQ control. The droop output P_{droop} and Q_{droop} of Droop control are zero. Thus, the reference values of the active and reactive powers are $P_{set} = P_{setting}$ and $Q_{set} = Q_{setting}$, acting on PQ control.

After disconnection of the MicroGrid from the main network, during islanded mode, CB2 is open. The outputs P_{set} and Q_{set} of the PQ control loop are set to zero. The reference values of the active and reactive powers are P_{droop} and Q_{droop}, acting on Droop control. The control scheme of the flywheel is thus switched from PQ control to Droop control.

If the inputs of PI controllers of the STATCOM are taken from the errors of the frequency and voltage ($f_{error} = f_{ref} - f_{microgrid}$ and $V_{error} = V_{ref} - V_s$), the control scheme of the flywheel will be Frequency/Voltage control.

3. Assumptions in this study

It is assumed that the micro sources and the flywheel of the MicroGrid are represented by the synchronous generators and the STATCOM-BES, respectively. Two representation modes of the MicroGrid are implemented in PSCAD/EMTDC and shown in Figures 13 and 14.

Figure 13 shows a simple MicroGrid mode, in which the micro source and the flywheel are represented by the synchronous generators.

Figure 14 shows a simple MicroGrid mode, in which the micro source and the flywheel are represented by the STATCOM-BES.

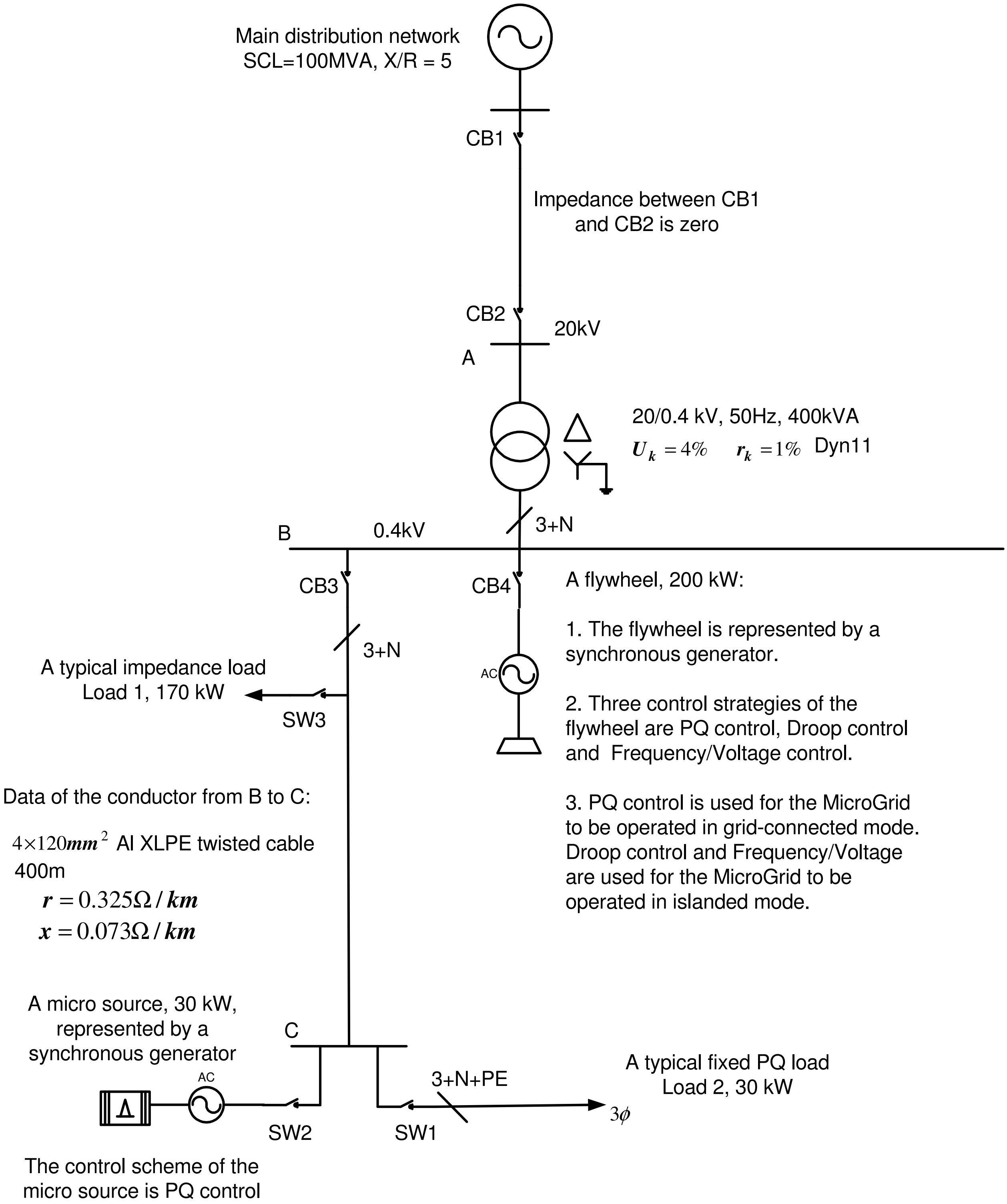

Figure 13 A simple MicroGrid model represented by the synchronous generators

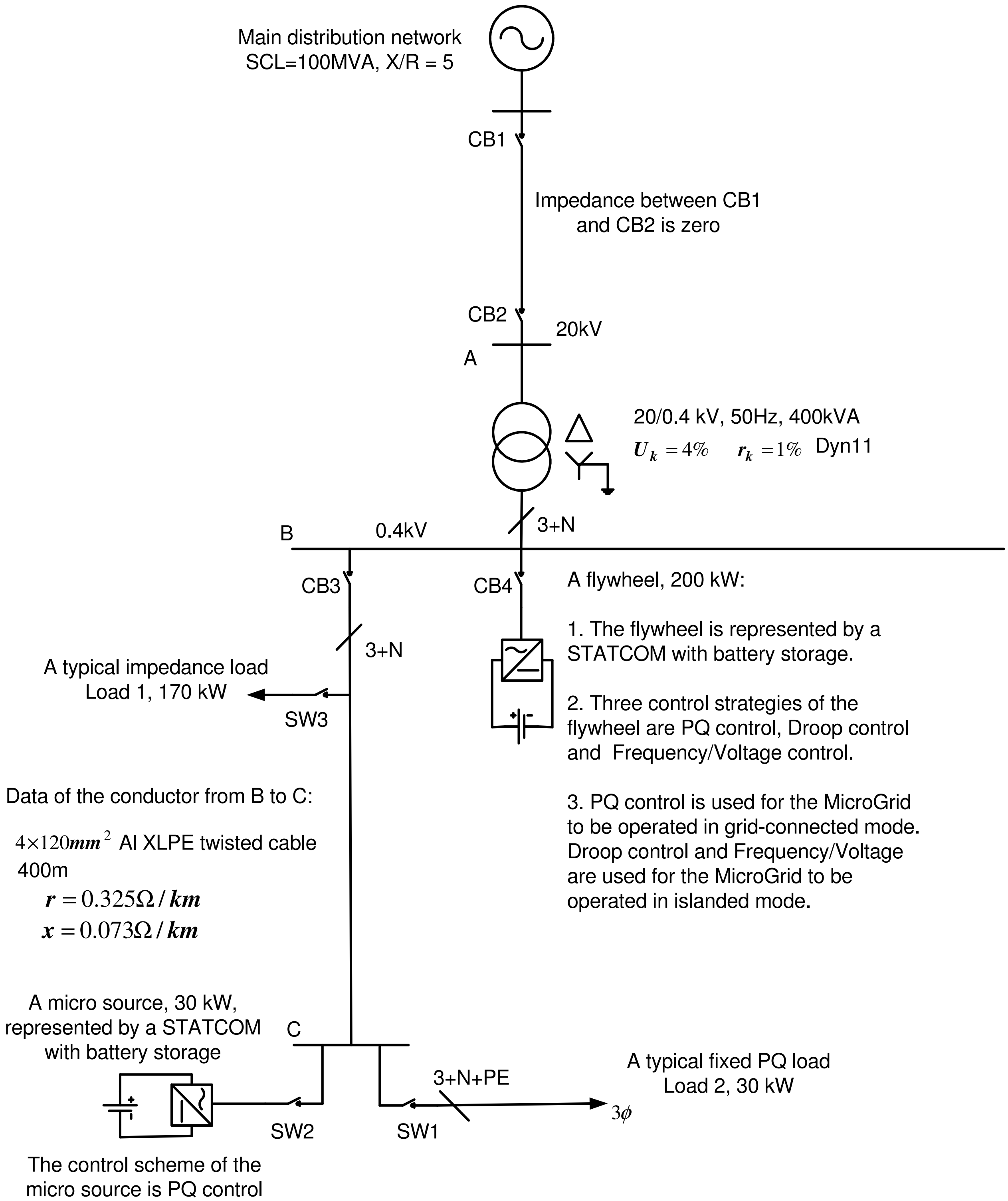

Figure 14 A simple MicroGrid model represented by the STATCOM-BES

For both representations of the MicroGrid above, the fault level at the 20kV main distribution network is 100MVA, with a X/R ratio of 5. One transformer (400kVA, 20/0.4kV) is installed at the substation between the main network and the MicroGrid. The impedance of the transformer is 0.01+j0.04 p.u. The MicroGrid consists of a flywheel and a feeder. The flywheel is connected to 0.4kV busbar, which is near to the substation. The capacity of the flywheel is 200kW (assuming the flywheel supplies 4MJ energy for 20 seconds continuously). The feeder is connected to a micro source and two loads (Load 1 and Load 2) through 400 meters of ALXLPE twisted cable (4×120mm^2). The impedance of the cable is 0.325+j0.073 ohms per kilometre [Bungay, 1990]. The capacity of the micro source is 30kW. Load 1 is an impedance load, with capacity of 170kW. Load 2 is a fixed PQ load, with capacity of 30kW.

In the synchronous generator representation, the parameters of the synchronous generators are the typical average values of the synchronous turbine generator constants [Glover, 2002]:

- Synchronous d-axis reactance (X_d): 1.10 [p.u];
- Synchronous q-axis reactance (X_q): 1.08 [p.u];
- Transient d-axis reactance (X'_d): 0.23 [p.u];
- Transient q-axis reactance (X'_q): 0.23 [p.u];
- Sub-transient d-axis reactance (X''_d): 0.12 [p.u];
- Sub-transient q-axis reactance (X''_q): 0.15 [p.u];
- Negative sequence reactance (X_2): 0.13 [p.u];
- Zero sequence reactance (X_0): 0.05 [p.u];
- Stator armature resistance (R_a): 0.005 [p.u];
- Transient time constant (T'_{do}): 5.60 [sec.];
- Sub- transient time constant ($T''_d = T''_q$): 0.035 [sec.];
- Inertia constant (H): 1.05 [MW/MVA].

In the STATCOM-BES representation, the ratings of the STATCOMs-BES are the same as the capacities of the micro source and flywheel, 30kW and 200kW.

The control scheme of the micro source is PQ control at all times. The control strategies of the flywheel are PQ control, Droop control or Frequency/Voltage control. The flywheel uses PQ control only when the MicroGrid is operated in grid-connected mode. During islanded mode, the control of the flywheel is switched from PQ control to Droop control or Frequency/Voltage control.

4. Simulation results

Based on two representations of the MicroGrid (synchronous generator representation and STATCOM-BES representation), the dynamic performances of the MicroGrid are investigated and demonstrated in PSCAD/EMTDC under three control strategies (PQ control, Droop control and Frequency/Voltage control) of the flywheel. In all cases, circuit breaker CB2 is tripped at 10 seconds. Following the trip of CB2, the MicroGrid is disconnected from the main network and operated in islanded mode.

1.3 (1) For the synchronous generator representation

The MicroGrid mode, used in PSCAD/EMTDC modelling, is shown in Figure 13. The control scheme of the micro source is PQ control. The control strategies of the flywheel are PQ control, Droop control and Frequency/Voltage control.

1.3.1 (a) PQ control

Figure 15 shows the dynamic performance of the MicroGrid when the flywheel uses PQ control during islanded mode. The control schemes of the micro source and the flywheel are PQ control. The implementation of PQ control is shown in Figures 3 and 5.

Obviously, the flywheel makes no contribution to the local frequency control of the MicroGrid. The frequency and voltage of the MicroGrid are unstable. The voltage of the MicroGrid collapses so that the MicroGrid can not be operated in islanded mode.

