Large Scale Integration of

Micro-Generation to Low Voltage Grids

Contract No: ENK-CT-2002-00610

WORK PACKAGE I

Deliverable DI2: Report on Steady State and Dynamic Analysis of MicroGrids.

Final Version 1.0

December 2005

Document Information

Deliverable:	**DI2**
Title:	**Report on Steady State and Dynamic Analysis of MicroGrids.**
Date:	**2005-12-21**
Task(s):	**I3: Construction of analytical models with existing or foreseen levels of RES and micro sources penetration forming MicroGrids**
	I4: Steady State and Dynamic Analysis of Study Case networks.

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Access:	**Project Consortium**
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Status:	_____	**For Information**
	_____	**Draft Version**
	_____	**Final Version (Internal document)**
	__X__	**Submission for Approval (deliverable)**
	_____	**Final Version (deliverable, approved on)**

Contents

1. Abstract

This report is produced as output of task TI3 “Construction of analytical models with existing or foreseen levels of RES and micro sources penetration forming µGrids” and TI4 “Steady State and Dynamic Analysis of Study Case networks”

Although MicroGrids project aims to LV networks it is extremely difficult to obtain real LV grids with significant distributed generation or renewable energy sources because most of these technologies are in a very pre-commercial state while MV generation sources examples are more easily found. Therefore, the existent LV test network has been the base for one study while others have been based on MV networks preferring applicable analysis results over theoretical outputs obtained from artificially ad-hoc created LV networks.

Studies have been conducted using different simulation tools looking for the most suitable application for the type of study being performed. For this reason, the simulation tool obtained at WPA has not been used: the study cases scope do not require the unbalance system modelling provided by deliverable DA2.

In a real case where network and DG are completely defined, DG integration could require a full range of studies involving both planning and operational issues before its integration. The set of presented study cases covers specific analysis and simulations focussing on relevant problems for each network.

Samothraki Island case of study is aimed towards system planning, over a given islanded system connected to the main land by two submarine cables a large wind farm is to be installed. The complexity of the large wind farm is simplified by using a reduced model by means of aggregation techniques derived from WPA results. The most suitable electrical system connection topology is investigated around voltage stability in order to cope with the sudden lose of one MV line; the used criteria to define the stable configuration is voltage stability.

Les Saintes island case study assesses the impact of a wind farm on the system dynamic response simulating a complete range of perturbations, including different types of short circuits and wind farm incidents. The report compares the simulated dynamic response with and without the wind farm in both connected and isolated modes and combined with alternative load behaviours.

Portuguese LV network case study covers the effect that DG may have on local losses during the steady state operation of the grid and ensures the dynamic stability of the μGrid during the transition from connected to islanded mode; a local storage device copes with the micro source lack of inertia when the transition faces power unbalances (export or import).

Spanish MV network case of study analyses the effect that distinct DG technologies (controllable and renewable) have on feeder loading and voltage profiles as the levels of DG increase. In spite of the conventional deterministic approach used at planning studies, the presented work is based on stochastically defined cases where demand and generation vary following normal distribution values.

A hybrid power system on Les Saintes islands network has been modelled and simulated in island mode. The dynamic behaviour has been investigated with 3 different configurations: diesel power system; diesel and wind turbines power system; diesel and wind turbines system with a storage device (power injector). Various events were considered, such as generation connection or disconnection, short circuits (1, 2 or 3-phase; at generation connecting point or on the MV network), load changes (in particular loss of the sub-sea cable connecting Terre-de-Bas and Terre-de-Haut) and wind variations.

2. Case Study: Samothraki Island Network

2.1. System Description

The one-line equivalent diagram of simplified Samothraki Island electrical network is shown in Figure 2.1-1.

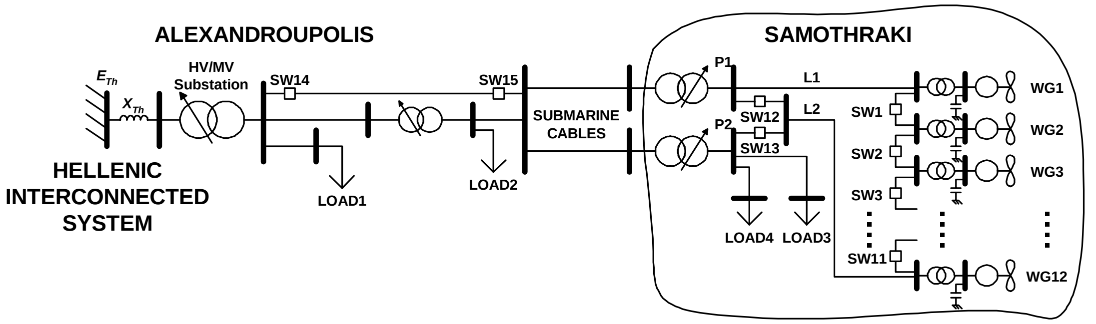

Figure 2.1-1: One-line equivalent diagram of simplified Samothraki Island electrical network

The examined system consists of one wind farm, two aggregate local loads (LOAD3 and LOAD4), two Distribution Voltage Regulators (DVRs) and a radial distribution network at 20 kV level.

The wind farm is equipped with twelve induction generators of nominal generation 0.6 MW each, that is, the nominal wind power installed capacity reaches 7.2 MW. The mechanical torque on the shaft of each wind generator is considered constant. In the terminal bus of each wind generator, capacitive compensation has been installed in order to regulate the power factor of the bus during steady-state operation in values not less than 0.96 lagging under nominal voltage. For simplicity reasons, the terminal voltage of each wind generator in the initial operating point is considered equal to nominal. Each wind generator is connected to the local distribution network through MV/LV transformers and two distribution lines L1 and L2 of ACSR-95 type at 20 kV.

Depending on the status of the switches SW1 to SW13, the wind power generation can be divided in two groups, which are injected to the network through the distribution lines L1 and L2 at points P1 and P2 respectively. For example, if all switches from SW1 to SW12 are closed and the switch SW13 is open, the whole wind power will be connected to the submarine cable through point P1 and the two lines L1 and L2 will operate in parallel. In this case, the other cable (connected to P2) is feeding only the two local loads. In addition, if all switches except SW6 (intermediate switch in the terminal of wind generators) and SW12 are closed, then half of the wind farm generation will be injected to the network in point P1 through line L1 and the other half in point P2 through line L2. Thus, the local loads will be fed by the wind generators from WG6 to WG12.

During the analysis, the wind farm is represented by one or two equivalent wind generators, aggregate capacitive compensation schemes and equivalent MV/LV transformers [9]. In the initial operating point, the terminal voltage of both equivalent wind generators is considered nominal. The first (second) equivalent machine is connected to the point P1 (P2) through the first (second) equivalent MV/LV transformer and the distribution line L1 (L2). Depending on the status of the switches from SW1 to SW13, the nominal active generation of each equivalent machine is the sum of all respective wind generators, while the machine parameters correspond to the parallel combination of the individual wind generators. Similarly, the impedance of each equivalent MV/LV transformer is calculated as the parallel combination of individual transformers, while the reactive compensation is the sum of respective individual compensation schemes.

Concerning the two aggregate local loads, their active power consumption is considered of constant current type, while their reactive one of constant impedance type. Note that the peak active load of the island reaches about 3 MW.

Each Distribution Voltage Regulator (DVR) is a 20/20 kV autotransformer, which is equipped with load tap changer mechanism. The role of DVRs is to secure the normal operation of Samothraki Island network, by keeping each autotransformer secondary voltage at a specified range. Due to the lack of local conventional generation, the existence of DVRs is of great importance.

The electrical network of Samothraki Island is connected to the mainland through two submarine cables of length 46 km each, operating at 20 kV level.

In the mainland, the distribution system of Alexandroupolis is represented by two aggregate local loads (LOAD1 and LOAD2). These loads are considered of the same type with the previously referred loads of Samothraki Island.

The distribution network of Alexandroupolis is connected to the transmission network at 150 kV level through an HV/MV substation.

During the analysis, the Hellenic Interconnected Power System is represented by a Thevenin equivalent. The total equivalent impedance is computed from the short circuit level of Alexandroupolis HV bus.

2.2. Voltage Stability Analysis

Voltage stability is concerned with the ability of a power system to maintain steady voltages at all buses in the system after being subjected to a disturbance from a given initial operating condition. A definition adopted for voltage instability is [1]:

Voltage instability stems from the attempt of load dynamics to restore power consumption beyond the capability of the combined transmission and generation system.

According to the above definition, voltage instability is load driven and requires a full network representation for its analysis. These are the main aspects separating the two classes of long-term stability problems.

Voltage instability occurs in the form of a progressive fall or rise of voltages of some buses. A possible outcome of voltage instability is loss of load in an area, or tripping of transmission lines and other elements by their protections leading to cascading outages.

The time frame of interest for voltage stability problems may vary from a few seconds to tens of minutes. Therefore, voltage stability may be either a short-term or a long-term phenomenon.

Short-term voltage stability involves dynamics of fast acting load components such as induction motors, electronically controlled loads and AC/DC converters that may connect distributed generation components. The study period of interest is in the order of several seconds, and analysis requires solution of appropriate system differential equations; this is in the same time scale as the analysis of rotor angle transient stability.

Long-term voltage stability involves slower acting equipment such as tap-changing transformers, thermostatically controlled loads and generator field current limiters.

The study period of interest may extend to several minutes, and long-term simulations are required for analysis of system dynamic performance. In many cases, static analysis can be used to determine stability margins, identify factors influencing stability, and examine a wide range of system conditions and a large number of post-contingency scenarios.

As far as the short-time scale is concerned, it should be noted that there is not a clear-cut separation between load-driven and generator-driven stability problems, as there is as between frequency and long-term voltage stability. Moreover, the identification of the driving force for an instability mechanism does not exclude the other components from affecting this mechanism. For example, load modelling does affect rotor angle stability and generator modelling is important for a correct voltage stability assessment.

The simulation tool used in this work for the analysis of short-term Voltage stability stems from educational purpose simulation software developed in *Matlab® / Simulink®* in conjunction with the University of Liege [11] and was adopted for research purposes in a package called WHSSP (Wind-Hybrid System Simulation Package). The package is appropriate for simulation and stability analysis of small interconnected or autonomous Power Systems that may include distributed generation, as well as renewable energy sources [10].

The system model is built using a library in *Simulink®*, which contains individual Power System models that are separately developed based on the available standard textbooks [2-8]. Such individual models refer to the transmission-distribution network, synchronous and induction machines (motors or generators), Automatic Voltage Regulators (AVRs) and Over-excitation Limiters (OELs) of synchronous machines, steam, hydraulic and diesel turbines with their corresponding governors, transformers equipped with Load Tap Changer (LTC) mechanism, Mechanically Switched Capacitors (MSCs) and finally Static Var Compensators (SVCs).

2.3. Simulation Results

Voltage stability is analyzed by simulating the response of the simplified equivalent Samothraki Island network, in case the switches SW14 or SW15 suddenly open, leading to the loss of the dedicated distribution line in Alexandroupolis network. Note that static analysis has proved that there is a steady-state equilibrium point after the examined disturbance. An unstable case and a stable one are examined.

Concerning LTC, discrete time model is considered for its operation. To be more specific, we assume for all DVRs that the time delay between two sequential tap changes is always equal to 10 s.

At first, we assume that the total nominal wind power penetration level of 7.2 MW is injected the network through point P1, that is the distribution lines L1 and L2 are working in parallel. The disturbance happens at t=1 s and Figure 2.3-1 shows the voltage evolutions for load buses, including equivalent wind generator terminal bus.

After the loss of the distribution line, the reactive support provided to Samothraki Island by the mainland is reduced, leading to bus voltages reduction. As a result, the mechanical input torque exceeds the respective electromagnetic torque, leading to wind generator acceleration, as shown in Figure 2.3-2.

From the latter figure, we also observe that the wind generator decelerates for a short time period, while trying to reach the stable post disturbance operating point. However, the machine is no longer attracted to its post disturbance equilibrium. This leads to the loss of its short-term stability and finally to over-acceleration. The evolution of the detected short-term Voltage instability phenomenon leads to Voltage collapse.

Note that during the above simulation we are not taking into account any over-speed protection of the wind generator, which would activate and disconnect it from the network.

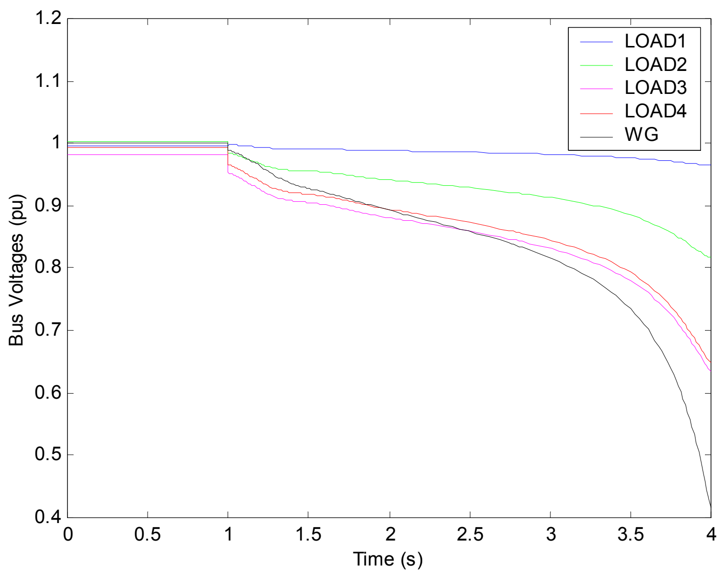

Figure 2.3-1: Bus voltages (unstable scenario)

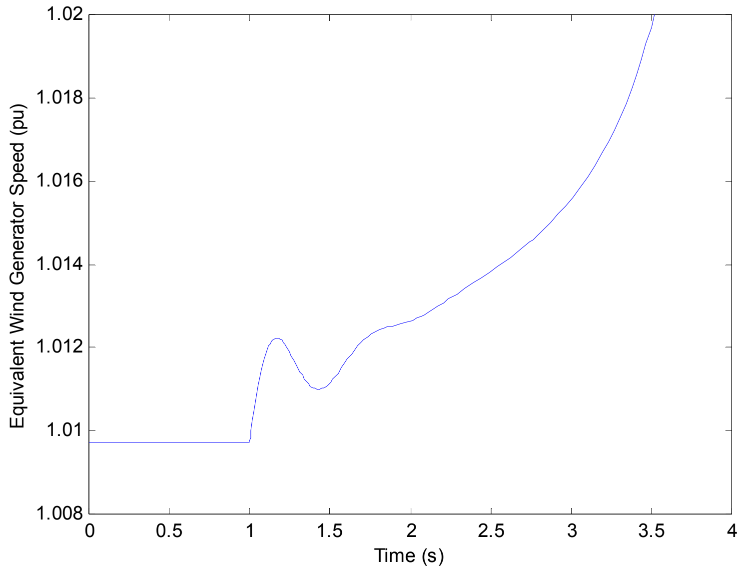

Figure 2.3-2: Equivalent wind generator speed (unstable scenario)

In the sequel, we assume that 75% of total nominal wind power installed capacity, corresponding to 5.4 MW, is transferred to the network through line L1, while the rest 25% (corresponding to 1.8 MW) is injected through line L2 and point P2. This wind generator grouping can be achieved, if all switches except SW9 and SW13 are closed. In this case, the wind farm is represented by two equivalent wind generators, WG1 of nominal active generation 5.4 MW and WG2 of 1.8 MW. The response of the network voltages under the loss of the distribution line is shown in Figure 2.3-3

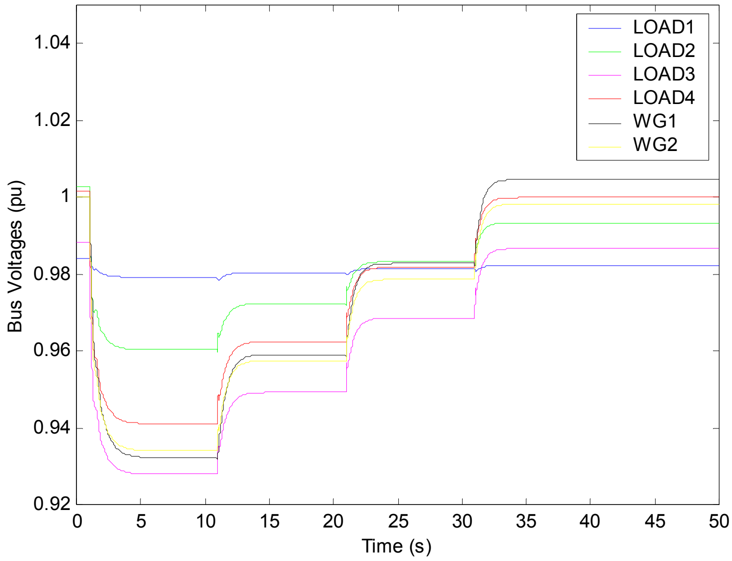

Figure 2.3-3: Bus voltages (stable scenario)

Similarly to previous case, the bus voltages are reduced after the loss of the line, leading to both equivalent wind generators acceleration. Following this, both generators decelerate and finally they reach a stable post disturbance operating point after some oscillations, as shown in Figure 2.3-4. These oscillations are due to the electrical and mechanical oscillation modes between the induction generators and the external system.

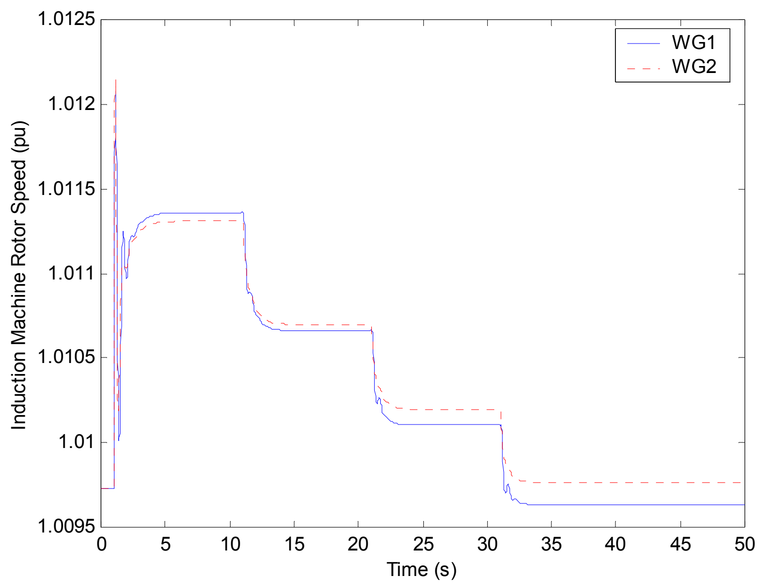

Figure 2.3-4: Equivalent wind generator speed (stable scenario)

In addition, after both wind generators reach a short-term stable equilibrium point, the DVRs act in long-term time scale and restore the controlled bus voltages.

Consequently, the network is secure for the considered contingency and also no Voltage instability problems appear during the simulation.

2.4. Conclusions

According to above-mentioned study, two different ways of wind power penetration were examined for the simplified Samothraki Island electrical network.

At first, the total wind power nominal generation of 7.2 MW was connected to the submarine cable through point P1 and the two distribution lines L1 and L2 were operating in parallel. In this case, short-term Voltage instability was detected, when the system was subjected to the loss of the dedicated distribution line in Alexandroupolis. The instability was driven by the equivalent wind generator, while the machine wan no longer attracted to its post disturbance equilibrium.

In the second case, 75% of total nominal wind power installed capacity (corresponding to 5.4 MW) was connected to the submarine cable through point P1 and line L1. The rest 25%

(corresponding to 1.8 MW) fed the local loads through point P2 and line L2. According to appropriate simulations, the new network topology was proved secure for the considered contingency and also no Voltage instability problems appear.

2.5. References

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[11] C. D. Vournas, E. G. Potamianakis, C. Moors, T. Van Cutsem, "An Educational Simulation Tool for Power System Control and Stability", IEEE Transactions on Power Systems, Special Section on Power Engineering Education, Vol. 19, No. 1, February 2004.

3. Case Study: Les Saintes Island Network

3.1. Introduction

This study case presents the results on dynamic behaviour of *Les Saintes* network operating in Medium Voltage based on wind power energy in both isolated and connected modes. The results analysis aim to assess the impact of the wind power generation on the network in term of stability under severe incidents allowing therefore the chose of adequate protections schema.

Several types of incidents and disturbances need to be considered under different loads intakes. The most influent parameters will be discussed. The study presented here is limited to Medium voltage's faults and incidents on the wind park like wind speed variation and sudden wind turbine connection and disconnection under islanded and connected modes.

A simulation platform under EMTP-RV environment was developed to evaluate the dynamic behaviour of this network.

3.2. Study Objectives

The present work involves system stability and dynamic behaviour issues of *Les Saintes* network study case.

The stability assessment is fulfilled by computer simulation (EMTP - RV) of the behaviour of all system components before, during and for a period after a fault on the system. Previous to these power stability assessment simulations, an effort of collecting some of the appropriate models of the network parts was accomplished by EDF. However, the results are subject to some unreal power system equipment modelling.

In fact the models should represent the features and phenomena likely to be relevant to stability study. These include the electrical characteristics of the generator, the mechanical characteristics of the turbine and generator, variation of power co-efficient (Cp, λ, β curves) and a realistic load modelling.

3.3. Stability Definition and Classification

Power system stability has been recognized as an important problem for secure system operation since the 1920s. Many major blackouts caused by power system instability have illustrated the importance of this phenomenon. Historically, transient angle instability has been the dominant stability problem on most systems, and has been the focus of much of industry's attention concerning system stability. As power systems have evolved through continuing growth in interconnections, use of new technologies and controls, and the increased operation in highly stressed conditions, different forms of system instability have emerged. For example, voltage stability, frequency stability and inter-area oscillations have become greater concerns than in the past. This has created a need to review the definition and classification of power system stability.

3.3.1. Definition

The definition provided by the "IEEE/CIGRE Joint Task Force on Stability Terms and Definitions" is:

Power system stability is the ability of an electric power system, for a given initial operating condition, to regain a state of operating equilibrium after being subjected to a physical disturbance, with most system variables bounded so that practically the entire system remains intact.

3.3.2. Classification

Classification is essential for meaningful practical analysis and resolution of power system stability problems. The same Task Force proposed a classification based on the physical nature of the resulting mode of instability as indicated by the main system variable in which instability can be observed, the size of the disturbance considered, which influences the method of calculation and prediction of stability and finally on the devices, processes, and the time span that must be taken into consideration in order to assess stability.

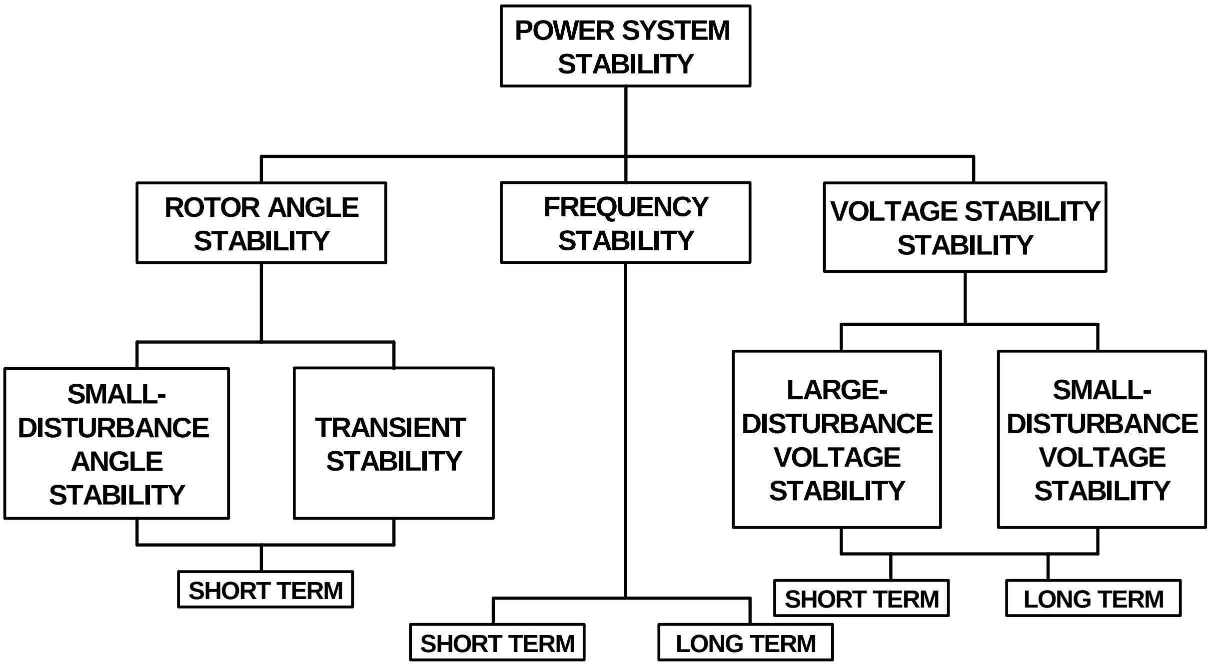

Figure 3.3.2-1: Power system stability classification

<u>Angular stability or transient stability</u>

Transient stability issues, also referred to as the first swing stability, are among the most important practical concerns in power system operation and planning studies. The assessment of transient stability, where the angle stability under large disturbances is investigated, is becoming an essential requirement for the security of electrical power systems. It is defined as the ability of the power system to maintain synchronism when subjected to a severe disturbance such as short circuits or loss of large loads or generation. Transient stability depends on the initial operating conditions of the system as well as the type, severity and location of the disturbance.

<u>Frequency stability</u>

Following large disturbances in power systems, significant imbalance takes place between generated power and load demands. Furthermore, imbalances occur between the electromagnetic and the mechanical torques of the generators. The consequential accelerations or decelerations of generators due to this imbalance result in changes in the frequency of the network, which can impact the stability of the system. Frequency stability refers to the ability of electrical power systems to maintain fixed frequency after being subjected to a severe disturbance. The frequency will not cause a stability problem if the equilibrium between generation and load is restored. This requires sufficient generation reserve and adequate response from the control and protection devices. If the disturbance results in sustained frequency oscillations, generating units will be sequentially tripped out of the network and the stability will be lost.

<u>Voltage stability</u>

Voltage stability is defined as the ability of a power system to maintain the voltages at all nodes within acceptable limits after being subjected to a disturbance. Voltage instability results from the progressive collapse or rise of voltages of network nodes, which may cause the loss of some loads or transmission lines. The tendency of induction motors to restore their power after disturbances by adjusting their operating slips would increase the reactive power consumption causing further voltage reduction. If the required power consumption by loads is beyond the capability of the generators or transmission systems, a run-down situation causing voltage instability takes place.

In highly stressed systems and for cascading events, as systems fail one form of instability may ultimately lead to another form. However, distinguishing between different forms is important for understanding the underlying causes of the problem in order to develop appropriate design and operating procedures.

While classification of power system stability is an effective and convenient means to deal with the complexities of the problem, the overall stability of the system should always be kept in mind. Solutions to stability problems of one category should not be at the expense of another. It is essential to look at all aspects of the stability phenomena and at each aspect from more than one viewpoint.

3.4. Les Saintes Network

Les Saintes is one of the little islands of the *Guadeloupe*. It is located in the Caribbean Sea. *Les Saintes* consists it self of two little islands: Terre de Bas and Terre de Haut (Figure 3.4-1: Schematical diagram).

The power is imported from the main island. In case of a disconnection, a diesel genset is started on *Les Saintes* islands. It is planned to install a wind power park in Terre de Bas.

The network on *Les Saintes* is a 20 kV network consisting of overhead lines and cables. The load level on *Les Saintes* is about 1.4 MW at peak load.