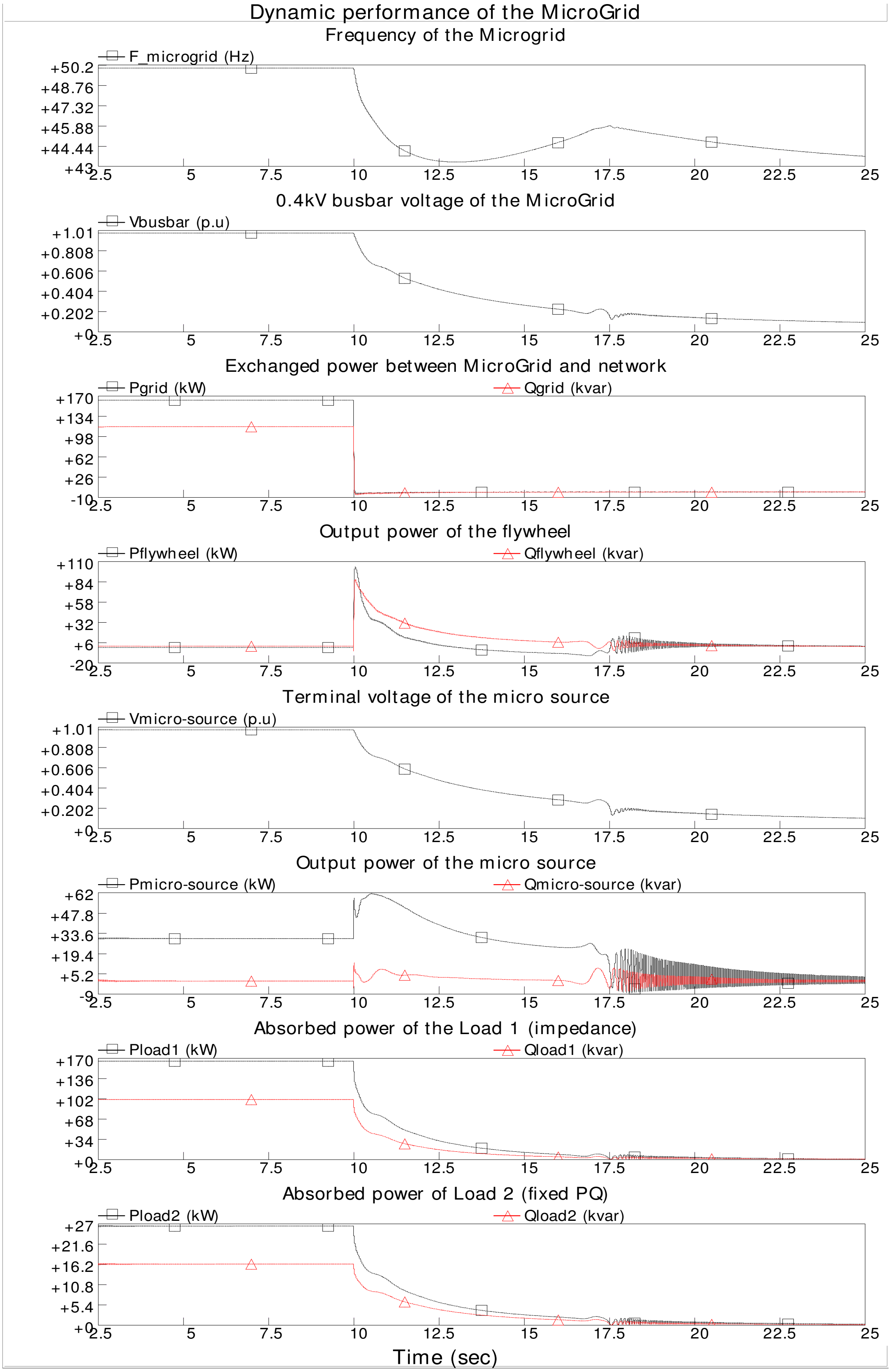

Figure 15 Dynamic performance of the MicroGrid (using synchronous generator representation) when the flywheel uses PQ control during islanded mode

1.3.2 (b) Droop control

Figure 16 shows the dynamic performance of the MicroGrid when the flywheel uses Droop control (shown in Figures 3 and 5, changes Switch1 from G to Id) during islanded mode. The control scheme of the micro source is still PQ control.

After disconnection of the MicroGrid from the main network, the output of the micro source is still retained at 30kW. But, the output of flywheel is changed from zero to the value of 149kW+j110kVar according to the droop settings ($\boldsymbol{R}_f = 4\%$ and $\boldsymbol{R}_v = 10\%$). Thus, the frequency and voltage of the MicroGrid are restored to the steady state values (48.35Hz and 0.9325p.u), associated with the droop characteristics.

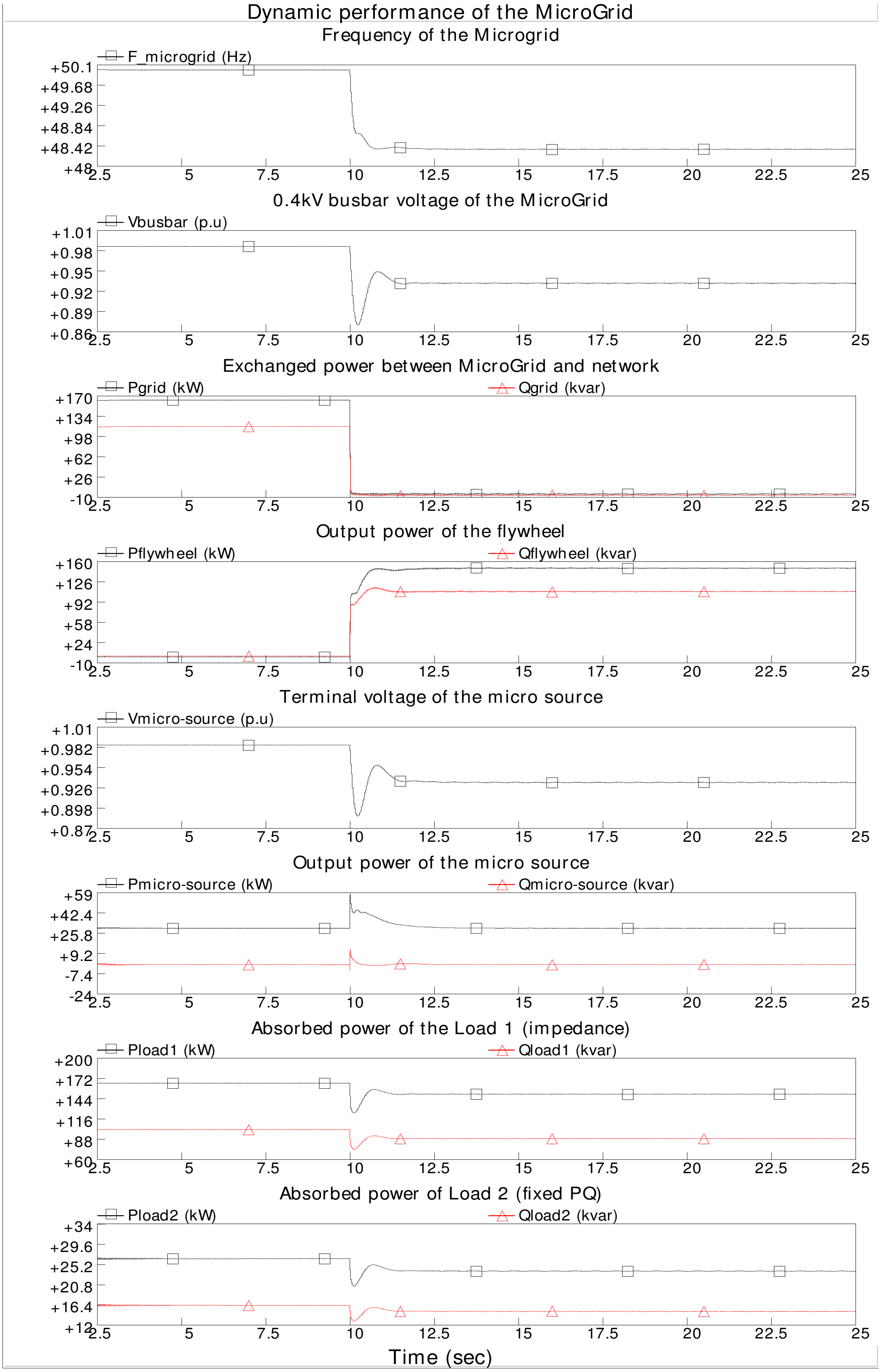

Figure 16 Dynamic performance of the MicroGrid (using synchronous generator representation) when the flywheel uses Droop control during islanded mode

1.3.3 (c) Frequency/Voltage control

Figure 17 shows the dynamic performance of the MicroGrid when the flywheel uses Frequency/Voltage control (shown in Figures 9 and 11) during islanded mode. The control of the micro source is still PQ control. The control of the flywheel is switched from PQ control to Droop control.

During islanded mode of the MicroGrid, the output of the micro source is maintained at a constant value of 30kW. However, the output of the flywheel is changed from zero to the value of 171kW+j127kVar. Consequently, the frequency and voltage of the MicroGrid are both brought back to the normal values (50Hz and 1.0p.u). It should be noted that the energy export of the flywheel using Frequency/Voltage control is larger than using Droop control.

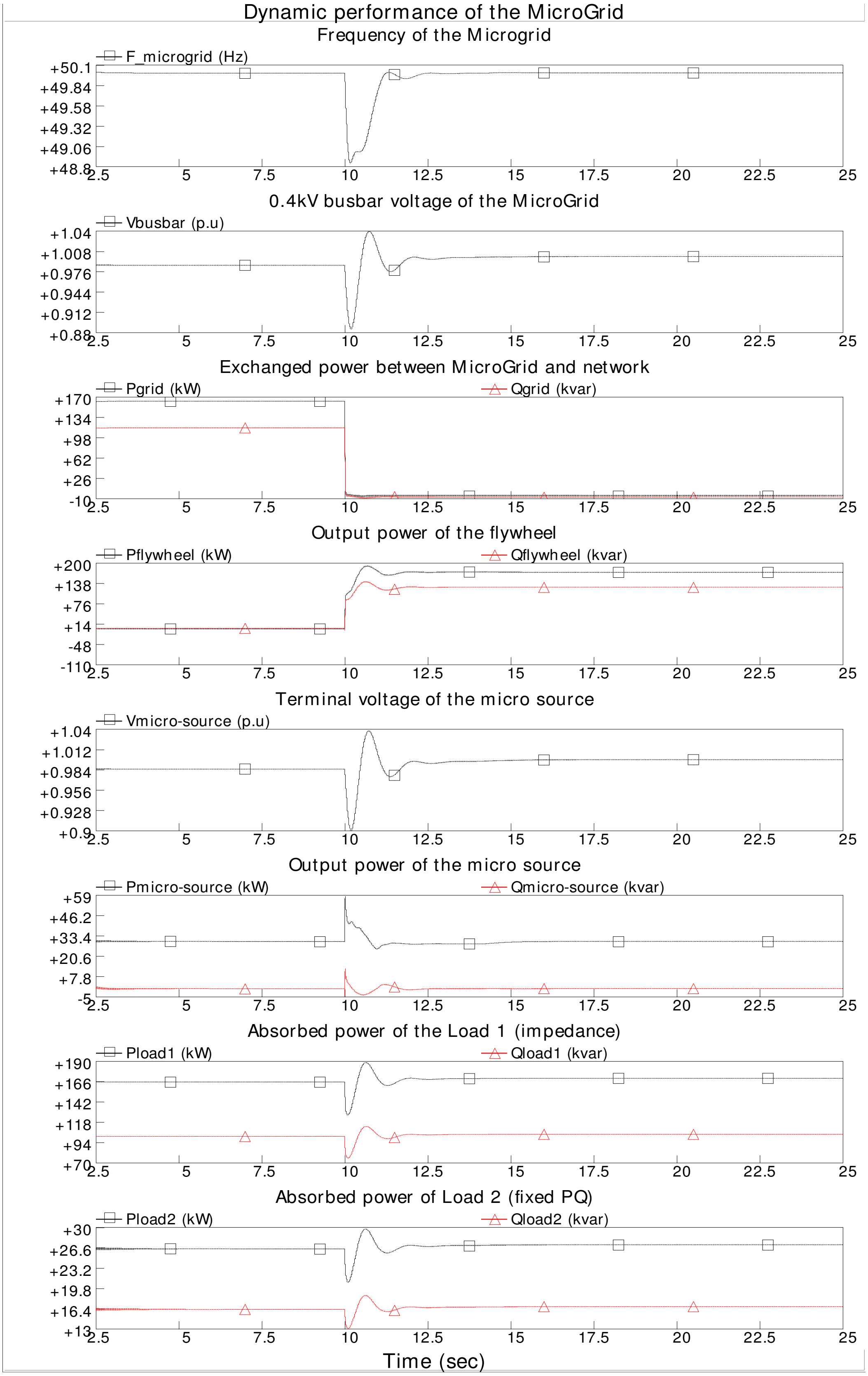

Figure 17 Dynamic performance of the MicroGrid (using synchronous generator representation) when the flywheel uses Frequency/Voltage control during islanded mode

1.4 (2) For the STATCOM-BES representation

The MicroGrid mode, used in PSCAD/EMTDC modelling, is a STATCOM-BES representation, as shown in Figure 14. The implementation of three control schemes (PQ control, Droop control and Frequency/Voltage control) is shown in Figure 12.

Figures 18, 19 and 20 show the dynamic performances of the MicroGrid when the flywheel uses PQ control, Droop control and Frequency/Voltage control during islanded mode, respectively. The deviations of the frequency and voltage depend on the mismatch between generation and demand in the MicroGrid.

Comparisons with Figures 15, 16 and 17 show that the simulation results of the STATCOM-BES representation are similar to the synchronous generator representation. However, after a disturbance, the dynamic response of the frequency and voltage of the STATCOM-BES representation MicroGrid is faster than the synchronous generator representation due to a low or zero inertia value of the STATCOM- BES.

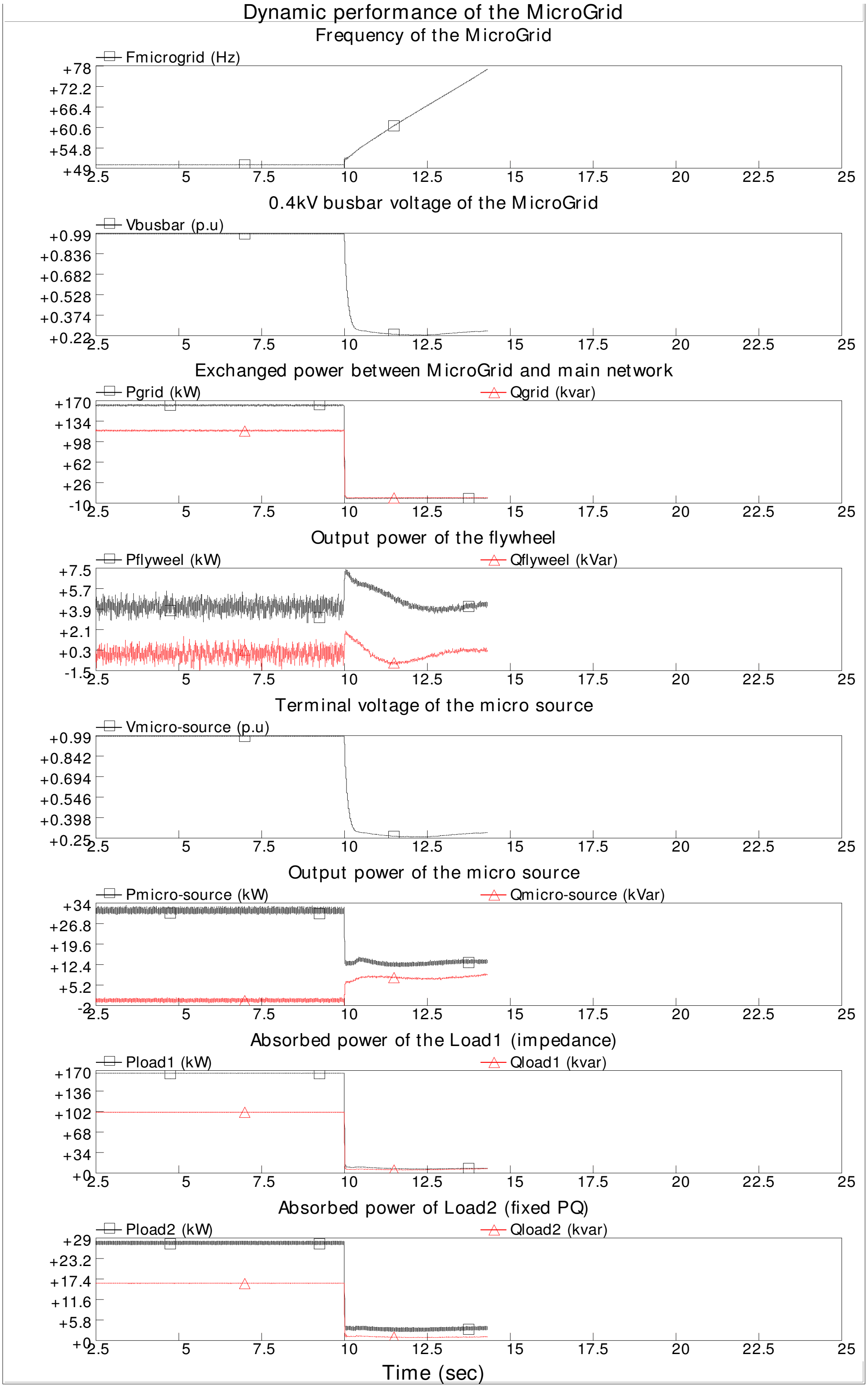

Figure 18 Dynamic performance of the MicroGrid (using STATCOM-BES representation) when the flywheel uses PQ control during islanded mode

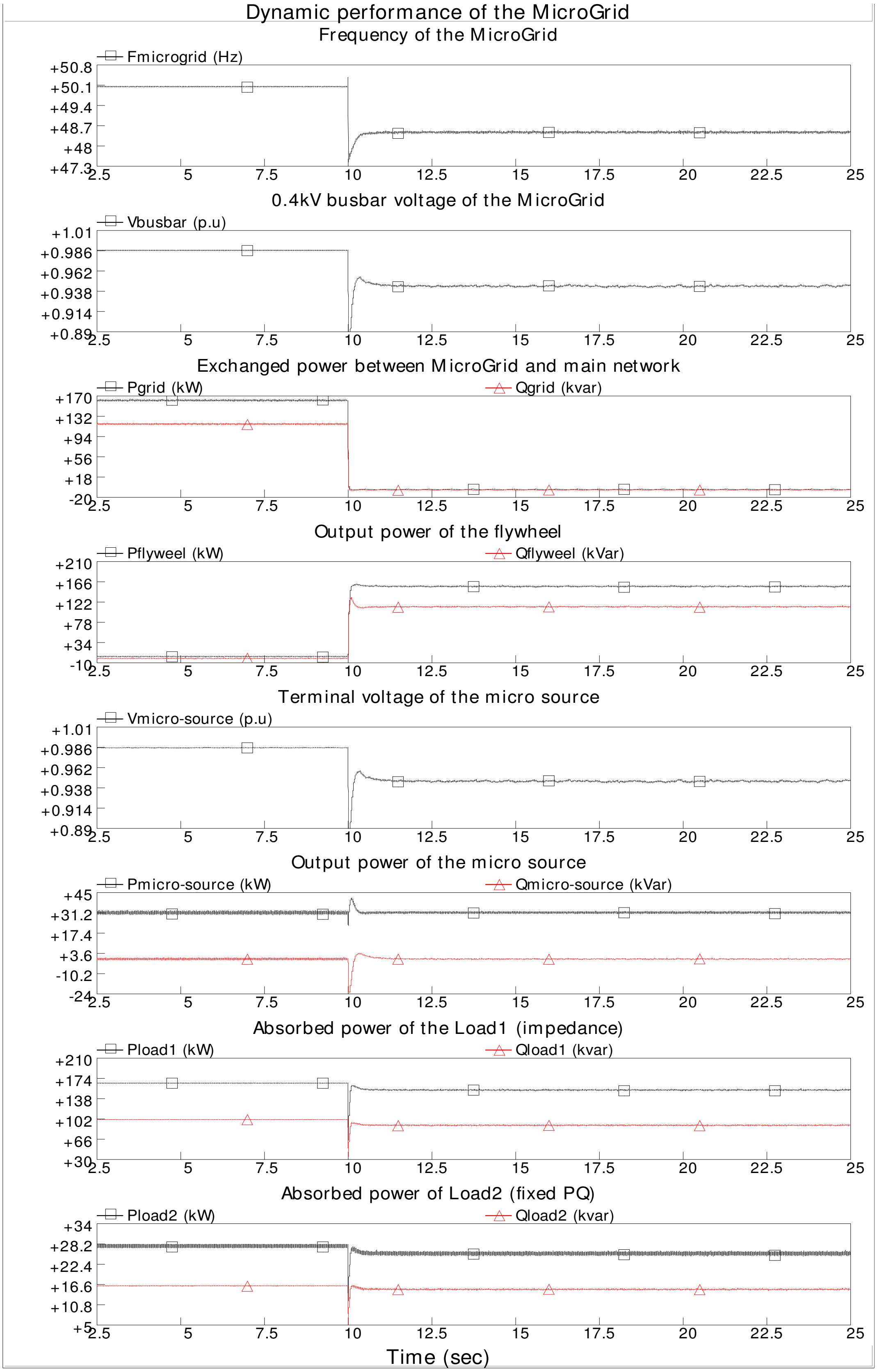

Figure 19 Dynamic performance of the MicroGrid (using STATCOM-BES representation) when the flywheel uses Droop control during islanded mode

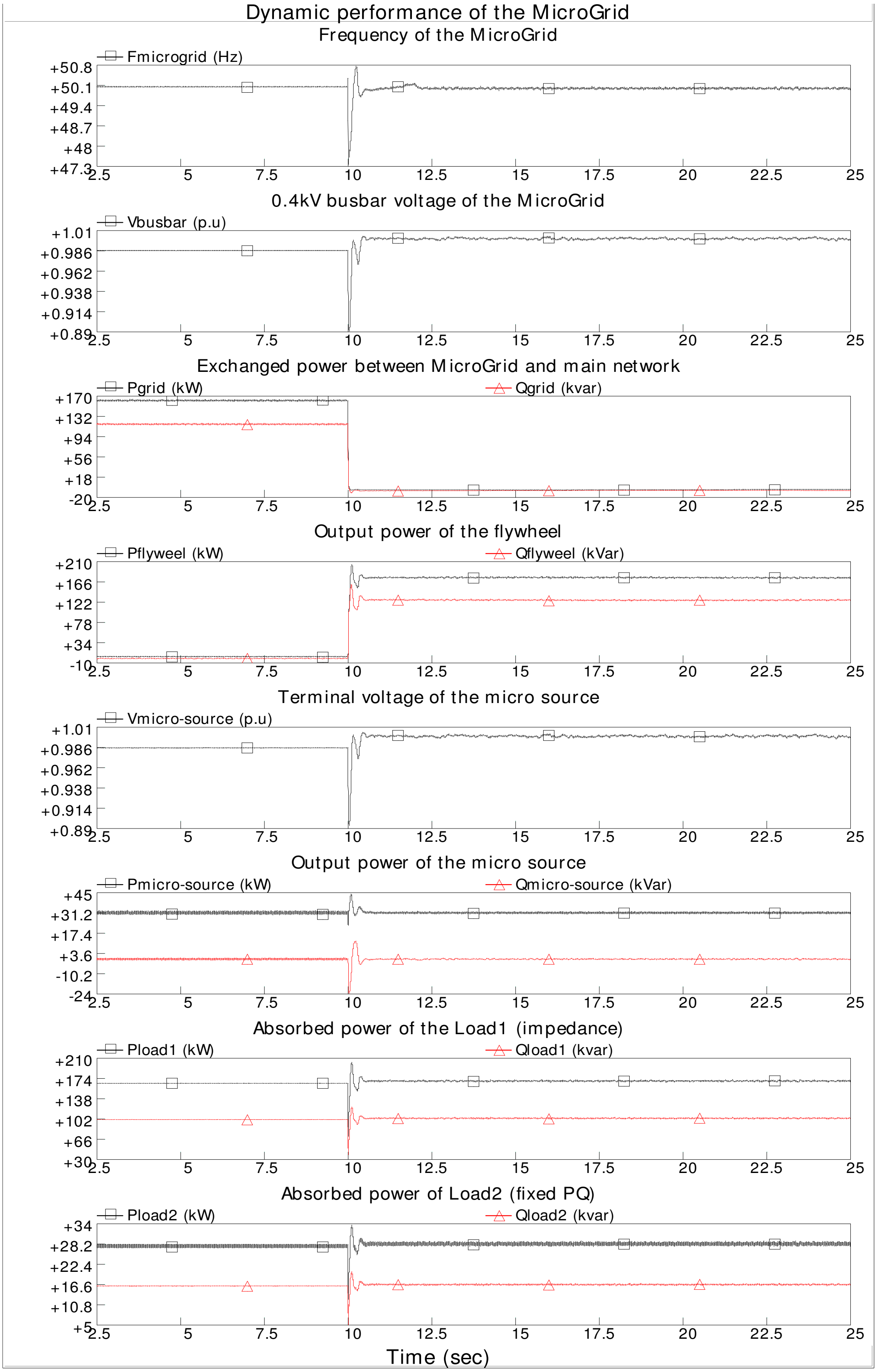

Figure 20 Dynamic performance of the MicroGrid (using STATCOM-BES representation) when the flywheel uses Frequency/Voltage control during islanded mode

6. References

Barsali S., et al. (2002), Control Techniques of Dispersed Generators to Improve the Continuity of Electricity Supply, Power Engineering Society Winter Meeting, 2002, IEEE, Volume: 2, 27-37 January 2002.

Bungay E., McAllister D. (1990), Electric Cables Handbook (second edition), BSP Professional Books, Blackwell Scientific Publication Ltd..

Glover J.D., Sarma M.S. (2002), Power System Analysis and Design (third edition), Brooks/Cole, Thomson Learning.

Kundur P. (1994), Power System Stability and Control (book), McGraw-Hill, Inc..

Lasseter R.H. (2002), MicroGrids, Power Engineering Society Winter Meeting, 2002. IEEE, Volume: 1, 27-31 January 2002

Appendix

1. Simple representation of the flywheel in the MicroGrid

To simplify modelling of the flywheel, two simple representations of the flywheel are presented by using controllable AC and DC voltage sources. The control schemes of the flywheel are still PQ control, Droop control and Frequency/Voltage control, as described in Chapter 2 of this report.

Figures A1 and A2 show the implementations of the control schemes of the flywheel represented by the AC and DC controllable voltage sources, respectively.