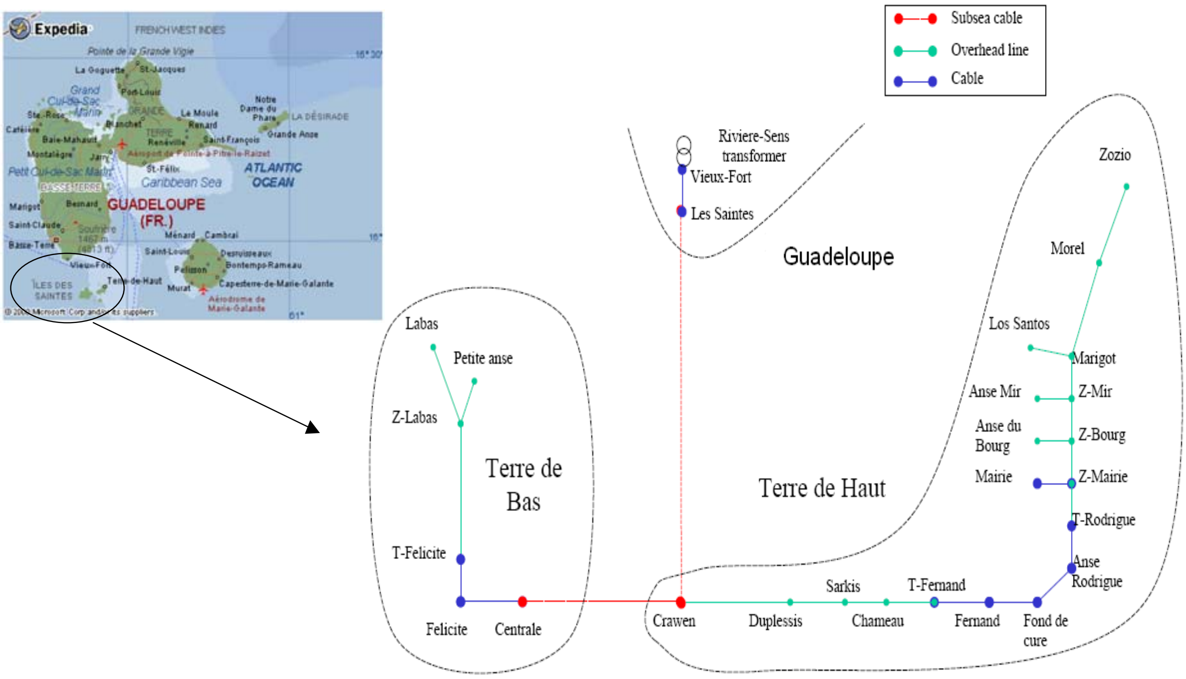

Figure 3.4-1: Schematical diagram

3.5. Data and Modelling

EMTP – RV platform (http://www.emtp.com/software/emtp_rv.html) has been used for the network modelling and data acquisition.

3.5.1. The Network

The network consists of three types of cables: submarine, underground and overhead line. These cables parameters are gathered from Deliverable DI1: Electrical and RES Data Collection and implemented under EMTP's PI line model.

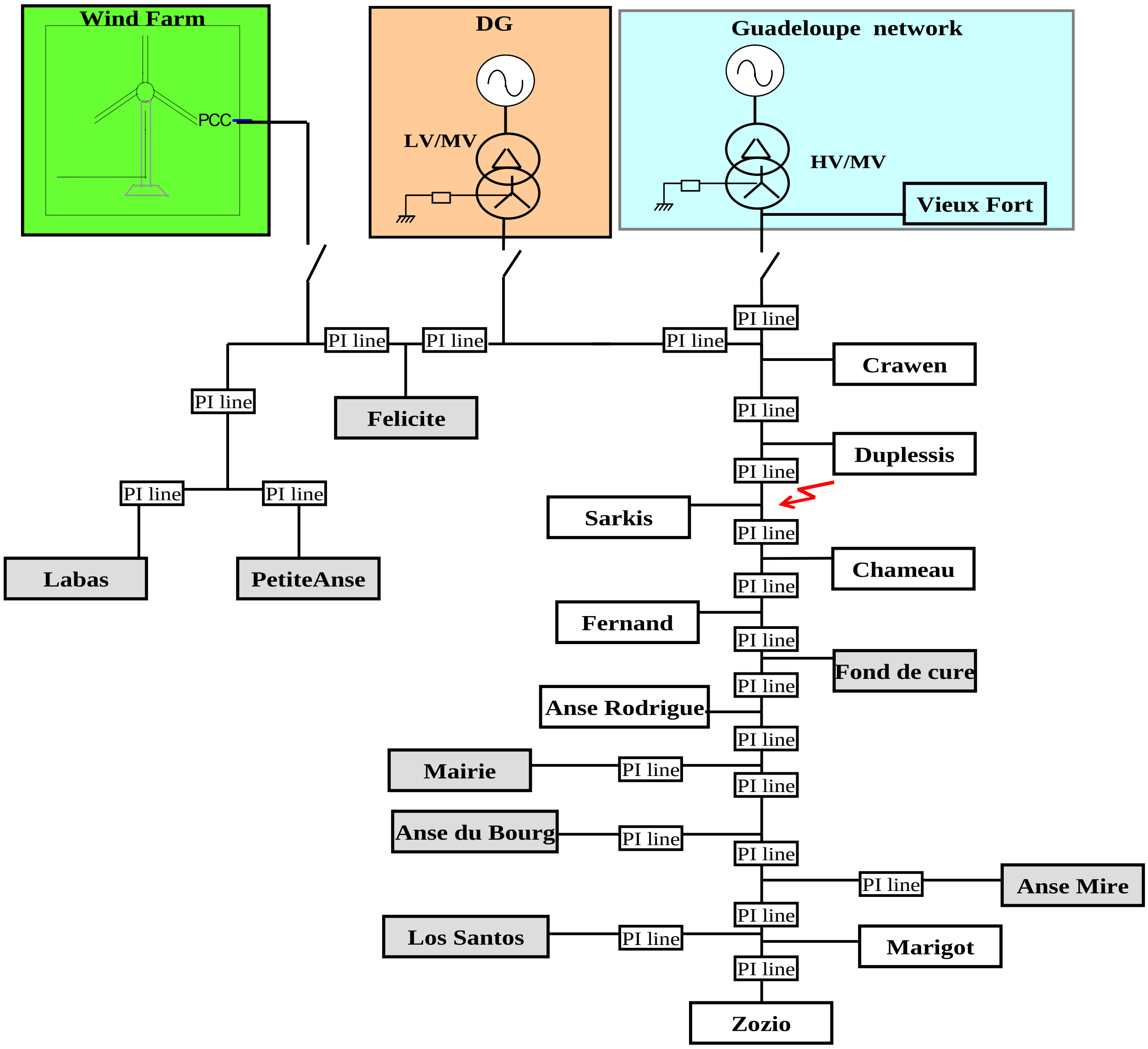

Figure 3.5.1-1: Les Saintes power sources and substations

3.5.2. Load Modelling

There are 18 substations (Figure 3.4-1 & Figure 3.5.1-1). The study was carried out using the peak load of the network which is 1.4 MW; the deliverable DI1: "Electrical and RES Data Collection" specifies the peak load of each substation. Two types of load modelling were used in the simulations (Figure 3.5.2-1):

- Static load: (P = f (V), Q= f (V)), in EMTP it is represented by a RLC Load.

- Static and Dynamic loads: The active and reactive powers at any instant of the time as functions of the bus voltage and frequency at past and present instants of the time.

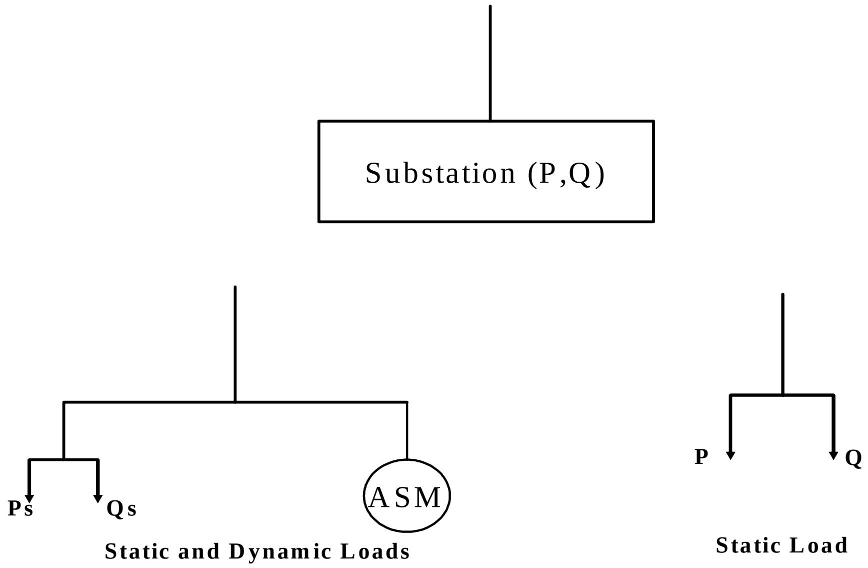

Figure 3.5.2-1: The two types of loads

Asynchronous machine was modelled as following (Table 3.5.2-1) to represent a substation equivalent dynamic load.

Table 3.5.2-1: Equvalent dynamic load: (ASM) parameters

Parameter	Value
Rotor type	Single squirrel cage
V rated line to line	0.4 kV
Number of poles	4
Rs	0,0137 pu
Lls	0,0728 pu
Lmd	2,6499 pu
Lmq	2,6499 pu
Rr1	0,0175 pu

Parameter	Value
Llr1	0,0278 pu
cos (φ)	0.84

Only the seven big substations (the substations in grey in Figure 2) were chosen to have this equivalent dynamic load with a proportion of 30% of their total load (Ps ≈ 70%.P, Pd ≈ 30%.P). It is the average proportion in a quite residential island.

The loads variations in time are not considered in our study. We've chosen a constant mechanical torque equal to 0.9 pu for the seven dynamic loads.

The Table 3.5.2-2 represents the active power and inertia constant of the seven dynamic loads.

Table 3.5.2-2: Dynamic loads: Power and Inertia

Substation	P Dynamic(kW)	H (s)	J (Kg.m^2)
LABAS	28.9	1.1	1.92
PETITEANSE	31.0	1.2	2.25
FELICITE	31.0	1.2	2.25
FOND DE CURE	51.0	1.4	4.37
MAIRIE	77.0	1.6	7.50
ANSE DU BOURG	73.0	1.5	6.60
ANSE MIRE	25.0	1.0	1.56

3.5.3. Wind Turbines

The wind farm is consisting of several constant speed wind turbines directly connected to the network (Squirrel cage induction WTGs).

The WTGs' operating point has a great impact on the system stability. For that reason, the adequate modelling of the induction machines has to be performed.

The machine's model used in simulation is provided by EDF (Table 3.5.3-1).

Table 3.5.3-1: Asynchronous generator parameters

Parameter	Value
Rotor type	Single squirrel cage
Power	300kW
V rated line to line	0.4 kV
J	50.5 kg.m^2
H	2.51 s
Rs	0.0076 Ω
Lls	0.107 Ω
Lmd	3,130 Ω
Lmq	3,130 Ω
Rr1	0.0063 Ω
Llr1	0.140 Ω

We have chosen five WTGs (Annexe C) that can provide 50 % of *Les Saintes* needs at peak load and at 10 m/s as wind speed. With a chosen compensation (Figure 3.5.3-1) the wind farm has at these conditions a power factor of 0.98 (see annexe D).

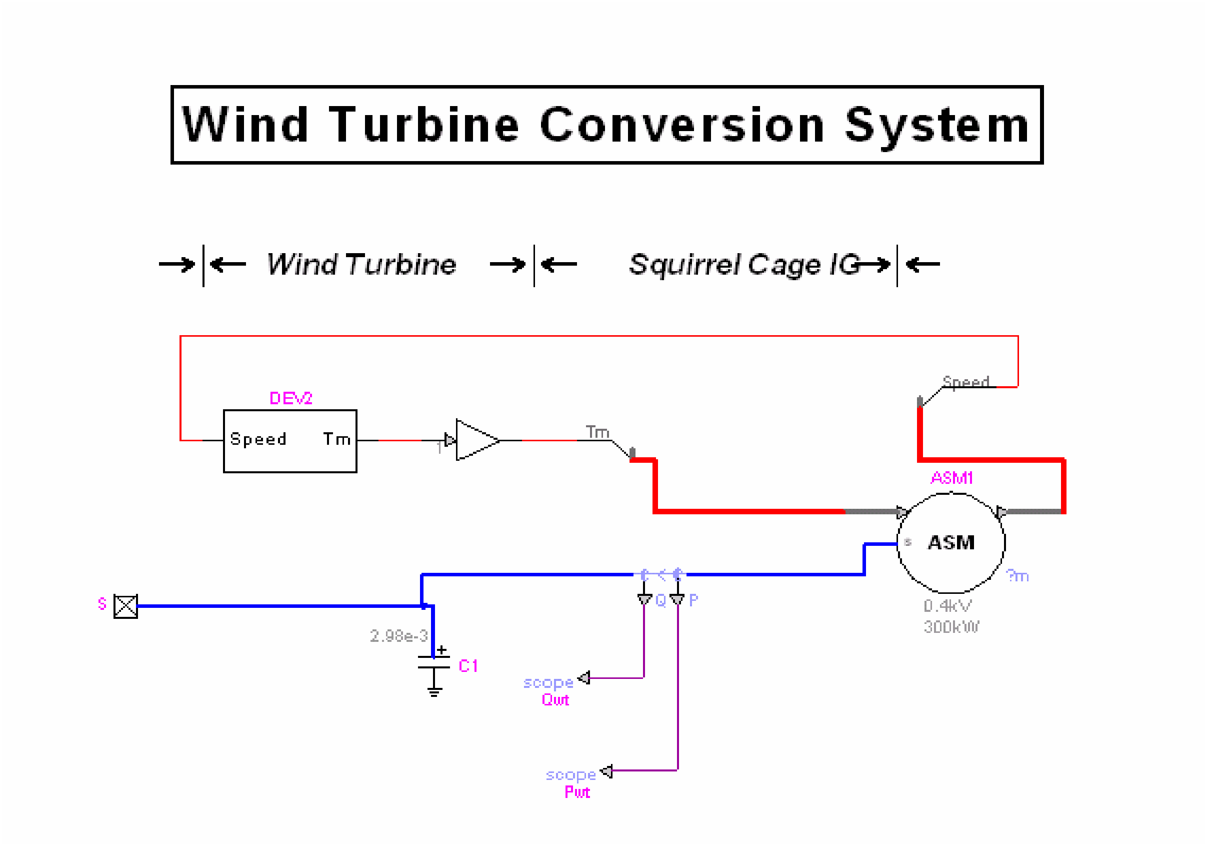

Figure 3.5.3-1: WT conversion system

3.5.4. Transformers

The Table 3.5.4-1 represents the LV/MV and the HV/MV transformers parameters. They are Delta – Wye coupled.

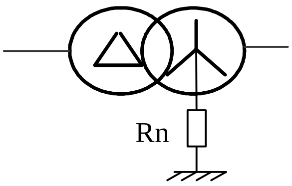

Figure 3.5.4-1: Transformer

Table 3.5.4-1: Transformer parameters

	LV/MV (0.4/21 kV)	HV/MV (63/21 kV)
Rn (Ω)	40	40

<table>
<tr><th colspan="2"></th><th>LV/MV (0.4/21 kV)</th><th>HV/MV (63/21 kV)</th></tr>
<tr><td colspan="2">DELTA – WYE coupled</td><td>-</td><td>-</td></tr>
<tr><td colspan="2">Rated Power (Sn)</td><td>2</td><td>36</td></tr>
<tr><td rowspan="3">Positive sequence excitation test</td><td>Exciting current (% of Sn)</td><td>0.1 %</td><td>0.1 %</td></tr>
<tr><td>3-phase Power rating (kW)</td><td>2</td><td>36</td></tr>
<tr><td>Excitation loss</td><td>1</td><td>18</td></tr>
<tr><td rowspan="3">Zero sequence excitation test</td><td>Exciting current</td><td>100% (In_1)</td><td>100% (In_2)</td></tr>
<tr><td>3-phase Power rating</td><td>2</td><td>36</td></tr>
<tr><td>Excitation loss (kW)</td><td>40</td><td>720</td></tr>
<tr><td rowspan="3">Short circuit test data</td><td>Positive sequence short circuit voltage (%)</td><td>6.5</td><td>16.9</td></tr>
<tr><td>Zero sequence short circuit voltage (%)</td><td>15</td><td>15</td></tr>
<tr><td>Excitation loss (kW)</td><td>20</td><td>360</td></tr>
</table>

3.5.5. Diesel Genset

The permanently functioning of DGS is essential for our microgrid in isolated mode. Indeed, WF cannot ensure the maintenance of the voltage and the frequency in the network.

The power generating unit is composed of a diesel and a synchronous machine (Table 3.5.5-1) associated to a speed control, an exciter and an automatic voltage regulator systems.

3.5.5.1. Speed Control

The rotational speed of the synchronous generator must be maintained at the frequency of 50Hz. This control is made by the mean of a governor which modifies the mechanical torque of the DGS's synchronous machine. The governor is characterized by the actuator and the engine times delay.

The speed control block diagram is shown in Figure 3.5.5-1. Its parameters values are presented in Table 3.5.5-2. The engine and the actuator are modelled by a delay. It is a simplified model and does not take into account the actual behaviours of the actuator, the turbocharger and the engine.

The integral action in the PI controller does not cause any difficulties when the loop is closed. The feedback loop will, however, be broken when the actuator saturates because the output of the saturating element is then not influenced by its input (rotor speed). This causes unstable situation. An anti wind-up feed back is then necessary to implement.

Tmin is equal to 0 because the mechanical torque has to be always positive and Tmax is equal to 1.1 pu

Table 3.5.5-1: DGS's: Synchronous machine parameters

Parameter	Value
Armature winding connection	Wye Grounded
Rated Power	2 MVA
V rated line to line	400 V
H	1 s
J	112.5 kg.m^2
Number of poles	4
Frequency	50 Hz
Ra	0.002 pu
Xl	0.15 pu
Xd	1.06 pu
Xq	0.6 pu
Xd'	0.255 pu
Xq'	0.53 pu
Xd''	0.177 pu
Xq''	0.213 pu

Parameter	Value
Td0’	6.09 s
Tq0’	0.002 s
Td0’’	0.05 s
Tq0’’	0.1 s

The rotational speed of the synchronous generator must be maintained at the frequency of 50Hz. This control is made by the mean of a governor which modifies the mechanical torque of the DG’s synchronous machine. The governor is characterized by the actuator and the engine times delay.

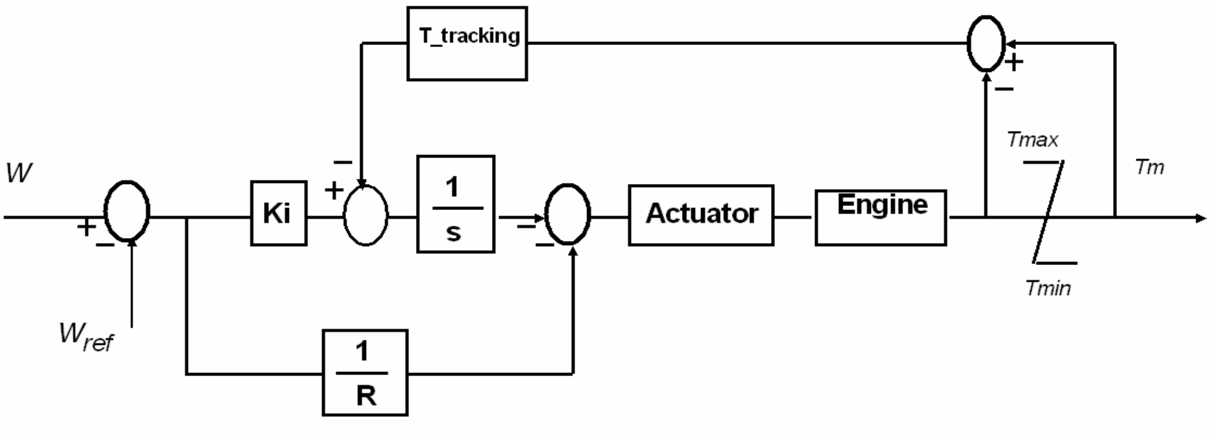

Figure 3.5.5-1: Governor Block diagram

Table 3.5.5-2: The Governor parameters ([1])

Parameter	Value
ω_{ref}	157.07 rd/s
K_I	41.5
R	0.0642
Td actuator	0 s
Td engine	0.039 s

Td tracking	10 s

3.5.6. Exciter and Automatic Voltage Regulator

A traditional permanent action exciter and an automatic voltage regulator were chosen for the simulations. The Figure 3.5.6-1 represents its block diagram.

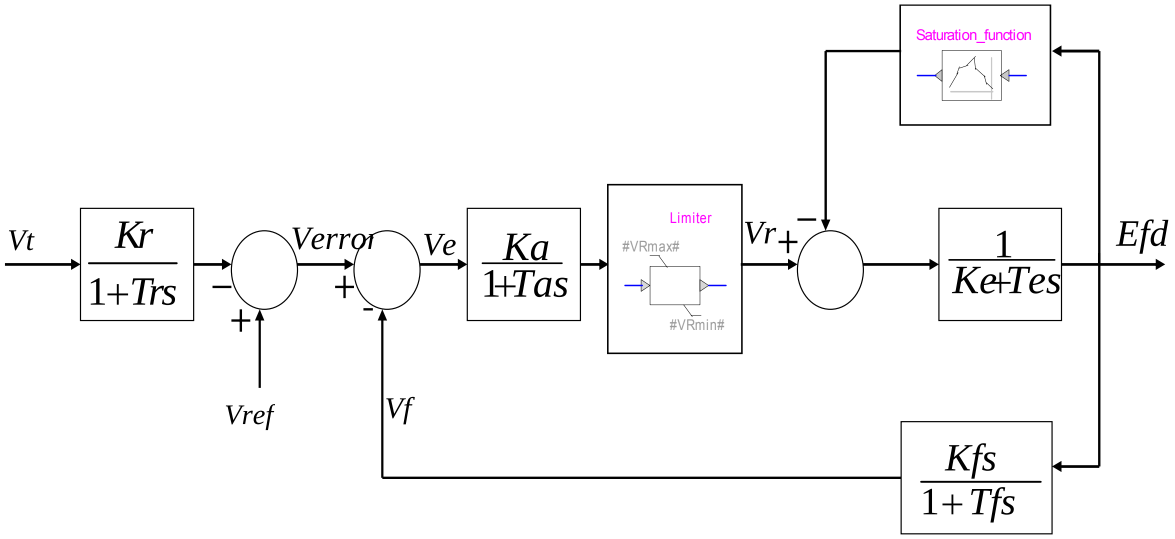

Figure 3.5.6-1: Type 1 exciter block diagram

The parameters values (Table 3.5.6-1) are taken from literature since the real ones are missing.

There is no specification that is convenient

Table 3.5.6-1: Exciter and AVR parameters ([1])

Parameter	Value
Amplifier's time constant (Ta)	0.06
Amplifier's gain (Ka)	200
Exciter's time constant (Te)	0.95
Exciter's gain (Ke)	-0.17
Regulator's time constant (Tr)	0
Regulator's gain (Kr)	1

Parameter	Value
Stabilizer's time constant (Tf)	1
Stabilizer's gain (Kf)	0.038
Maximum value of Vr	-6
Minimum value of Vr	6
Exciter’s Max limit	10

3.6. Scenarios

3.6.1. The Instability

Squirrel-cage induction generators used in constant-speed turbines can lead to voltage and rotor-speed (transient) instability. During a fault, they accelerate due to the unbalance between mechanical power extracted from the wind and electrical power supplied to the grid. When the voltage restores, they consume much reactive power, impeding voltage restoration. When the voltage does not return quickly enough, the wind turbines continue to accelerate and to consume large amounts of reactive power.

Induction machine transient stability and system voltage stability are then not inherent phenomena. Moreover, there are more likely to happen in case of presence of motor loads in the network. In fact, the critical short circuit clearing time (Tcc) diminishes in this case because of the increase of motor’s reactive power consumption.

The Table 3.6.1-1 shows the 3-phase critical clearing time for Les Saintes network.

Table 3.6.1-1: 3-phase critical clearing time for Les Saintes network (found by trial and error method)

	Load Model	
	100% Static	70% Static + 30% Motor
Tcc	0.500 s	0.325 s

Assuming that the mechanical torque of the wind turbines at fault period is constant, the rotor speed ω (slip) grows almost linearly (equation (2)) in time domain until the clearance of the fault.

$$J.d\omega/dt = -Tem + Tmech - Tdamp \qquad (1)$$

Where, J is inertia constant, ω is the rotor speed in a fault period, Tmech is the externally applied mechanical torque and Tem is the electromechanical torque, and Tdamp is the damping torque. For the sake of simplicity, in the fault period Tdamp = 0 and Tem << Tmech.

$$\omega = (Tmech/J)*(t - T0) + \omega 0 \qquad (2)$$

The wind turbines machine stay stable as long as the electromechanical torque after fault clearance is bigger than mechanical torque. Otherwise the rotor speed grows until the protections trigger, leading to a voltage collapse (big reactive consumption).

Considering 100% of static load, the voltage rises right after the clearance to V2 (Figure 3.6.1-1) which is smaller than V1 (1 pu) because of the wind turbine magnetizing power. The slip limit before instability is then sl2. With a proportion of motor load (30% by example), the magnetizing power needed is bigger. This leads to a smaller voltage after short circuit: V3. The slip limit is then sl3 (<sl2).

Then   Tcc3<Tcc2<Tcc1

For a certain proportion of motor load, the system loses its stability automatically after the short circuit (V4). The wind farm is then islanded.

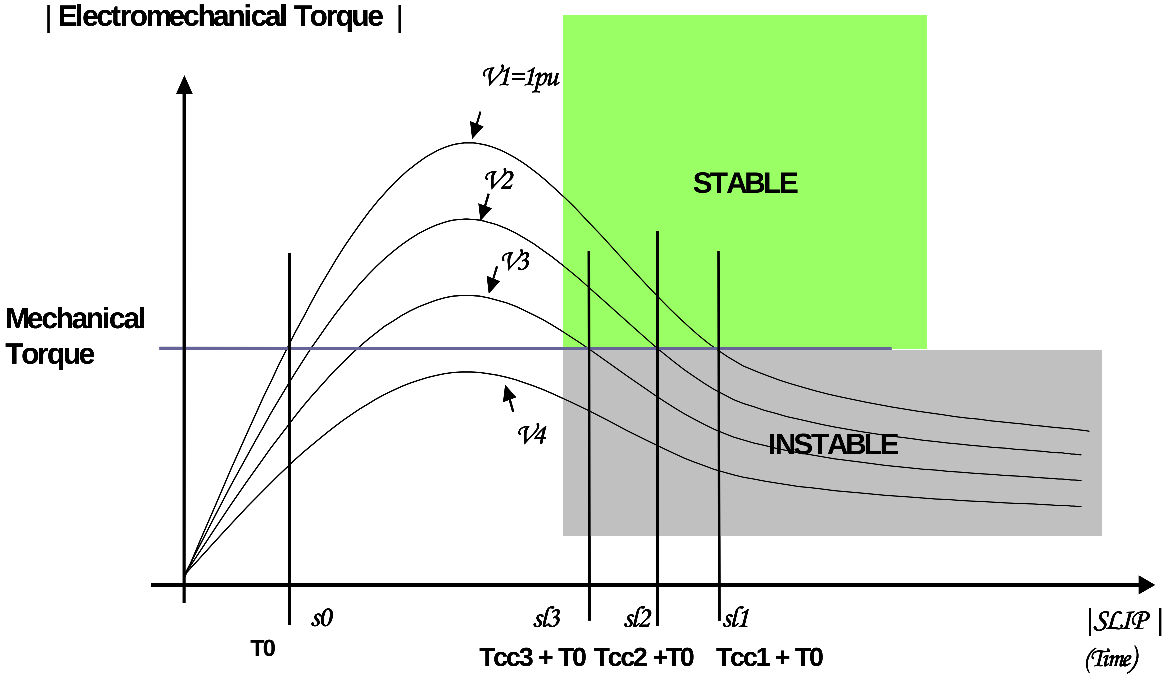

Figure 3.6.1-1: Induction Machine (WTG) Torque

To illustrate the network instability, two simulations of Les Saintes network in isolated mode (WF+DGS) with 30% of dynamic load were run: the first one with a three-phase short duration of 0.3 s (stable case) and the second one duration of 0.4 s (instable case).

Note that the second duration is bigger than the critical clearing time mentioned in Table 3.6.1-1 (Tcc =0.325 s)

The two next figures confirm what was explained above.

The wind turbine speed rises linearly during and after the fault. The reactive consumption of the motor rises with the fall of its speed.

In Figure 3.6.1-3 we see clearly that the electromechanical torque managed to overshoot the mechanical torque in stable case (red).