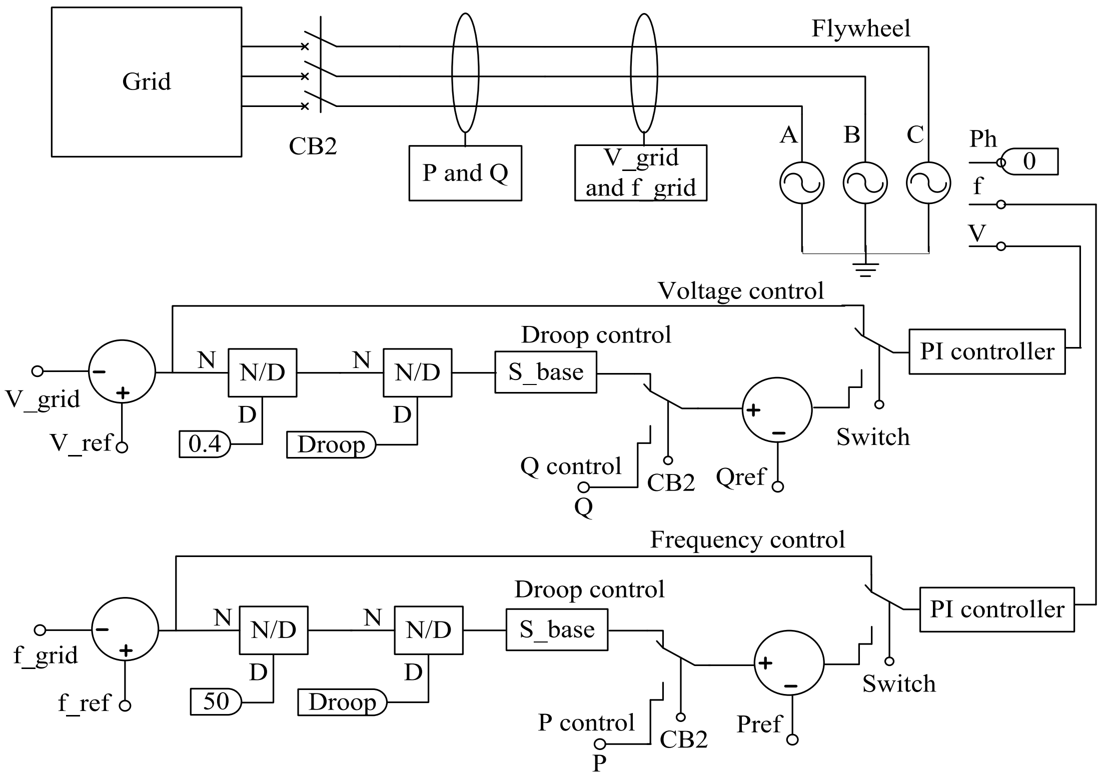

Figure A1 Control schemes of the flywheel represented by a controllable AC voltage source

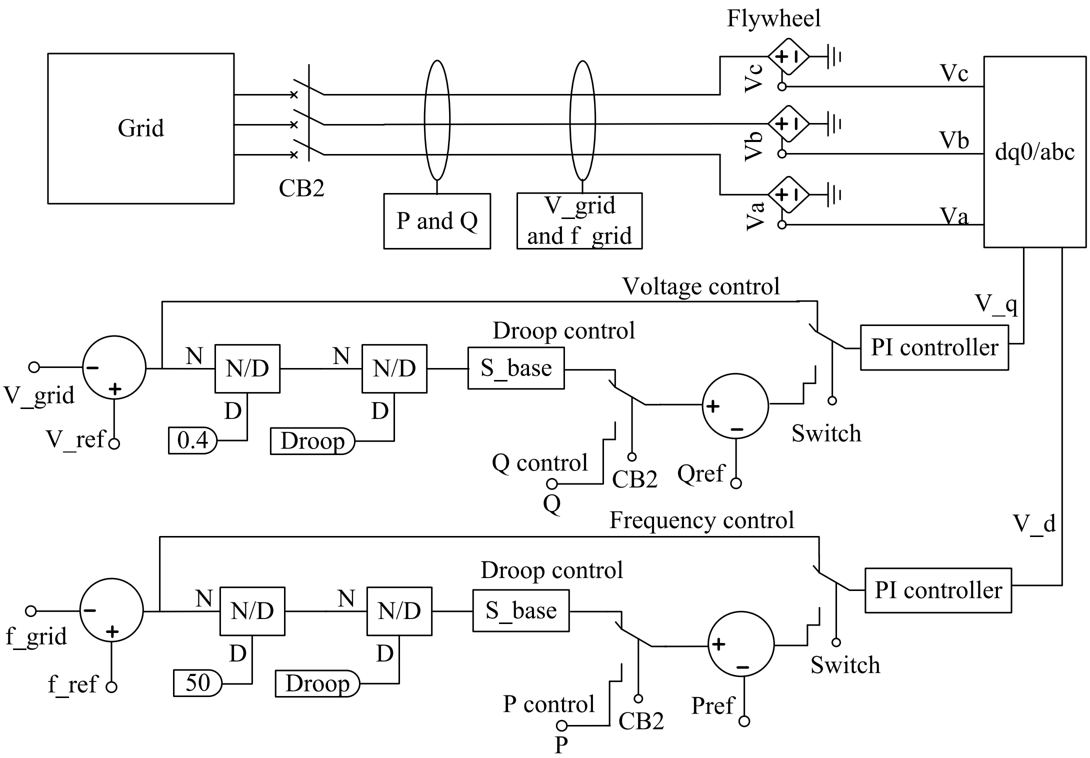

Figure A2 Control schemes of the flywheel represented by a controllable DC voltage source

2. Simulation results

The MicroGrid model used in this study is shown in Figure 14. The flywheel is represented either by a controllable AC voltage source or a controllable DC voltage source. Control strategies of the flywheel are PQ control, Droop control and Frequency/Voltage control. The flywheel uses PQ control only when the MicroGrid is operated in grid-connected mode. After disconnection of the MicroGrid from the main network at 10 seconds, during islanded mode, the control scheme of the flywheel is switched from PQ control to Droop control or Frequency/Voltage control. Simulation results produced in PSCAD/EMTDC are shown in Figures A3, A4, A5 and A6.

Figure A3 shows the dynamic performance of the MicroGrid when the flywheel, represented by a controllable AC voltage source, uses Droop control during islanded mode. The control scheme of the flywheel is switched from PQ control to Droop control after disconnection of the MicroGrid from the main network.

Figure A4 shows the dynamic performance of the MicroGrid when the flywheel, represented by a controllable AC voltage source, uses Frequency/Voltage during islanded mode. The control scheme of the flywheel is switched from PQ control to Frequency/Voltage control after disconnection of the MicroGrid from the main network

Similarly, Figures A5 and A6 show the dynamic performance of the MicroGrid when the flywheel, represented by a controllable DC voltage source, uses Droop control and Frequency/Voltage control during islanded mode.

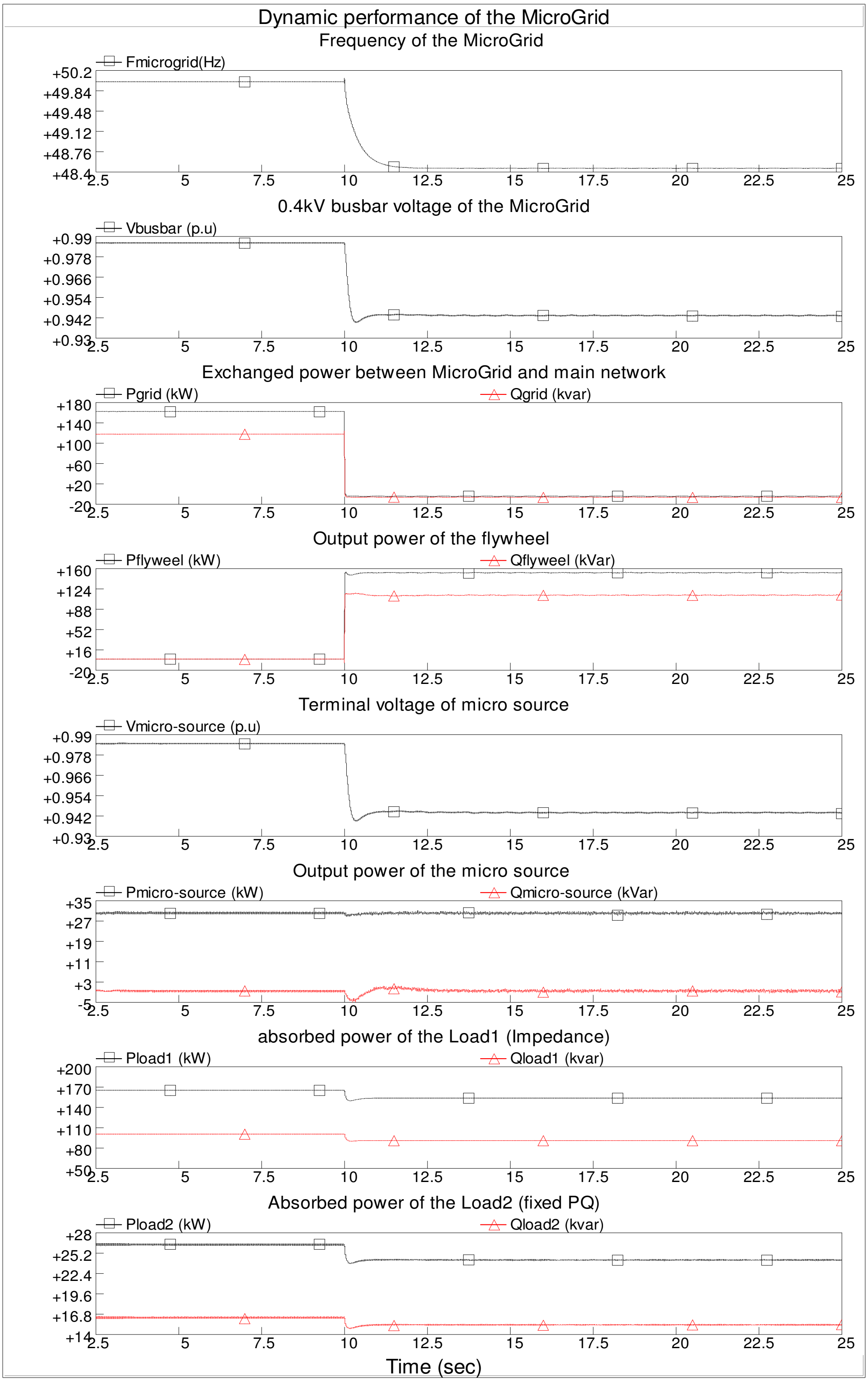

Figure A3 Dynamic performance of the MicroGrid when the flywheel, represented by a controllable AC voltage source, uses Droop control during islanded mode

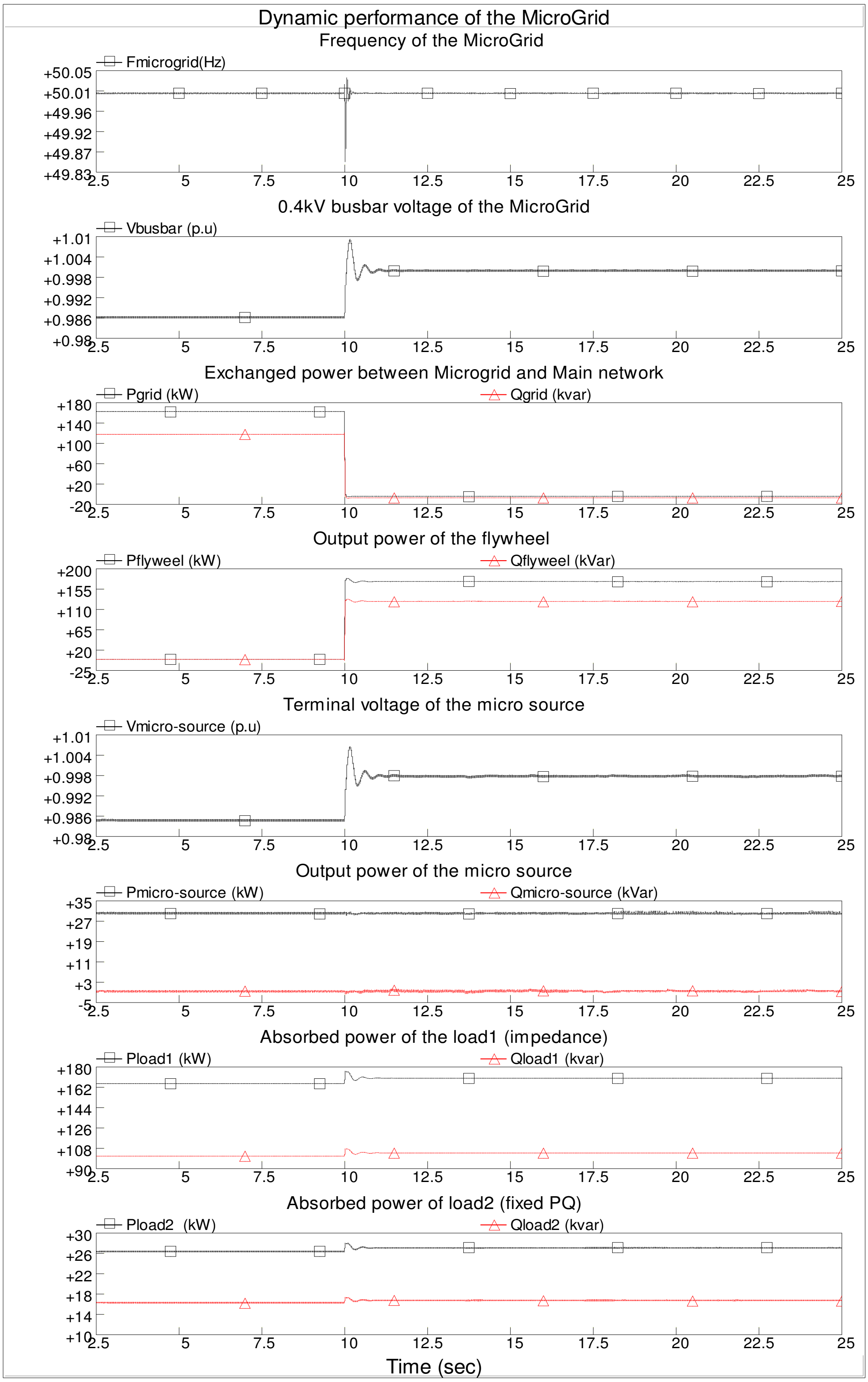

Figure A4 Dynamic performance of the MicroGrid when the flywheel, represented by a controllable AC voltage source, uses Frequency/Voltage control during islanded mode