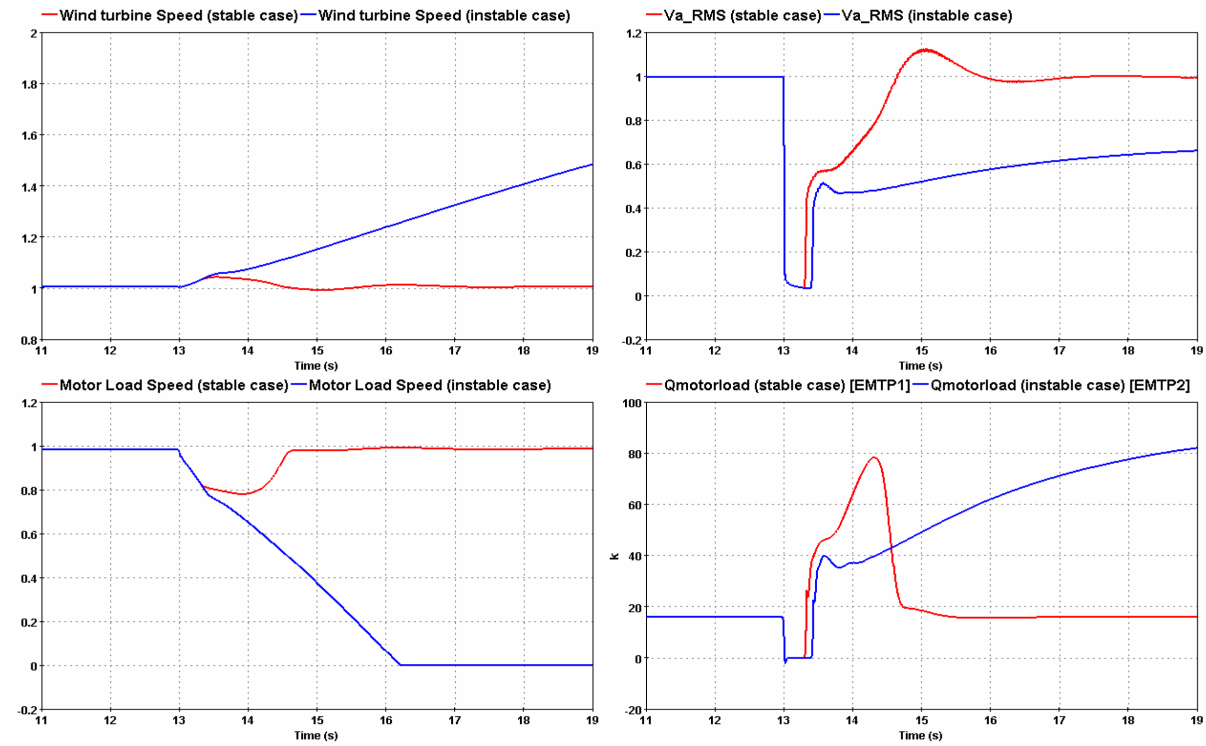

Figure 3.6.1-2: Stable and instable cases comparison

The instability case (in blue) would never take place. The motors would be disconnected by protections because they don't succeed in speeding up and the current will have big a proportion. The power system will not withstand the short circuit leading to the blackout.

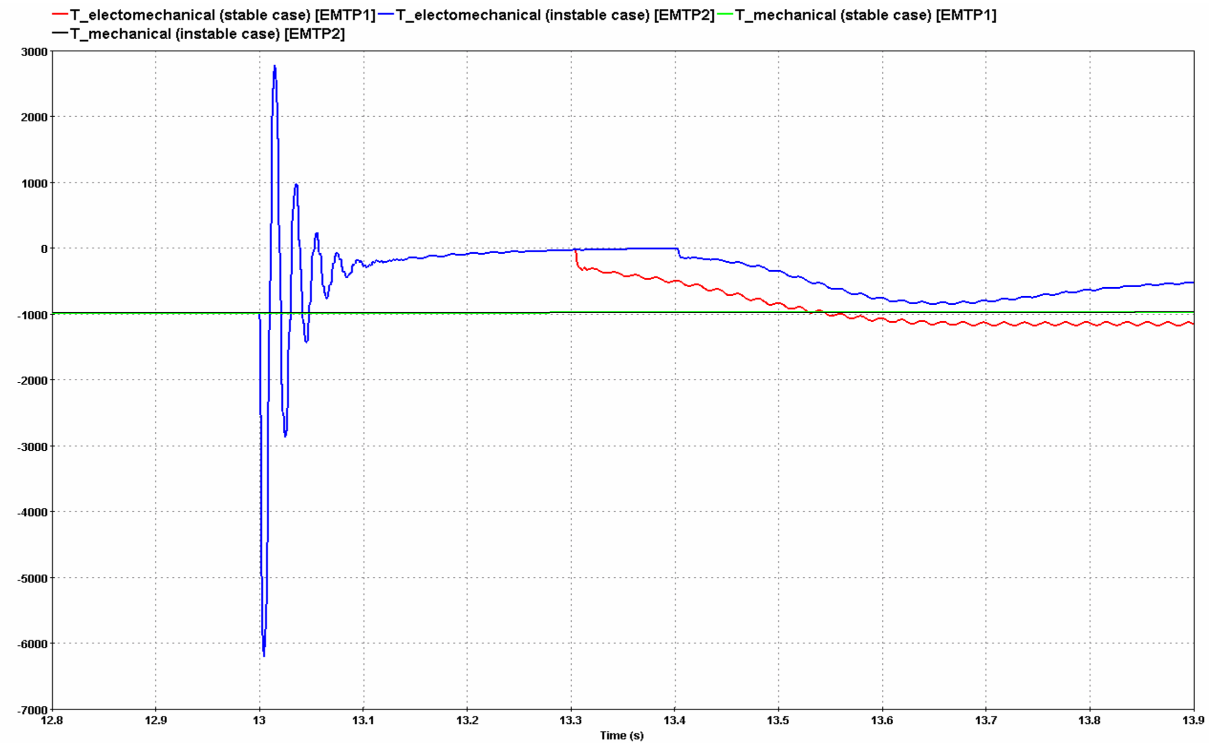

Figure 3.6.1-3: Electromechanical and Mechanical Torque Comparison for Stable (in red) and Instable (in blue) Cases

3.6.2. Short Circuit

The output active power of the wind farm grows with the wind speed and the number of wind turbines. For short circuit simulations, we assume that the wind blows at 10 m/s (normal wind) making each wind turbine produce around 50 % of the nominal power (Pn = 300kW): 150kW.

Two short circuit durations were chosen to investigate on the impact of the wind power on the microgrid stability and in regard of table 7:

- t1 = 150 ms
- t2 = 300 ms

The investigations involve three kinds of direct short circuits:

- PN: phase-to-ground short circuit.
- 2P: phase-to-phase short circuit.

- 3P: three phase short circuit.

Primary simulations showed that the location of the short circuit does not influence on the dynamic stability: The microgrid has small dimensions. Figure 3.5.1-1 shows the short circuit location.

3.6.3. Incidents on the wind farm

Three kinds of incidents on the wind farm are studied here. The first one is the disconnection of the wind turbines in steady state; the second one is there connection.

The last one is wind speed variation (as it is represented in Figure 3.6.3-1).

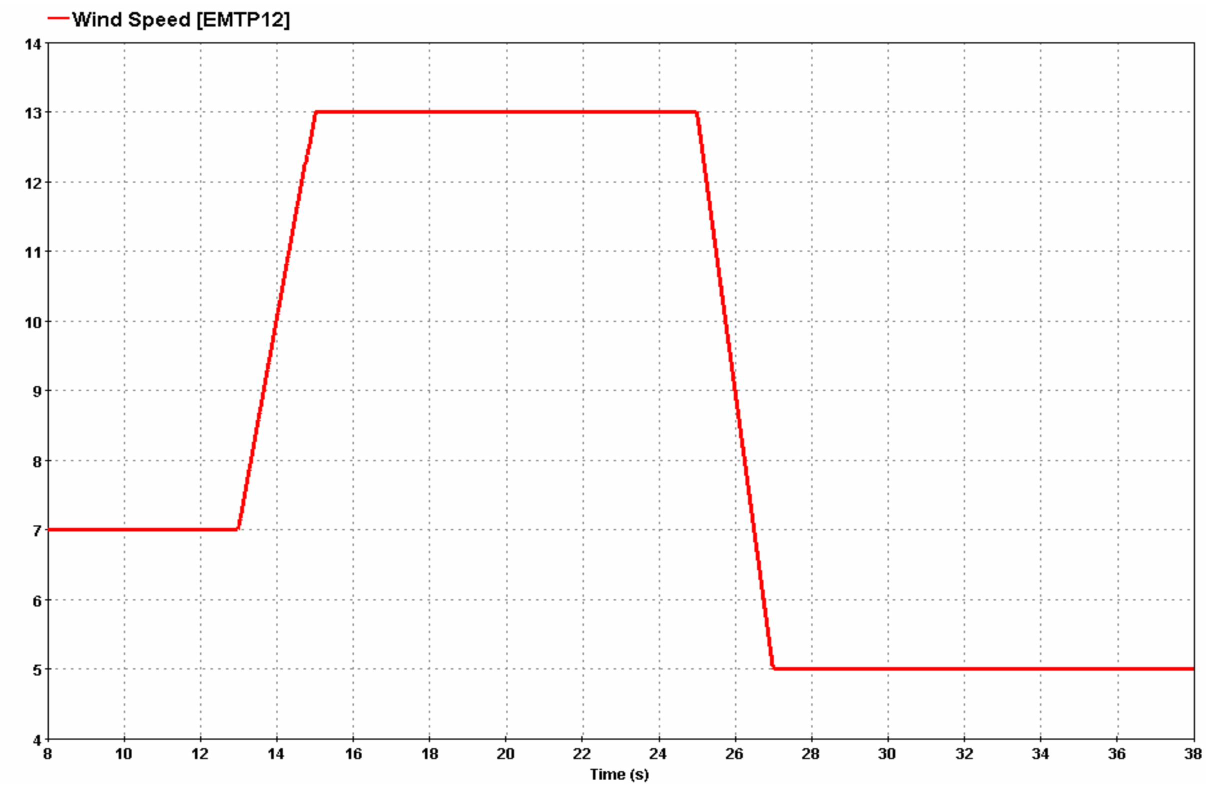

Figure 3.6.3-1: Wind speed Variation

For wind farm connection simulations, the time of the connection is thoroughly chosen. In fact, the wind turbines speed should be close to synchronism speed when it is connected to the grid in order to make the incident as smooth as possible. The wind blows at 5 m/s after the connection.

The RMS voltages and currents are computed at 50 Hz. We assume that these curves are quite representative since the frequency deviations stay at reasonable proportions.

The currents represented in the results curves are the transformers currents in MV side (LV/MV transformer in isolated mode and HV/MV transformer in connected mode). There currents are computed at the DGS – LV/MV Transformers base current. (50.2 A,Figure 3.6.3-2)

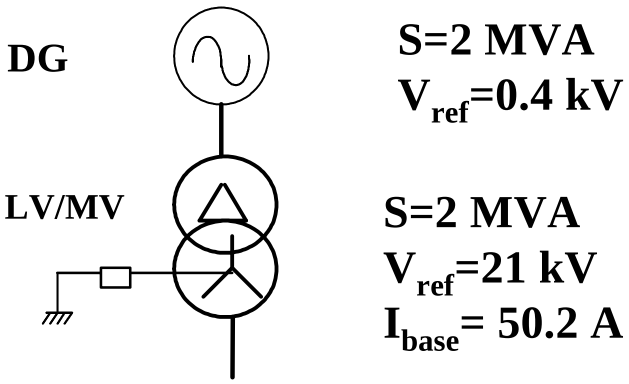

Figure 3.6.3-2: I base

In all simulations, we are not taking into account any over-speed protection of the wind generators.

Annex A and Annex B show the simulations schemas of connected and isolated modes. The Table 3.6.3-1, Table 3.6.3-2 and Table 3.6.3-3 enumerate the list of simulations.

Table 3.6.3-1: Isolated mode (DGS only, no WF)

	Load Model: Static						**Load Model: Static & Dynamic**					
	MV Short Circuit						MV Short Circuit					
	PN		2P		3P		PN		2P		3P	
Simulation Number	t1	t2	t1	t2	t1	t2	t1	t2	t1	t2	t1	t2
1A	X											
2A		X										
3A			X									
4A				X								
5A					X							
6A						X						
10A							X					
11A								X				
12A									X			

Simulation Number	Load Model: Static						Load Model: Static & Dynamic					
	MV Short Circuit						MV Short Circuit					
	PN		2P		3P		PN		2P		3P	
	t1	t2	t1	t2	t1	t2	t1	t2	t1	t2	t1	t2
13A										X		
14A											X	
15A												X

A and B's simulations results will be compared in order to analyze the impact of the wind turbines on diesel genset system.

Table 3.6.3-2: Case studies in isolated mode (DGS + WTs)

Simulation Number	Load Model: Static									Load Model: Static & Dynamic								
	MV Short Circuit						WF Incidents			MV Short Circuit						WF Incidents		
	PN		2P		3P					PN		2P		3P				
	t1	t2	t1	t2	t1	t2	Disconnection	Connection	WS variation	t1	t2	t1	t2	t1	t2	Disconnection	Connection	WS variation
1B	X																	
2B		X																
3B			X															
4B				X														
5B					X													
6B						X												
7							X											
8								X										
9									X									
10B										X								
11B											X							
12B												X						
13B													X					
14B														X				
15B															X			
16																X		
17																	X	
18																		X

Table 3.6.3-3: Case studies in connected mode (DGS + WTs)

	Load Model: Static									Load Model: Static & Dynamic								
	MV Short Circuit						WF Incidents			MV Short Circuit						WF Incidents		
	PN		2P		3P					PN		2P		3P				
Simulation Number	t1	t2	t1	t2	t1	t2	Disconnection	Connection	WS variation	t1	t2	t1	t2	t1	t2	Disconnection	Connection	WS variation
19B	X																	
20B		X																
21B			X															
22B				X														
23B					X													
24B						X												
25							X											
26								X										
27									X									
28B										X								
29B											X							
30B												X						
31B													X					
32B														X				
33B															X			
34																X		
35																	X	
36																		X

3.7. Numerical results

- Simulations A: Isolated mode without WF
- Simulations B (1 to 18): Isolated mode with WF
- Simulations B (19 to 36): Connected mode with WF

We will be interested in our analyses by the transient durations and amplitudes. We will observe the system frequency, the machines speeds, the voltages, the currents and the active powers.

Note that the frequency will not be presented in connected mode: it doesn't vary.

3.7.1. Three phase (3P) sort circuit

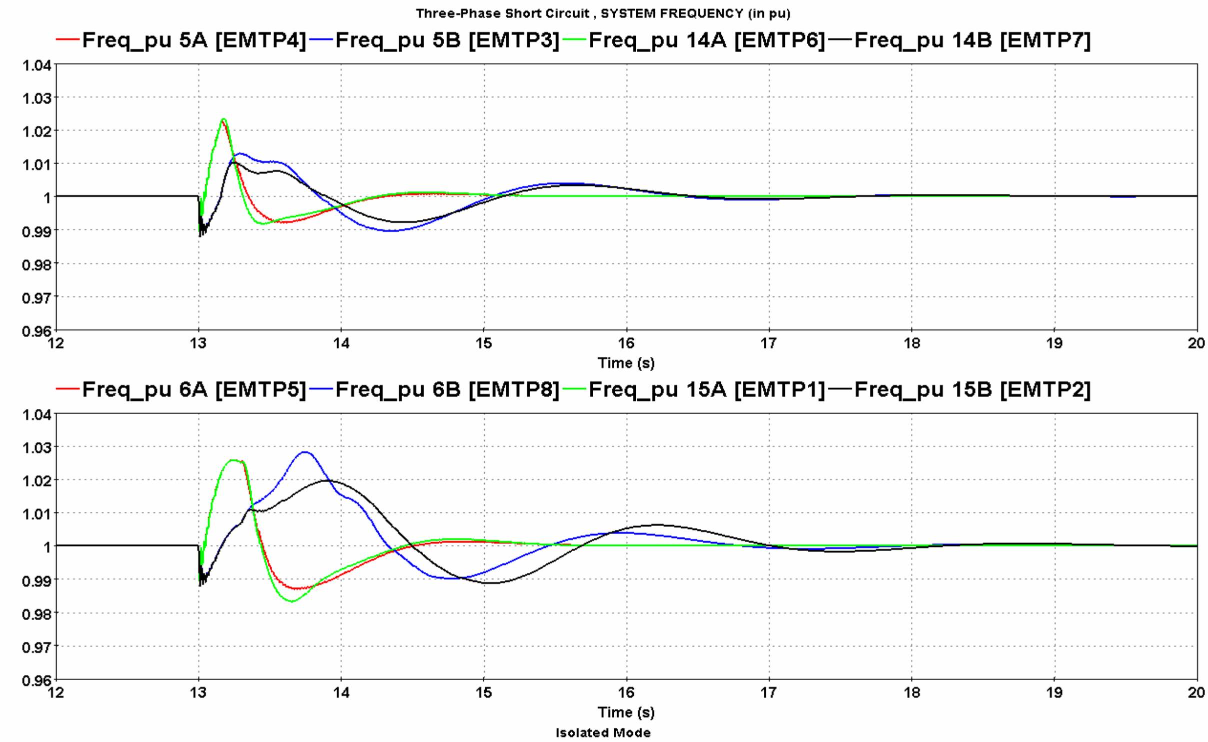

Figure 3.7.1-1: System frequency (Isolated mode - 3P Short Circuit)

The frequency depends on the speed control system.

We see clearly that the wind farm has a big influence on the transient duration. It is 2 times the duration without the WF.

The influence on the frequency excursions is different. For t1 short circuit duration simulations (5 - 14), we see that excursions are smaller with the wind farm connected. There are however bigger for t2 3-phase short circuit simulations.

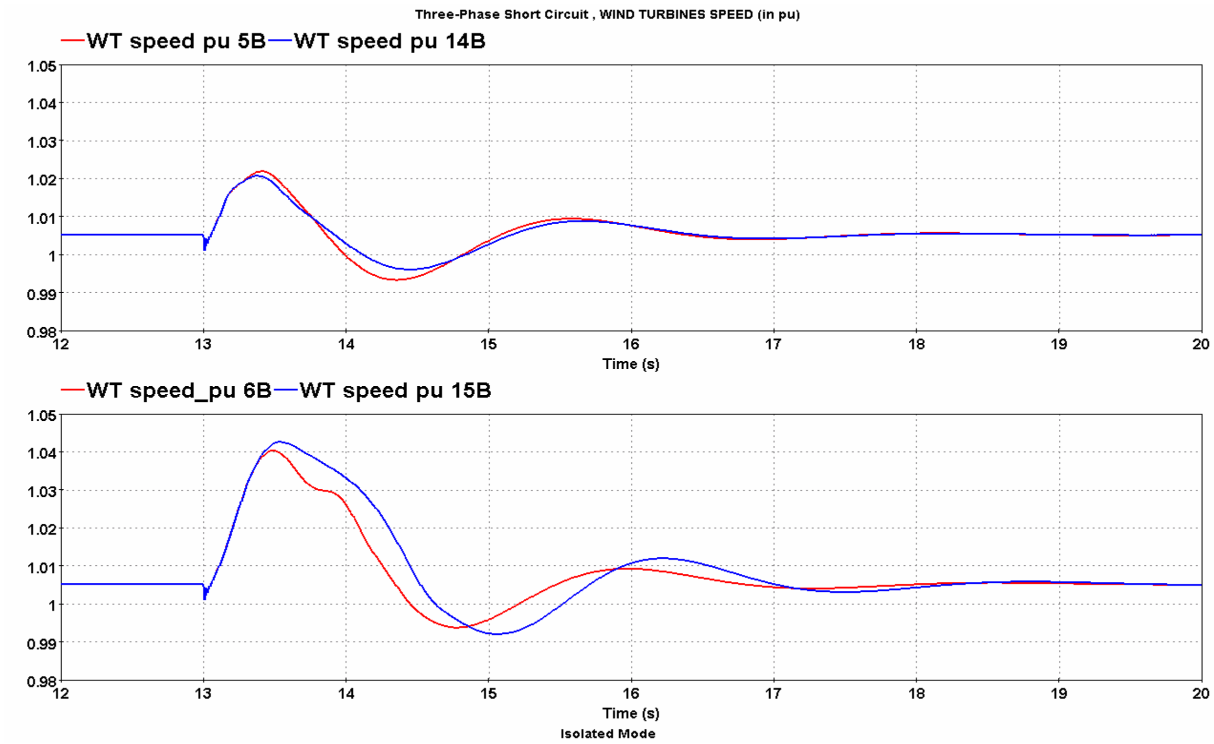

Figure 3.7.1-2: WTG Speed (Isolated mode - 3P short circuit)

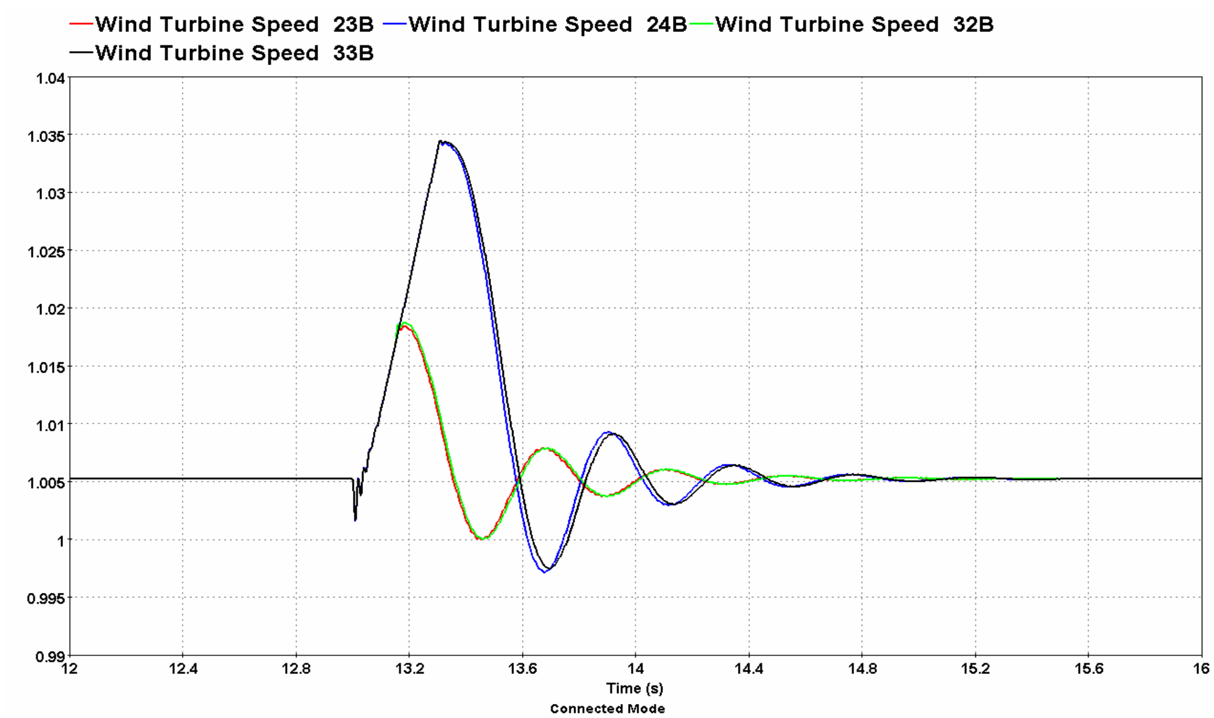

Figure 3.7.1-3: WTG Speed (Connected mode - 3P short circuit)

Figure 3.7.1-2, Figure 3.7.1-3 , Figure 3.7.1-4 and Figure 3.7.1-5 illustrate the machines speeds.

Figure 3.7.1-2 and Figure 3.7.1-3:

- In connected mode, the transient is very fast. It is almost 2 seconds.
- In isolated mode, it is around 5 seconds in case t2 duration and around 4 in case of t1 duration.

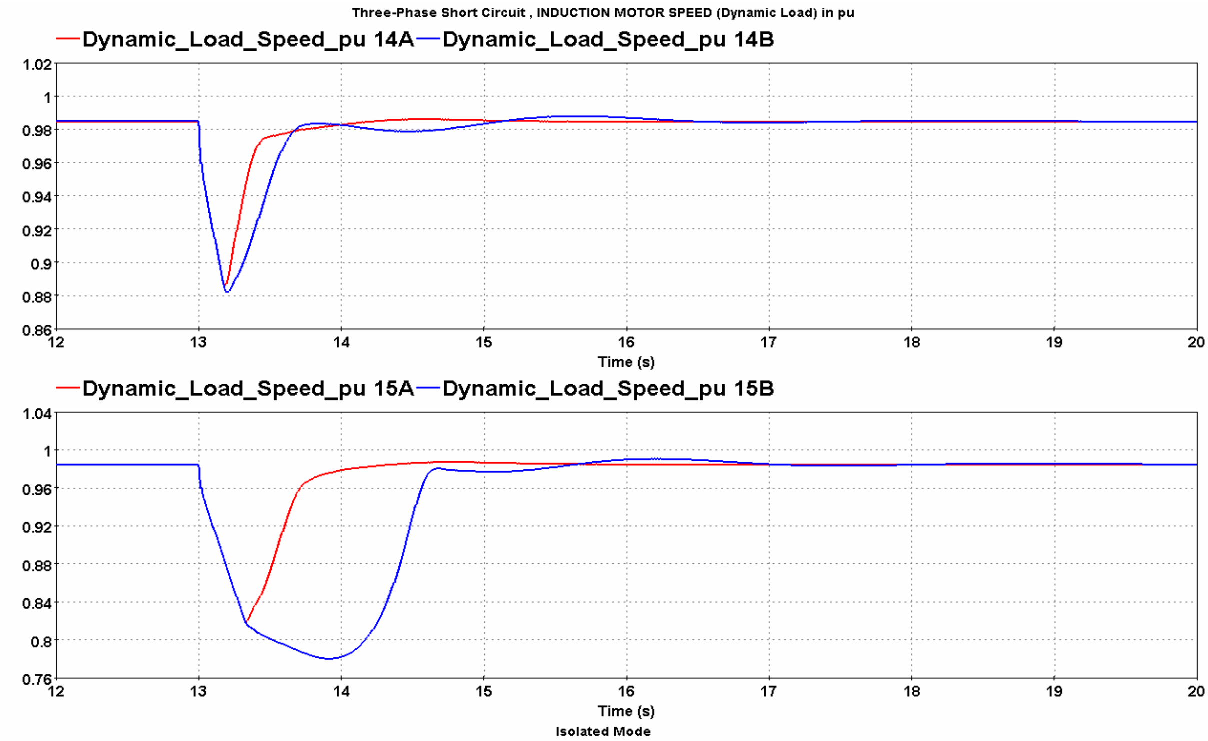

Figure 3.7.1-4: Dynamic load speed (Isolated mode - 3P short circuit)

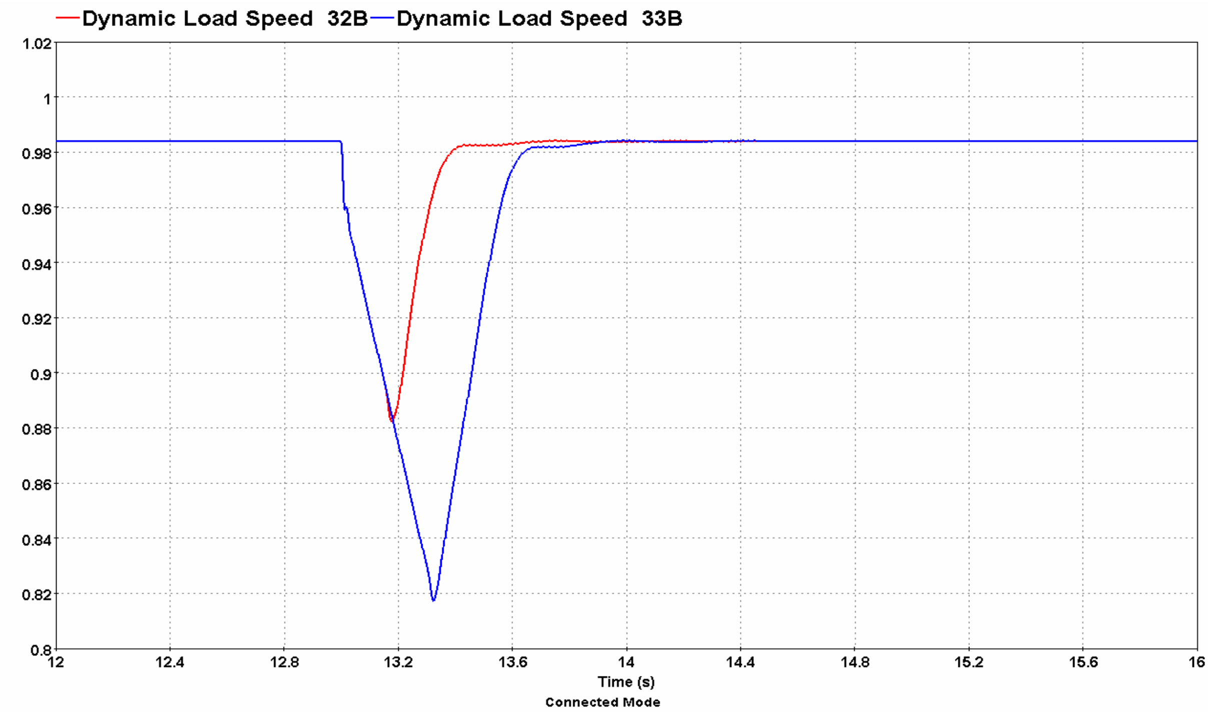

Figure 3.7.1-5: Dynamic load speed (Connected mode - 3P short circuit)

Figure 3.7.1-4 and Figure 3.7.1-5:

- For t1case in isolated mode and for connected mode, the motor load speed recovers faster to its normal speed. For t2 case in isolated mode, it takes more time (15 B).