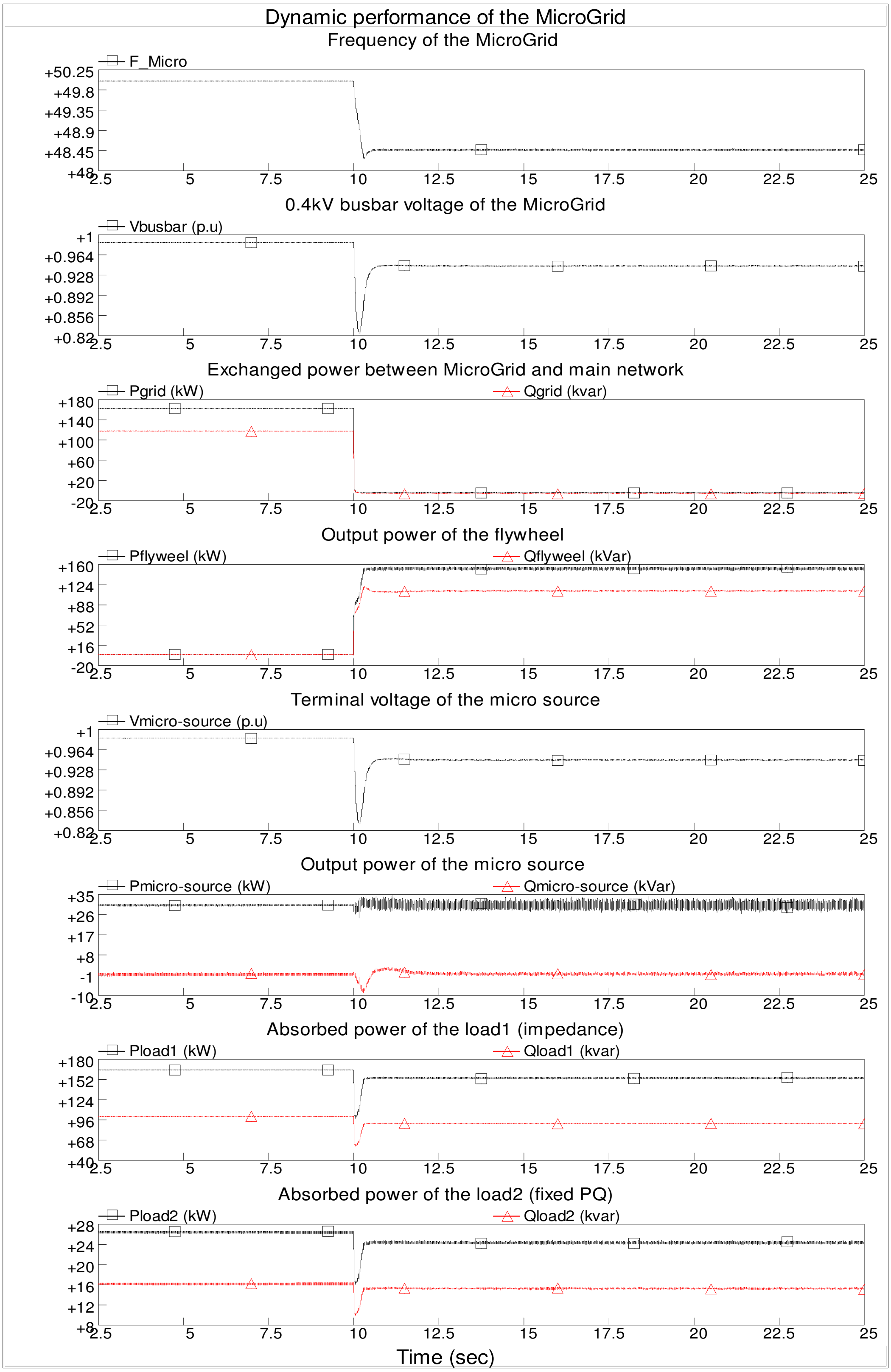

Figure A5 Dynamic performance of the MicroGrid when the flywheel, represented by a controllable DC voltage source, uses Droop control during islanded mode

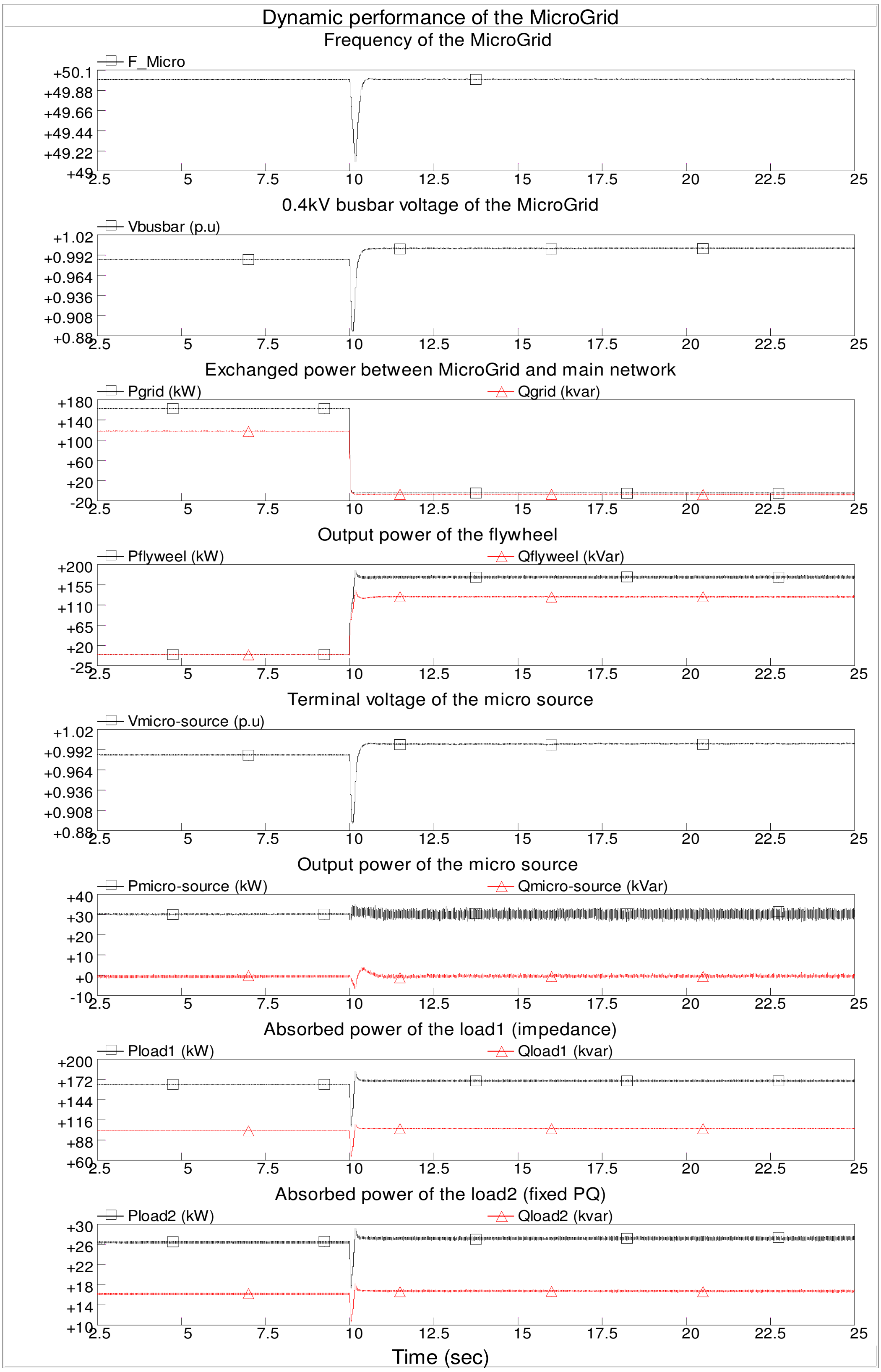

Figure A6 Dynamic performance of the MicroGrid when the flywheel, represented by a controllable DC voltage source, uses Frequency/Voltage control during islanded mode

NTUA CONTRIBUTION

CONTENTS

1. Introduction

A large number of DG technologies (e.g. micro gas turbine, fuel cells, photovoltaic system and several kinds of wind turbines) used in Microgrid are interfaced to the grid via power electronic converters. The use of power electronic interfaces leads to a series of challenges in the design and operation of the Microgrid. One of the main challenges is local frequency control of the Microgrid operated in islanded mode.

For overhead networks with low resistance to reactance ratios, frequency has a strong coupling with active power in the network, although in LV Microgrids this is not the case. The following sections assume strong frequency/active power coupling, i.e. frequency is mainly function of the difference between generation and demand plus network losses. The rate of change of frequency depends on the inertia of the system. The larger the inertia, the smaller the rate of frequency change. During a disturbance, the frequency of the Microgrid may change rapidly due to the low inertia (or zero inertia) present in the Microgrid. In grid-connected mode, the frequency of the Microgrid is maintained within a tight range by the main network. However, in islanded mode, the local frequency control of the Microgrid is not straightforward.

Further to the micro sources, storage devices (e.g. flywheel, BESS *etc*) can play an important role to maintain the frequency of the Microgrid during islanded operation, if used as frequency regulating devices. The controllers of the micro sources and storage inverters respond in milliseconds. For basic operation of the Microgrid, the controllers should use only local information to control storage output and micro sources, so that communication among them is not required. A micro source, should be added to the Microgrid without any changes to the control of the units, which are already part of the network. For the storage device, the inverter should be able to respond to the change of load in a predetermined manner automatically.

Possible control strategies may be:

(a) PQ control (fixed power control)
(b) Droop control

(c) Frequency/Voltage control.

PQ control is adopted so that the micro sources and the flywheel run on constant power output. As PQ control delivers a fixed power output, it makes no contribution to local frequency control of the Microgrid. The power output of the regulating device may be fixed at zero when the Microgrid is operated in grid-connected mode.

Therefore, the control scheme of the flywheel has to be changed from PQ control to Droop control or Frequency/Voltage control during islanded operation. In droop control the frequency of the Microgrid can be restored to a steady state value determined by the droop characteristic, including a steady state error. Frequency/Voltage control an additional integral control loop is included. The frequency and voltage of the Microgrid can be brought back to the normal values after a disturbance with zero steady error.

In this report, three control strategies (PQ control, Droop control and Frequency/Voltage control) for the local frequency/voltage control of the Microgrid are presented. The model of a Constant Speed Wind Turbine (CSWT) is also presented. The above models are used for the simulation of a simplified model of a Microgrid comprising a CSWT and a BESS. P, Q control during grid-connected mode of operation and Frequency, Voltage Control during islanded mode of operation are examined.

2. Control Modes of the Microgrid

(a) PQ control

Using this control, the outputs of the micro sources and the compensating devices (e.g. flywheel, BESS etc) are fixed at their constant settings. The PQ control consists of a P controller and a Q controller. The P controller adjusts the frequency-droop characteristic of the device up or down to maintain the output active power at a constant value (P_{ref}, desired active power) when the frequency is changed. Figure 1 shows the effect of frequency-droop characteristic adjustment.

At output P_{ref}, characteristic A corresponds to 50Hz frequency of the grid, characteristic B corresponds to 51Hz frequency of the grid and characteristic C corresponds to 49Hz frequency of the grid.

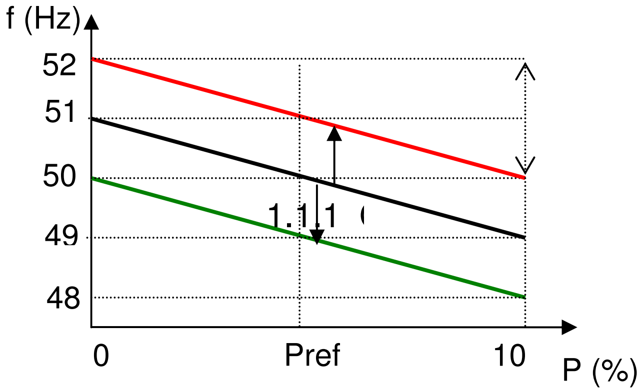

Figure 1 Effect of the frequency-droop characteristic adjustment

Similarly, the Q controller adjusts the voltage-droop characteristic by moving the droop lines upon or down to maintain the output reactive power at a constant value (Q_{ref}, reference reactive power) when the voltage is changed. Figure 2 shows the effect of voltage-droop characteristic adjustment.