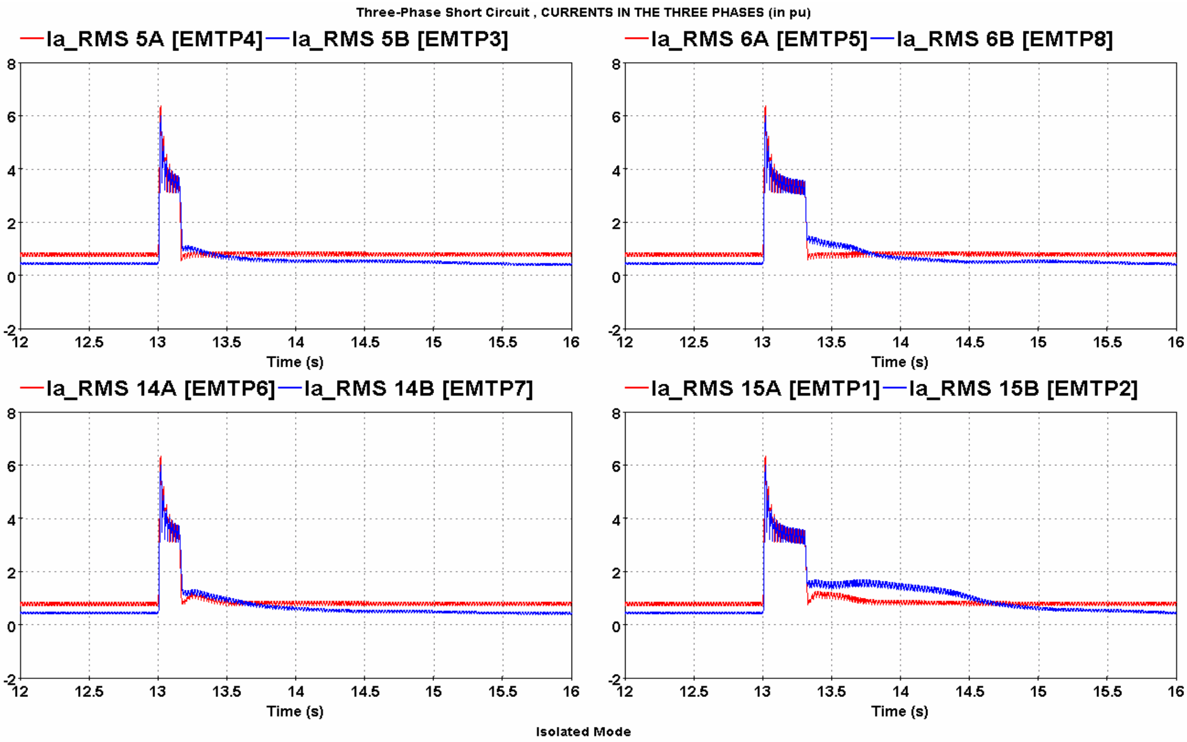

Figure 3.7.1-6: Current at MV side (Isolated mode - 3P short circuit)

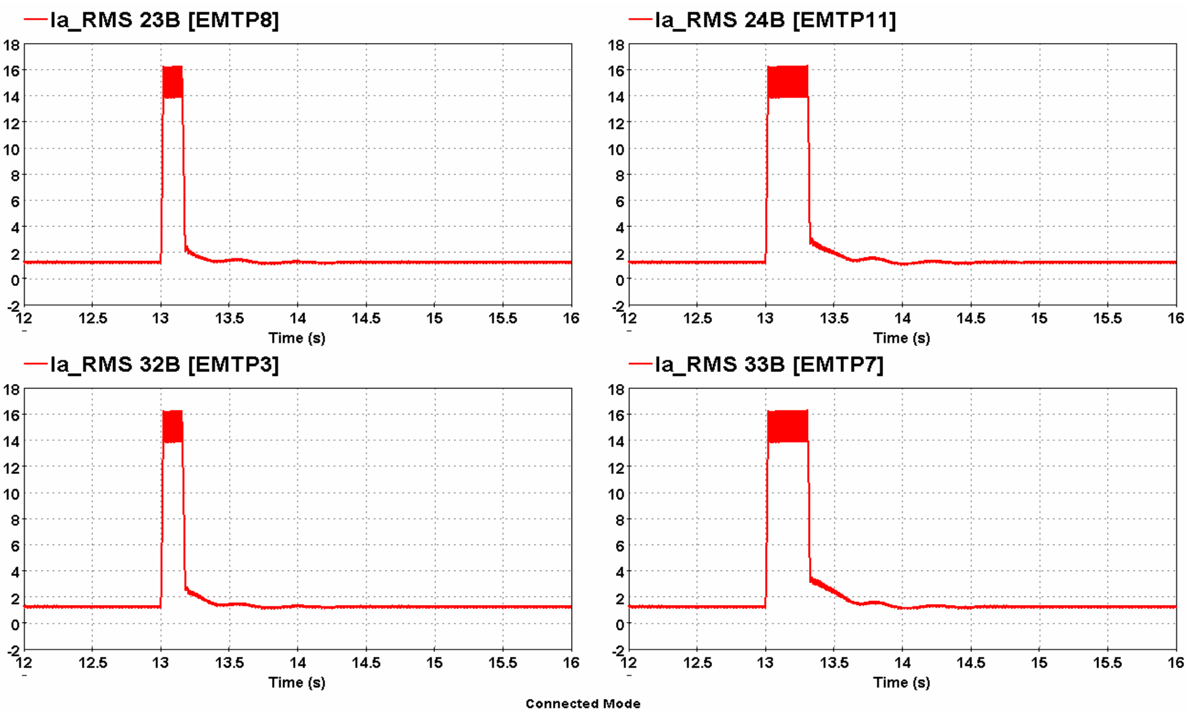

Figure 3.7.1-7: Current at MV side (Connected mode - 3P short circuit)

Figure 3.7.1-6 and Figure 3.7.1-7 show the current overshoot.

- In connected mode it reaches 16 pu and in isolated mode is around 3.5 pu.
- After the short circuit clearance, it takes some seconds to the current to reach back its normal value in case of t2 short circuit duration and dynamic load (15B).

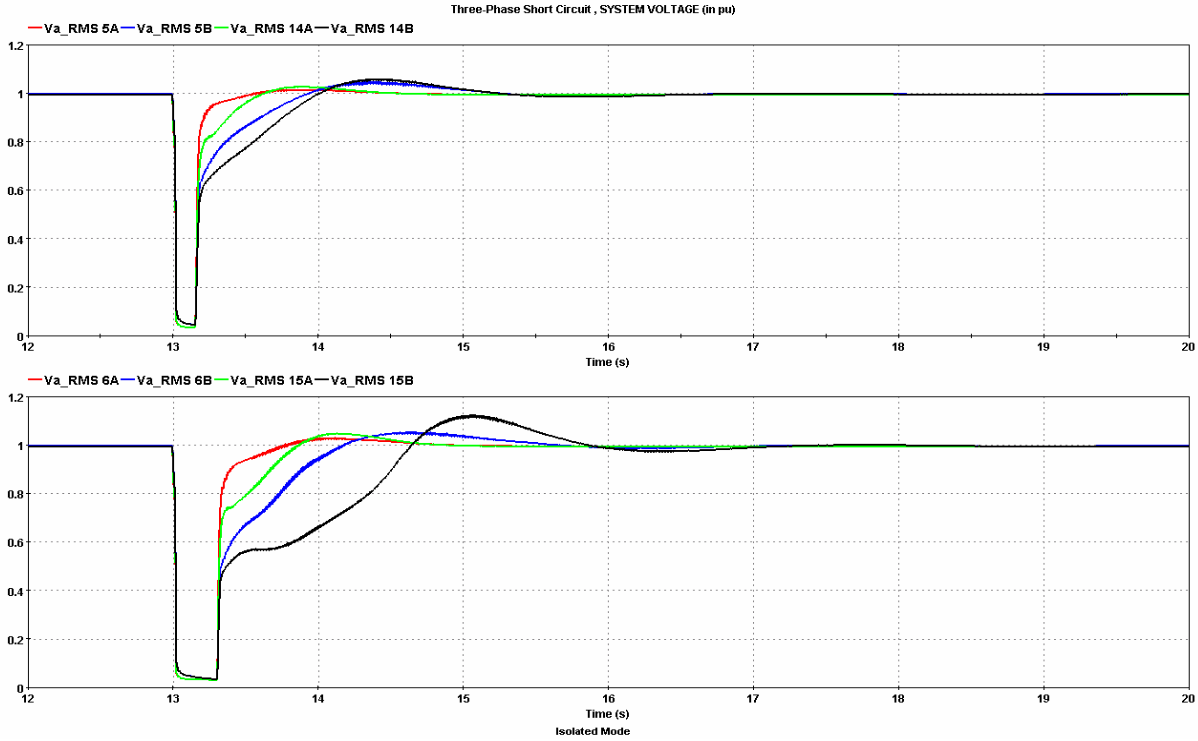

Figure 3.7.1-8: Voltage (Isolated mode - 3P short circuit)

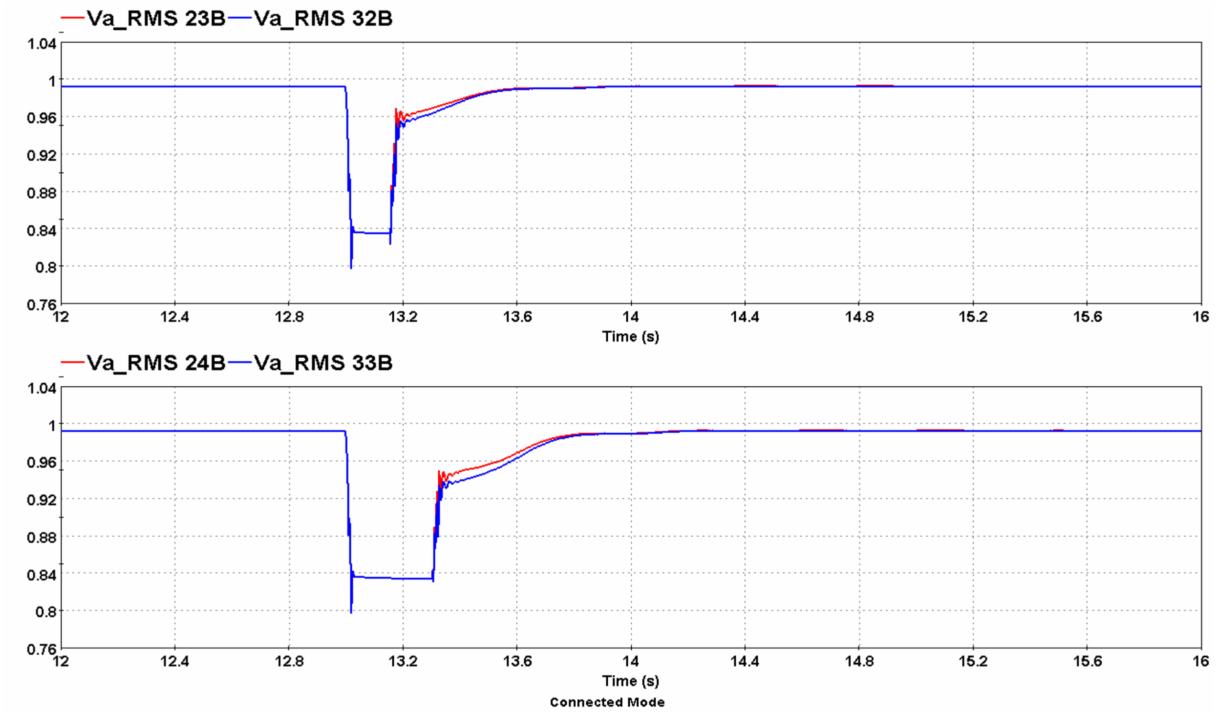

Figure 3.7.1-9: Voltage (Connected mode - 3P short circuit)

Figure 3.7.1-8 and Figure 3.7.1-9:

- In isolated mode, the voltage collapses during the short circuit. When it is over, the voltage oscillates rises smoother when the WF and dynamic load are considered. The voltage overshoots are not excessive.
- In connected mode, the voltage doesn't collapse at the transformer MV side.

The main problem is the voltage recovery time: it may take long (quality questions rise).