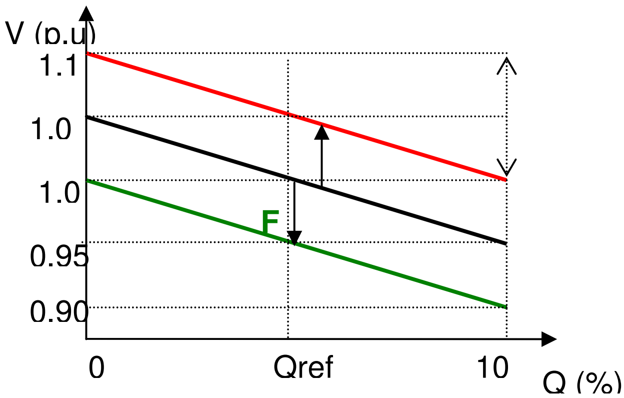

Figure 2 Effect of the voltage-droop characteristic adjustment

At output Q_{ref}, characteristic D corresponds to 1.00 voltage of the network, characteristic E corresponds to 1.05 voltage of the grid and characteristic F corresponds to 0.95 voltage of the grid. For a voltage change, the reactive power output of the generator is maintained at the desired value Q_{ref} by shifting the voltage-droop characteristic up or down. A typical droop of voltage characteristic is about 10%.

(b) Droop control

When the Microgrid is operated in islanded mode, the control scheme of the micro sources is still PQ control. However, the control scheme of the regulating device should be changed to enable local frequency and voltage control. E.g. the flywheel may use Droop control so the power output of the flywheel is regulated according to the predetermined droop characteristics. Droop control consists of a frequency-droop controller and a voltage-droop controller.

Figure 3 shows a frequency-droop characteristic, which would be used in frequency-droop controller.

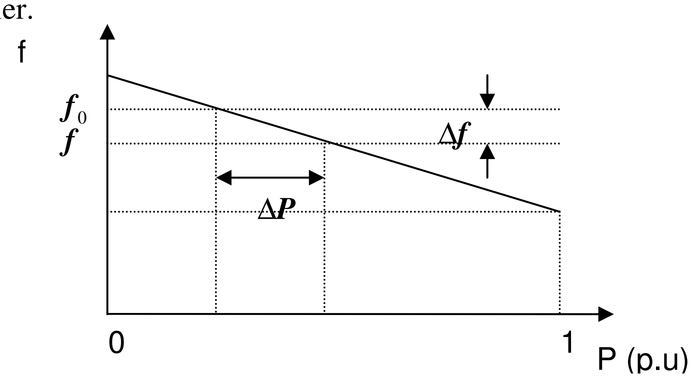

Figure 3 A typical frequency -droop characteristic

The value of droop R_f is a ratio of frequency deviation Δf to change in active power output ΔP. It can be expressed in percentage as equation (1).

$$R_f = \frac{\Delta f(p.u)}{\Delta P(p.u)} \times 100\% \tag{1}$$

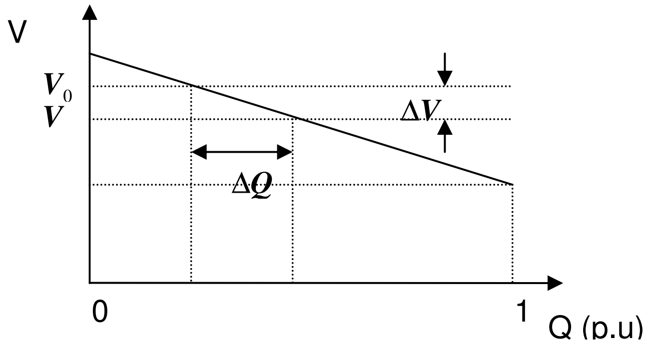

Figure 4 A typical voltage -droop characteristic

The value of droop R_V is the ratio of voltage deviation ΔV to change in reactive power output ΔQ. It can be expressed in percentage as equation (2).

$$R_V = \frac{\Delta V(p.u)}{\Delta Q(p.u)} \times 100\% \tag{2}$$

(c) Frequency/Voltage control

With droop control action, a load change in the Microgrid will result in steady-state frequency and voltage deviations, depending on the droop characteristics and Frequency/Voltage sensitivity of the load. The flywheel will contribute to the overall change in generation. Restoration of the Frequency/Voltage of the Microgrid to their normal values requires a supplementary action to adjust the output of the regulating device. As the load of the Microgrid changes continually, it is necessary to automatically change its output.

The objective of the frequency control is to restore the frequency to its normal value. This is accomplished by moving the frequency-droop characteristic left or right to maintain the frequency at a constant value. The frequency control adjusts the output of the flywheel to restore the frequency of the Microgrid to normal (e.g. 50Hz). Figure 5 shows the effect of this adjustment.

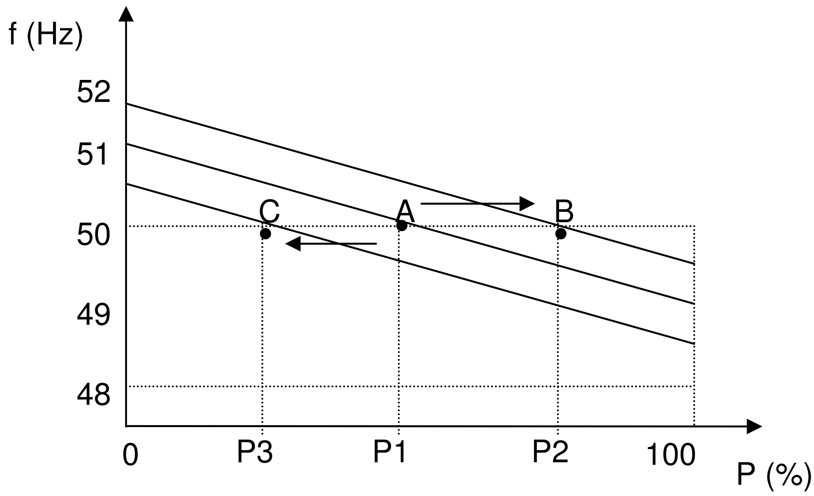

Figure 5 Effect of the adjustment on the frequency-droop characteristic

At 50Hz, characteristic A corresponds to P1 output active power, characteristic B corresponds to P2 output active power and characteristic C corresponds to P3 output active power. The frequency of the Microgrid is fixed at a constant value (50Hz) by moving the frequency-droop characteristic left or right.

Figure 6 shows the block diagram of P, Droop and Frequency control of the regulating device. The implementation of Frequency control is similar to P control. But, the connection of the supplementary control loop needs to be changed from Gp of Switch2 to If and from Id of Switch1 to G. The implementation of Droop control can be achieved by changing Switch1 from G to Id.

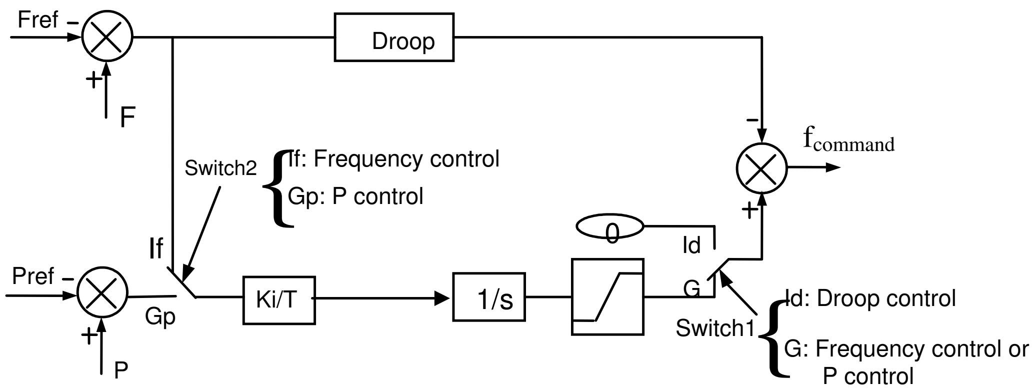

Figure 6 Implementation of P, Frequency control.

Similarly, the voltage control adjusts the voltage-droop characteristic left or right to maintain a constant voltage when the voltage of the Microgrid is changed. Thus, the voltage of the Microgrid is fixed at a desired value (e.g. 1.0p.u). The effect of this adjustment is shown in Figure 7.

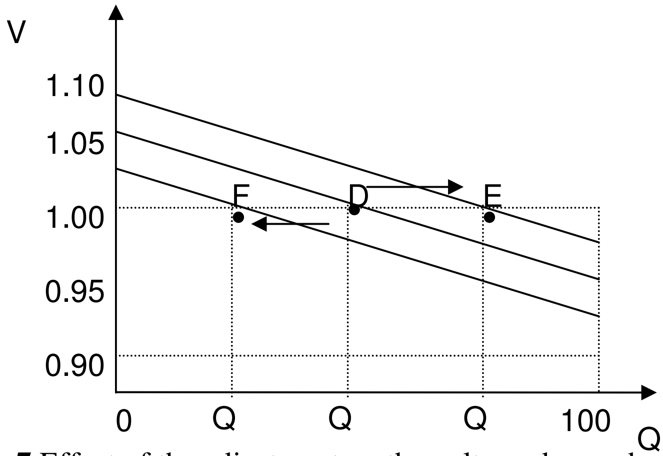

Figure 7 Effect of the adjustment on the voltage-droop characteristic

At 1.0 p.u voltage, characteristic D corresponds to output Q1 reactive power, characteristic E corresponds to Q2 reactive power output and characteristic F corresponds to Q3 reactive power output. The voltage of the Microgrid is fixed at a constant value (1.0 p.u) by moving the voltage-droop characteristic left or right. Figure 8 shows the implementation of Q, Voltage control.

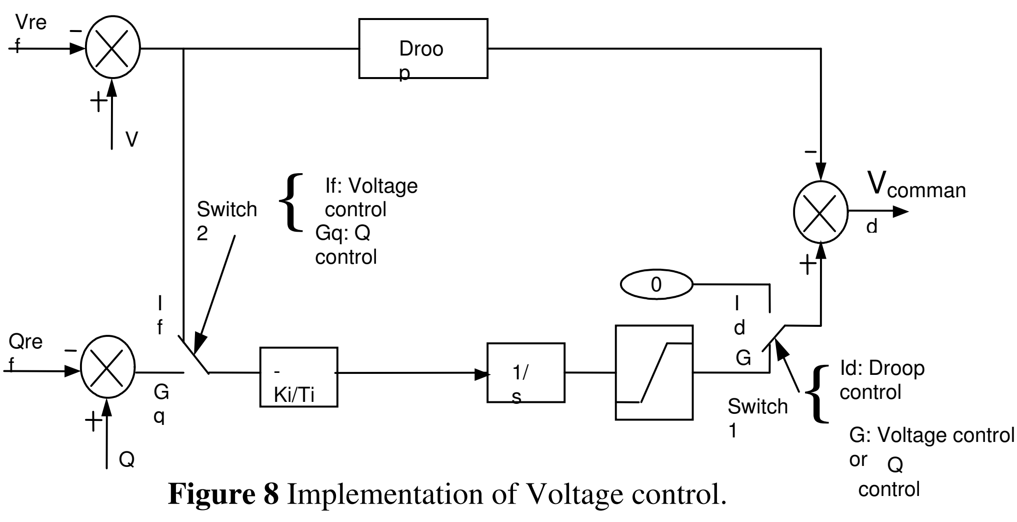

Figure 8 Implementation of Voltage control.

3. Wind Turbine model

Wind Turbines (WTs) comprise several subsystems, as shown in figure 9, that are modeled independently. These subsystems are the aerodynamic, the generator, the mechanical and the power converters in case of Variable Speed Wind Turbines (VSWTs). The models of each subsystem are described next.

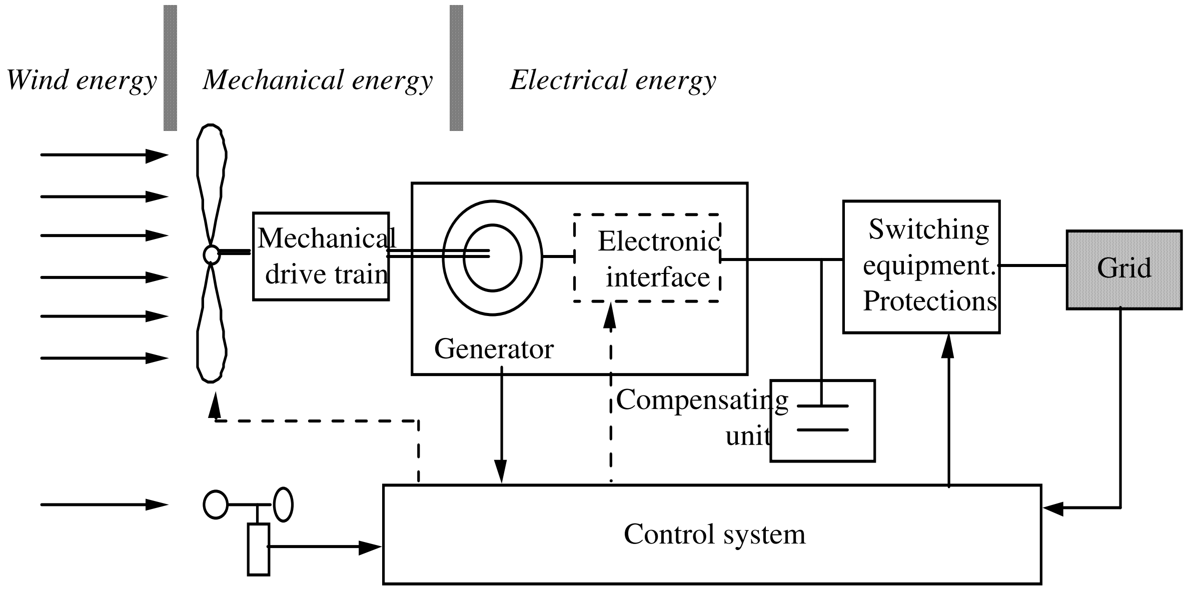

Figure 9 Schematic representation of a WT

(a) Aerodynamic subsystem

The aerodynamic coefficient curves are used for the study of the blades dynamics:

$$P_w = \omega_r \cdot T_w = \frac{1}{2}\rho \cdot A \cdot C_p(\lambda, \beta) \cdot V_w^{\ 3} \tag{3}$$

Where $C_p(\lambda,\beta)$ is the dimensionless performance coefficient, $A=\pi R^2$ the rotor area, λ the tip speed ratio, V_w wind speed, ω_r the blade rotating speed and T_w the aerodynamic torque.

The rotor mechanical torque can be calculated from P_w by

$$T_w = \frac{P_w}{\omega_R} \tag{4}$$

where ω_R is the rotor angular velocity, in rad/sec.

The rotor aerodynamic power coefficient, C_p, is the percentage of the kinetic energy of the incident air mass that is converted to mechanical energy by the rotor, and it is expressed as a function

$$C_p = C_p(\lambda, \beta) \tag{5}$$

where β is the blade pitch angle and

λ is the tip speed ratio of the blade, defined as

$$\lambda = \frac{R\omega_R}{V_w} \tag{6}$$

Using the above relations and the rotor $C_p(\lambda)$ characteristic, the rotor aerodynamic torque and power curves can be calculated.

<u>(b) Induction Generator</u>

Induction generator can be represented by the fourth order model expressed in the arbitrary reference frame. Its equations are the following, using generator convention for the stator currents:

$$\begin{aligned} u_{sd} &= -r_s \cdot i_{sd} - \omega \cdot \Psi_{sq} + p\Psi_{sd} \\ u_{sq} &= -r_s \cdot i_{sq} + \omega \cdot \Psi_{sd} + p\Psi_{sq} \\ u_{rd} &= 0 = r_r \cdot i_{rd} - (\omega - \omega_r) \cdot \Psi_{rq} + p\Psi_{rd} \\ u_{rq} &= 0 = r_r \cdot i_{rq} + (\omega - \omega_r) \cdot \Psi_{rd} + p\Psi_{rq} \end{aligned} \tag{7}$$

Where $p = \frac{1}{\omega_o}\frac{d}{dt}$, ω_o is the base cyclic frequency, ω is the rotating speed of the arbitrary reference frame and subscripts {d}, {q}, {s}, {r} denote *dq*-axis, stator, rotor, respectively. r_s, r_r are the stator and rotor windings resistances, X_s, X_r the stator and rotor windings reactances and X_m is the magnetizing reactance The fluxes are related to the winding currents by the following equations:

$$\begin{aligned}
\Psi_{sd} &= -X_s \cdot i_{sd} + X_m \cdot i_{rd} \\
\Psi_{sq} &= -X_s \cdot i_{sq} + X_m \cdot i_{rd} \\
\Psi_{rd} &= -X_m \cdot i_{sd} + X_r \cdot i_{rd} \\
\Psi_{rq} &= -X_m \cdot i_{sq} + X_r \cdot i_{rq}
\end{aligned} \tag{8}$$

Using the currents as state variables the following state space model is derived

$$\frac{d}{dt}\begin{bmatrix} i_{sd} \\ i_{sq} \\ i_{rd} \\ i_{rq} \end{bmatrix} = \frac{\omega_o}{D}\begin{bmatrix} -r_s X_r & (\omega D+\omega\Psi) & -r_r X_m & -\omega_r X_r X_m \\ -(\omega D+\omega_r X_m^2) & -r_s X_r & \omega_r X_r X_m & -r_r X_m \\ -r_s X_m & \omega_r X_s X_m & -r_r X_s & (\omega D-\omega_r \Psi_s \Psi_r) \\ -\omega_r X_s X_m & -r_s X_m & -(\omega D-\omega_r \Psi_{sr}) & -r_r X_s \end{bmatrix}\begin{bmatrix} i_{sd} \\ i_{sq} \\ i_{rd} \\ i_{rq} \end{bmatrix} + \frac{\omega_1}{D}\begin{bmatrix} -X_r & 0 \\ 0 & -X_r \\ -X_m & 0 \\ 0 & -X_m \end{bmatrix}\begin{bmatrix} u_{sd} \\ u_{sq} \end{bmatrix} \tag{9}$$

Where D = $X_s X_r$ - X^2_m

If the stator currents are used as the output of the system, then

$$\mathbf{Y} = \begin{bmatrix} I_{sd} \\ I_{sq} \end{bmatrix} = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \end{bmatrix}\mathbf{X} \tag{10}$$

The developed electromagnetic torque (positive when decelerating and negative when accelerating) is given by the

$$T_e = \Psi_{rd} i_{rq} - \Psi_{rq} i_{rd} = X_m (i_{sq} i_{rd} - i_{sd} i_{rq}) \tag{11}$$

(c) Mechanical subsystem

The equivalents of three or six elastically connected masses, shown in figure 10, can be optionally used for simulating the mechanical system of the WT. The use of at least two masses is necessary for the representation of the low-speed shaft torsional mode. In case of the three connected masses the state space equations of the mechanical system are the following:

$$\frac{d}{dt}\begin{bmatrix}\theta \\ \omega\end{bmatrix} = \begin{bmatrix} [0]_{3\times3} & [I]_{3\times3} \\ -\frac{1}{2}[H]^{-1}[C] & -\frac{1}{2}[H]^{-1}[D] \end{bmatrix}\begin{bmatrix}\theta \\ \omega\end{bmatrix} + \begin{bmatrix} [0]_{3\times3} \\ \frac{1}{2}[H]^{-1} \end{bmatrix} T \tag{12}$$

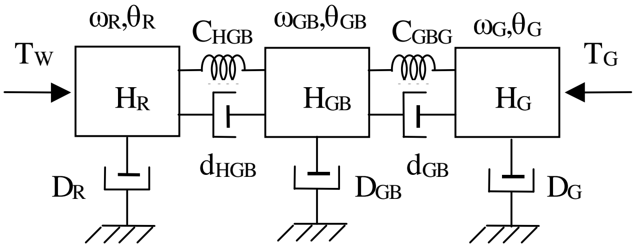

Figure 10 3-mass mechanical equivalent

In case of the three elastically connected masses $\theta^T = [\theta_R, \theta_{GB}, \theta_G]$ is the angular position vector, $\omega^T = [\omega_R, \omega_{GB}, \omega_G]$ is the angular speed vector and $T^T = [T_W, 0, T_G]$ is the external torque vector comprising the aerodynamic and the electromagnetic torque, T_w and T_G, acting on the turbine and generator rotor, respectively. $[0]_{3x3}$ and $[I]_{3x3}$ are the zero and identity 3x3 matrices, respectively. $[2H] = diag(2H_R, 2H_{GB}, 2H_G)$ is the diagonal 3x3 inertia matrix

$$[C] = \begin{bmatrix} C_{HGB} & -C_{HBG} & 0 \\ -C_{HBG} & C_{HBG} + C_{GBG} & -C_{GBG} \\ 0 & -C_{GBG} & C_{GBG} \end{bmatrix}$$

C is the 3x3 stiffness matrix and D is the damping matrix. C matrix represents the low and high-speed shaft elasticities

$$[D] = \begin{bmatrix} D_R + d_{HGB} & -d_{HGB} & \\ -d_{HGB} & D_{GB} + d_{HGB} + d_{GBG} & - \\ 0 & -d_{GBG} & D_G \end{bmatrix}$$

D is the 3x3 damping matrix and represents the internal friction and the torque losses.

While subscripts {gb}, {g} denote gear-box and generator, respectively.

4. Study Case

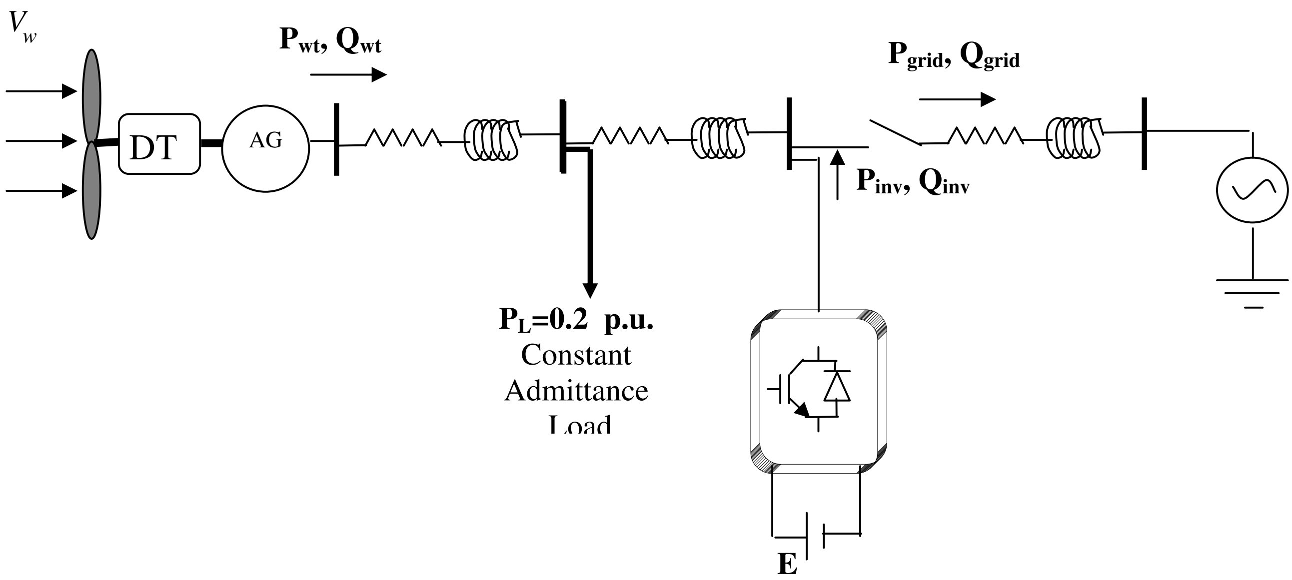

Figure 11. Study Case Network

The network shown above is simulated for network-connected and islanded mode of operation. BESS provides local frequency and voltage control. The dynamic response of BESS control system is examined during step changes of the wind speed. Also, the effect of different integral gains is examined. For simplicity reasons the dc part of the BESS is modeled as a constant voltage source.

At t= 15secs Microgrid is disconnected from the network and transient changes occur at voltage and frequency of the Microgrid as shown in figures 15, 16. Subsequently at t= 20, 30 secs a step increase and decrease in the wind speed are applied as shown in figure 12. Before the Microgrid is disconnected from the network P, Q control is applied to BESS. So, P and Q are maintained to 0 as shown in all figures. After the Microgrid is disconnected, droop and frequency/voltage control modes are applied. As it is expected the steady state errors are 0 in case of frequency/voltage control. This is not the case when droop control mode is applied as shown in figures 15, 16. The effect of different integral gains is shown in figures 17, 18. The larger the integral gain the smaller the frequency, voltage deviation and time needed to minimize error. Of course there are limits beyond which the system becomes unstable.

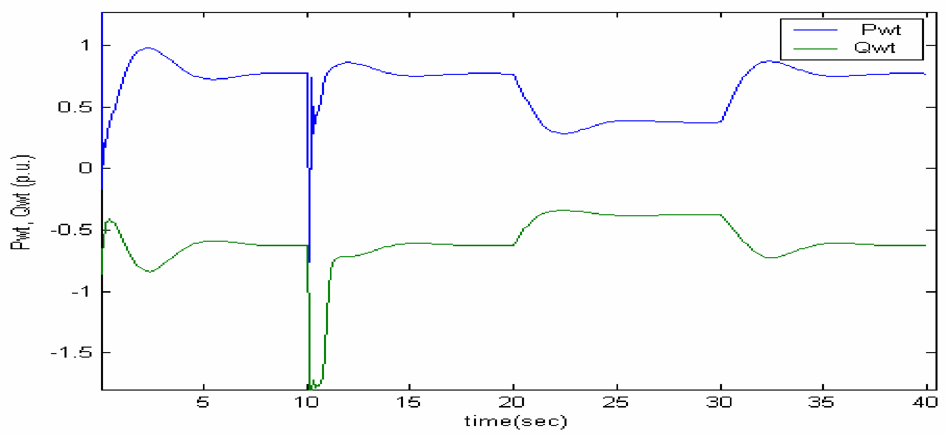

Figure 12. Active, Reactive Power of Wind Turbine

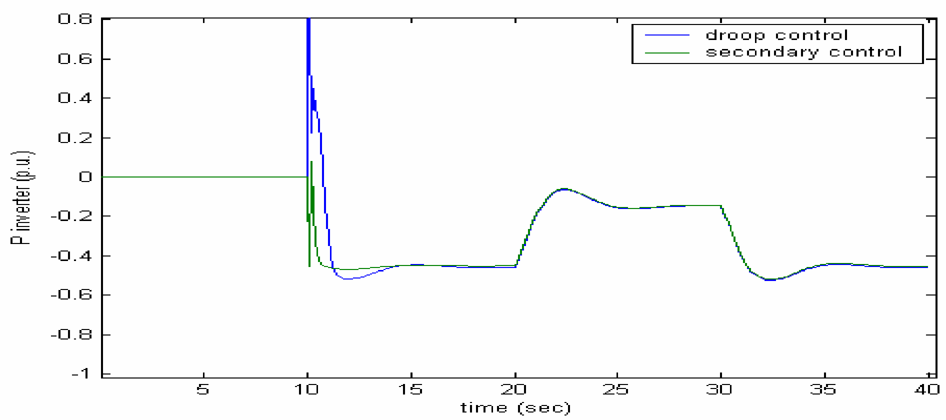

Figure 13. BESS Active Power

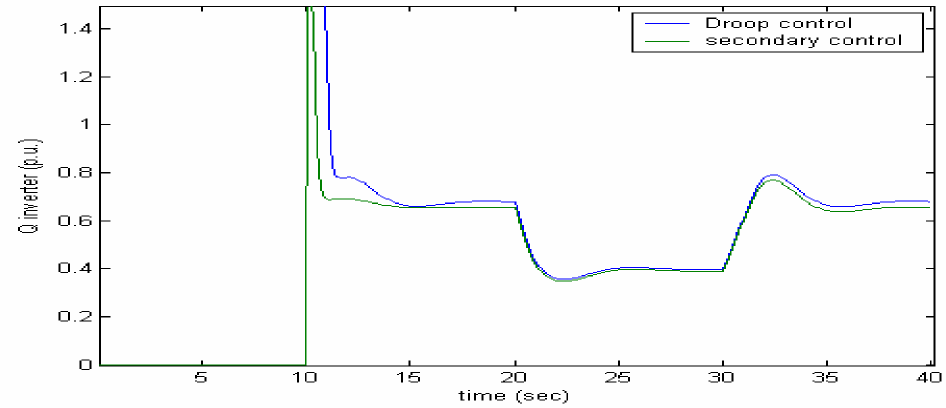

Figure 14. BESS Reactive Power

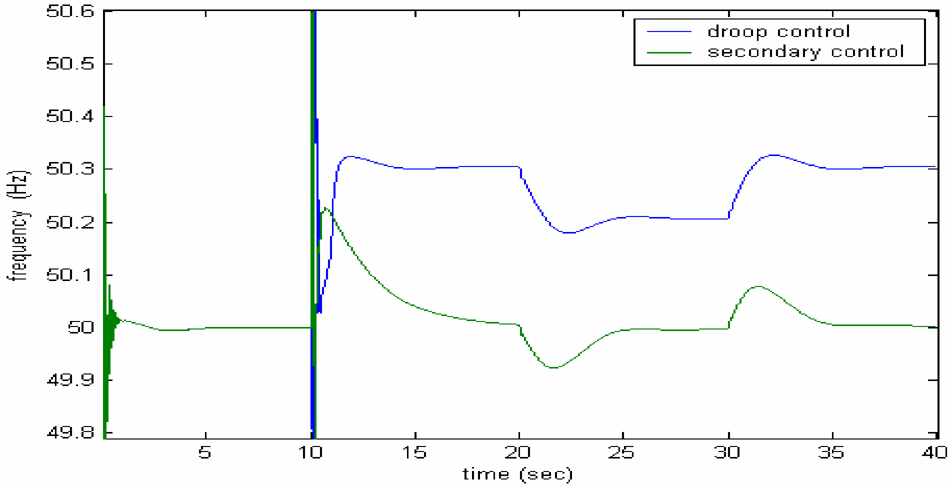

Figure 15. Microgrid's frequency

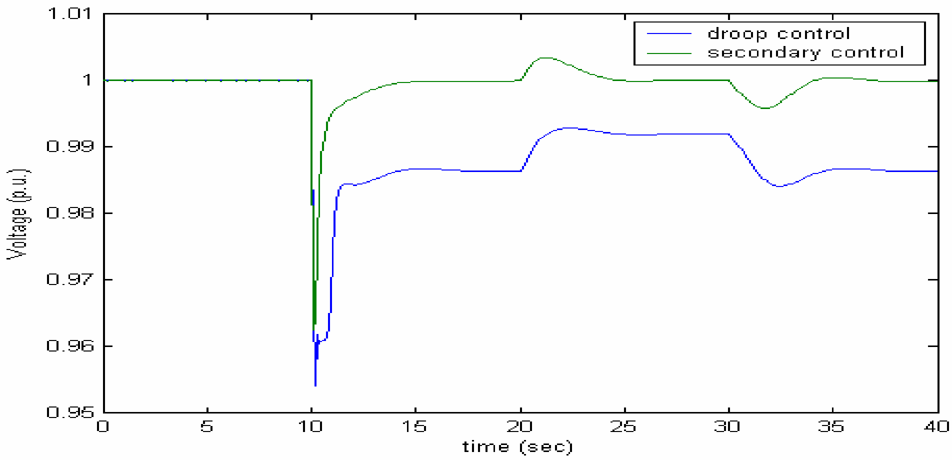

Figure 16. BESS output voltage

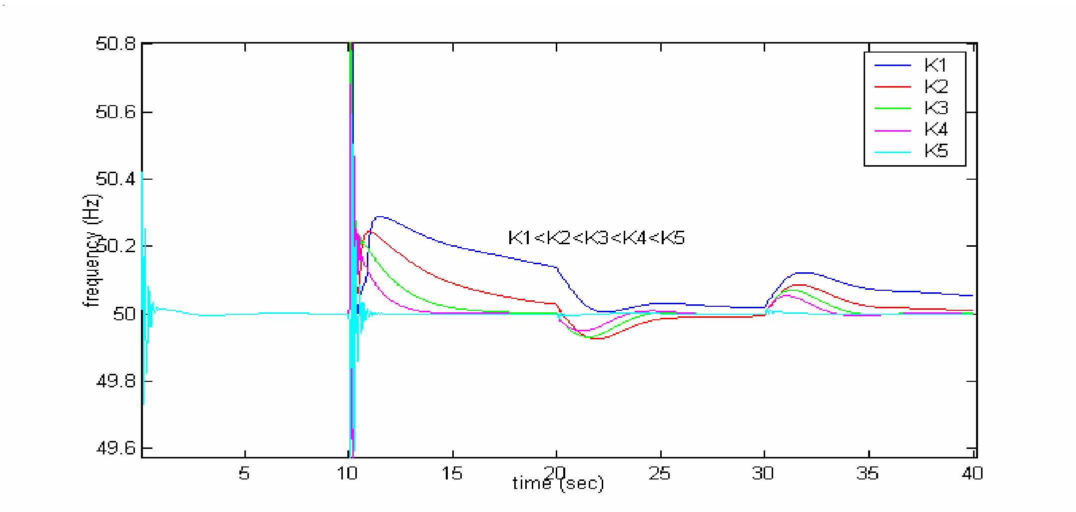

Figure 17. Frequency restoration for different integral gains.

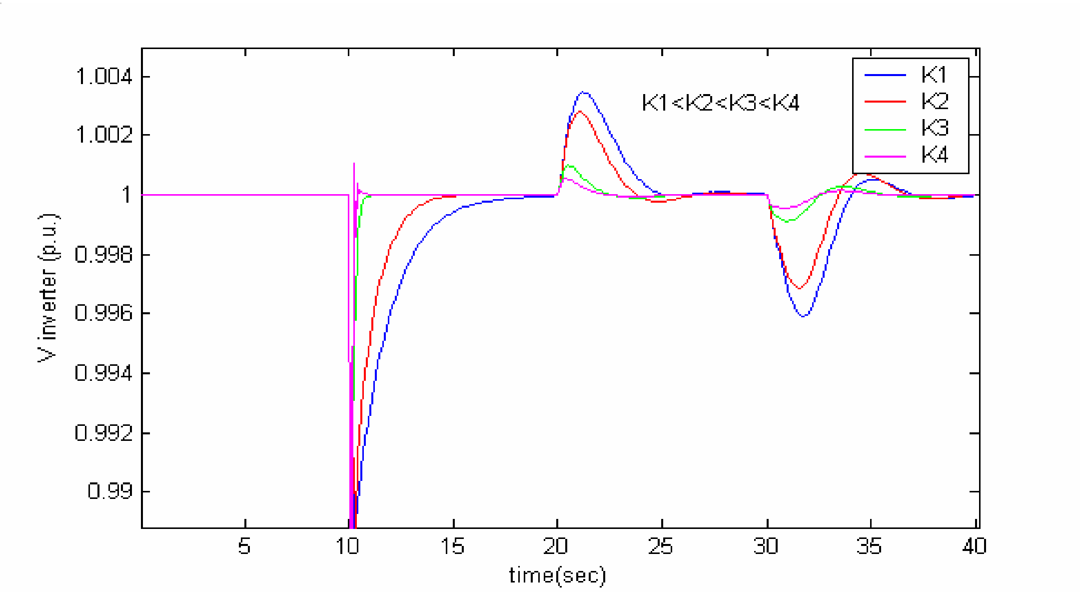

Figure 18. Voltage restoration for different integral gains.

Conclusions

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From the analysis performed the following main conclusions can be drawn regarding the dynamic behaviour of the microgrid:

- It was proved that the islanding of the microgrid can be done in several initial different importing and exporting load conditions.
- It was also proved that storage devices are absolutely essential to implement adequate control strategies for microgrid operation in islanded mode. Particularly in the case of the flywheel, the participation in terms of available power for load-following is enormous, especially since the microgenerators present in the microgrid have a very low inertia and slow ramp-up rates (as in the microturbines and the SOFC cases).
- A combination of droop control mode together with an integral control loop has proved to be effective in controlling frequency during islanded operation. A centralized secondary control (to be hosted in the MGCC) is presently under development.
- The load-shedding procedure is also of very high importance to sustain fast and long frequency deviations. Thus, a smart, well-designed load-shedding strategy is in order.
- Special attention should be given to the load reconnection issue after the load has been shedded. The load reconnection should be made in a slower way than the load-shedding, using more load steps and taking more time between consecutive steps.
- The large number of load/generation scenarios simulated for use in Work Package C – Dynamic Security Assessment proved the robustness of the simulation platform developed.
- Simple black-start sequences were developed and tested using the *EMTP-RV®*

and the *MatLab® Simulink®* platforms, demonstrating through simulations the feasibility of these procedures and providing a deep analysis of the most critical issues within this emergency stage.

UMIST

With increasing penetration levels of the DGs, a number of MicroGrids will exist in the distribution network system in the near future. The safety and reliability of the MicroGrid are becoming more and more important. The unique nature of the MicroGrid requires local frequency control of the MicroGrid. The local frequency control of the MicroGrid can be mainly achieved through control of the flywheel. The possible control schemes of the flywheel for this purpose are PQ control, Droop control and Frequency/Voltage control. The control schemes are implemented in both synchronous generator representation and STATCOM-BES representation of the MicroGrid.

PQ control is only used by the flywheel while the MicroGrid is operating in grid-connected mode. The PQ control of the flywheel makes no contribution to the local frequency control of the MicroGrid due to its fixed active and reactive power outputs. After disconnection of the flywheel from the main network, during islanded mode, the control of the flywheel has to be switched from PQ control to Droop control or Frequency/Voltage control.

Droop control is similar to the Primary frequency control of a conventional synchronous generator. For a change of frequency in the MicroGrid, the active power output of the flywheel is regulated automatically according to a predetermined frequency-droop characteristic. The frequency of the MicroGrid can be restored to a steady state value determined by the droop.

Frequency/Voltage control is similar to the Secondary frequency control of a conventional synchronous generator. It controls the frequency and voltage of the MicroGrid at the normal values (e.g. f = 50Hz and V = 1.0 p.u.). The frequency and voltage of the MicroGrid can be brought back to their normal values after the disturbance. The frequency and voltage of the MicroGrid in which the flywheel uses Frequency/Voltage control are better than the flywheel use Droop control. However, it should be noted that the flywheel using Frequency/Voltage control has to supply higher active and reactive powers to the MicroGrid than using Droop control. The control capability of the flywheel in practice may be limited by its available capacity.

NTUA

It is shown, that the frequency and voltage of Microgrids operating in isolated mode can be effectively controlled by applying droop concepts in the power electronic converters of regulating storage devices, as long as the line resistances are relatively small. This technique should be further investigated in LV grids with high resistance to reactance ratio, in order to prove its general effectiveness in Microgrids operation.

A description of emergency strategies and control algorithms for microgrid operation in emergency conditions was provided in this report. Control strategies for micro source controllers, load controllers and MGCC operation were identified and tested, through extensive simulations in the LV NTUA test system, providing a validation of the approaches developed. A description of the required inverter characteristics, regarding frequency and voltage control has also been included.
More results regarding the test of these strategies under different operating conditions are expected to be presented later under deliverable DD2.