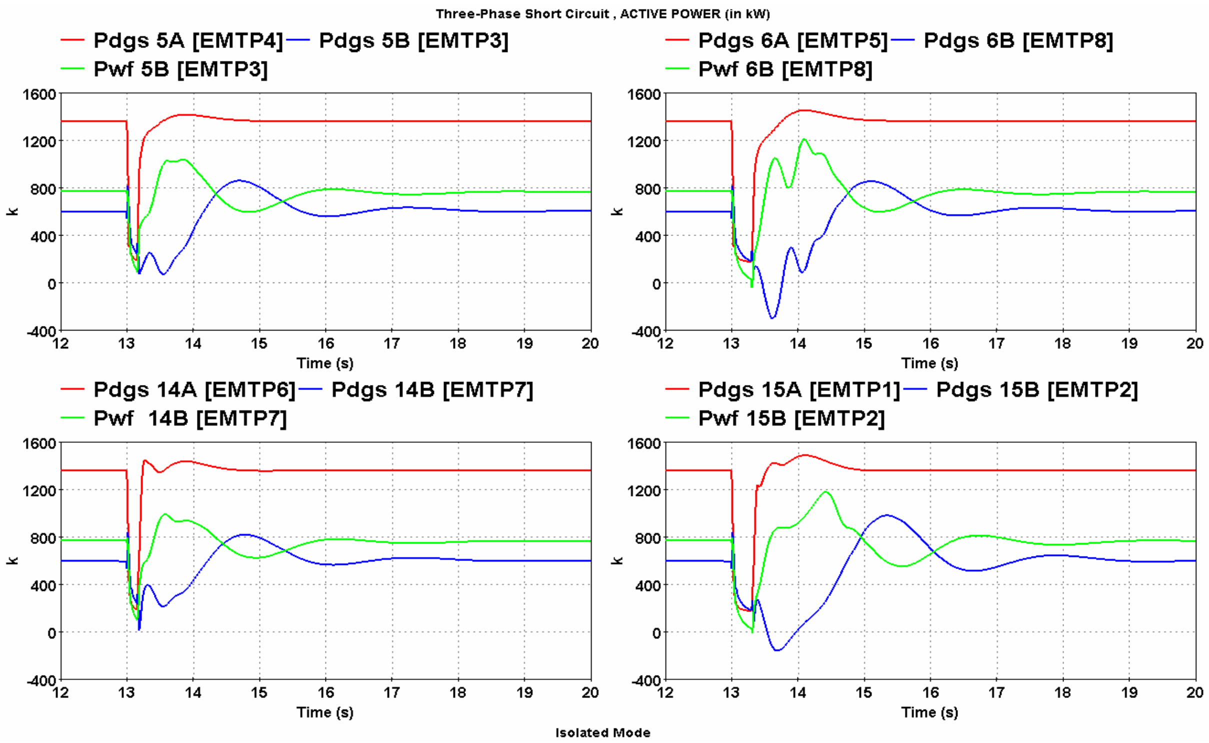

Figure 3.7.1-10: Active power (Isolated mode - 3P short circuit)

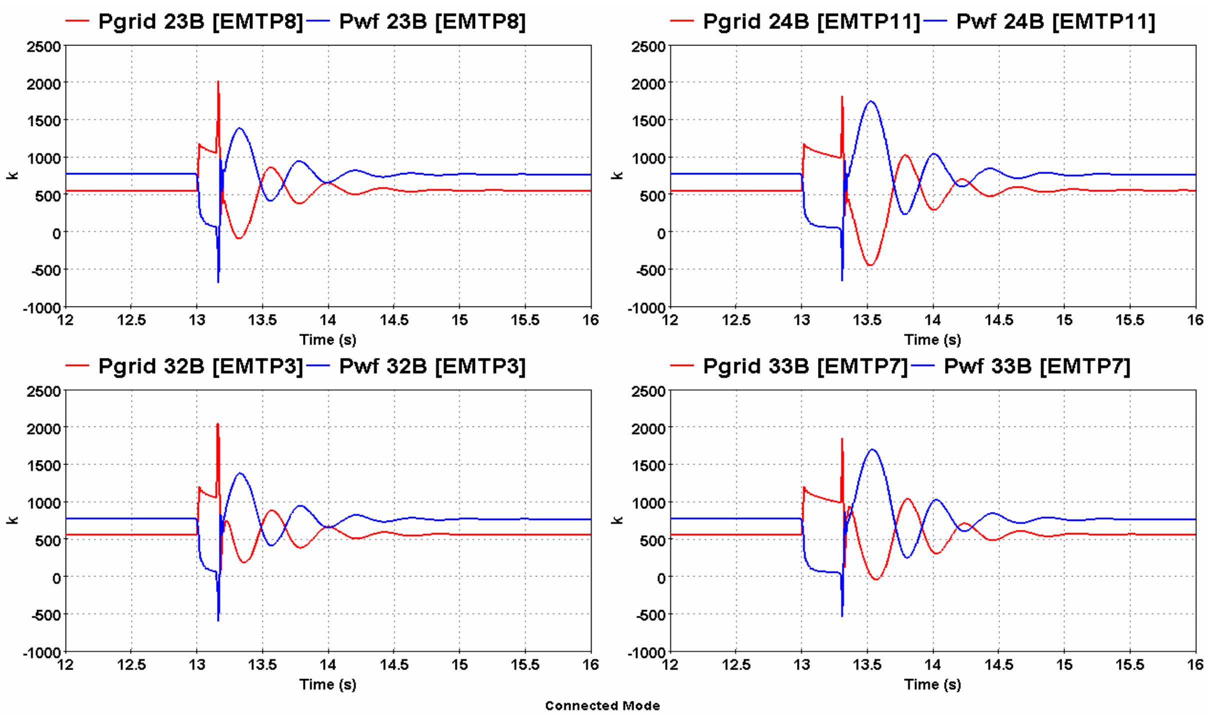

Figure 3.7.1-11: Active power (Connected mode - 3P short circuit)

Figure 3.7.1-6 and Figure 3.7.1-11:

When the short circuit occurs, the WF active power falls to almost 0 in isolated case. The wind turbines store kinetic energy (See WT Speed in Figure 3.7.1-3) all along the short circuit duration. When the SC is over, the WF can supply the microgrid until this energy stored is consumed. At that time the DGS starts producing power. The DGS and WF active powers oscillate. These oscillations are bigger for dynamic loads and t2 cases.

3.7.2. Phase to Phase (2P) short circuit

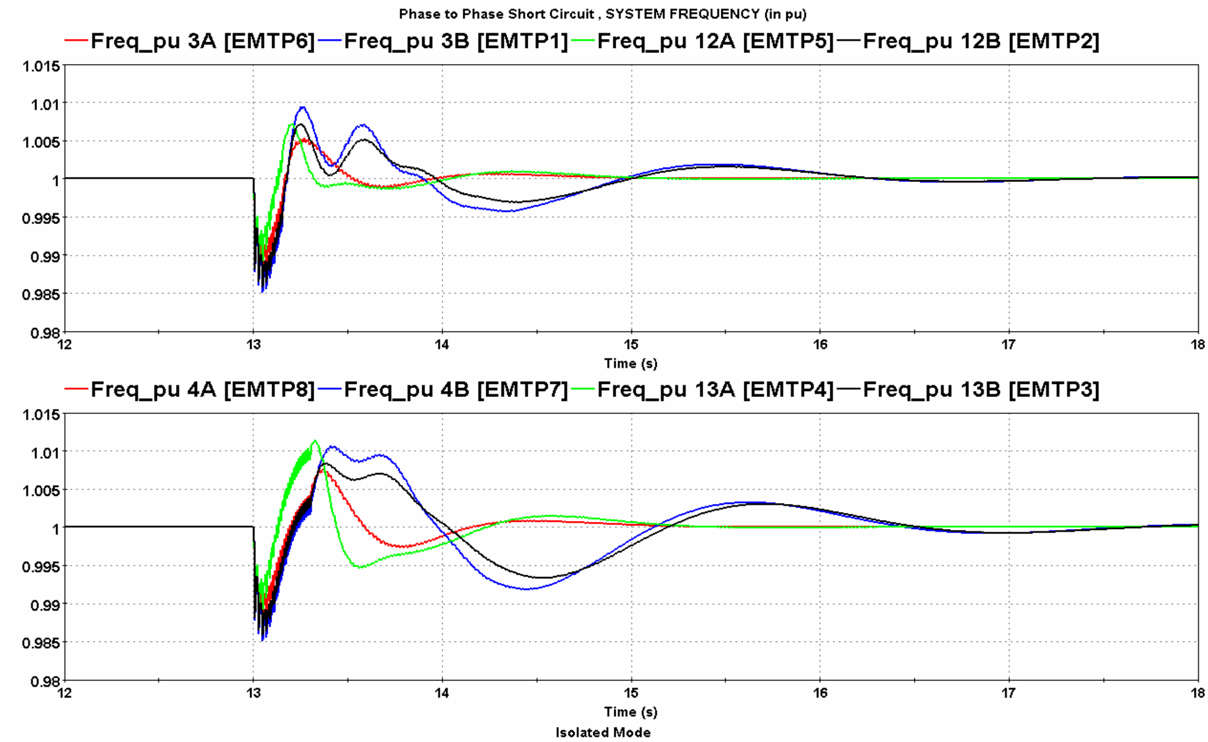

Figure 3.7.2-1: System frequency (Isolated mode - 2P short circuit)

Figure 3.7.2-1:

- The transient durations have slightly smaller proportions than in 3P.
- For the worst case (4B), the frequency reaches a peak of 1.01 pu.

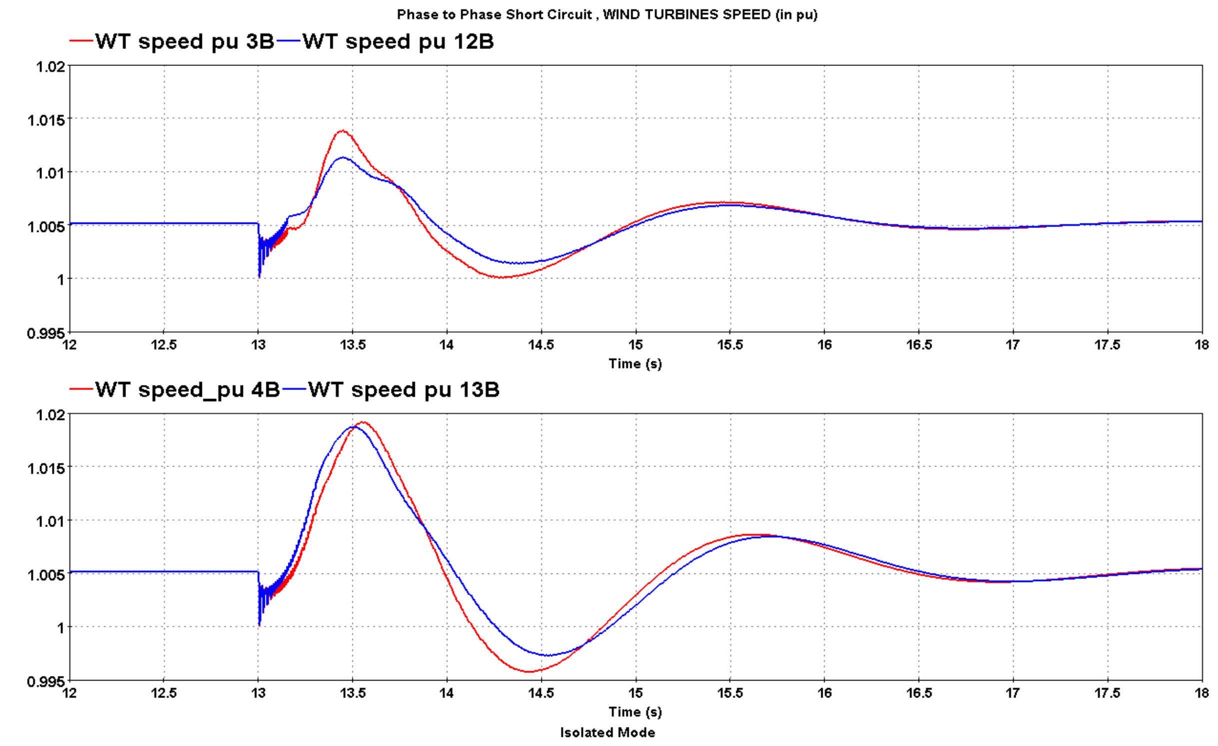

Figure 3.7.2-2: WTG Speed (Isolated mode- 2P short circuit)

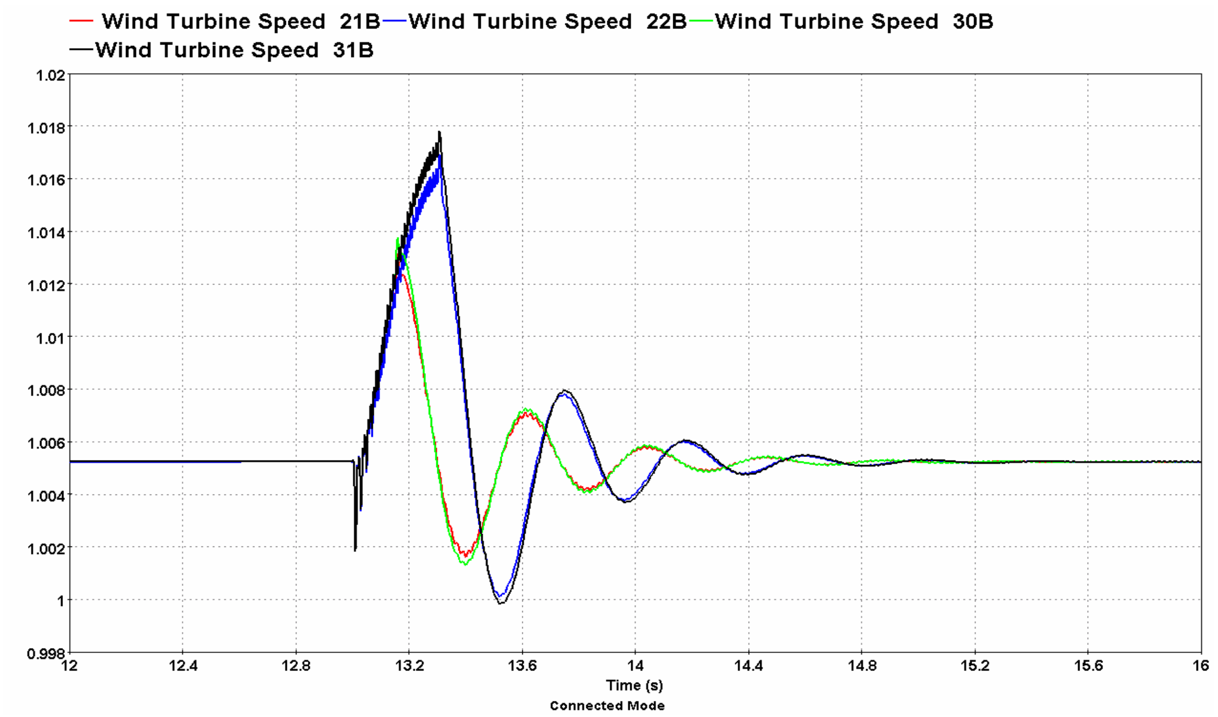

Figure 3.7.2-3: WTG Speed (Connected mode - 2P short circuit)

Figure 3.7.2-2 and Figure 3.7.2-3: The same remarks as in 3P are available here.

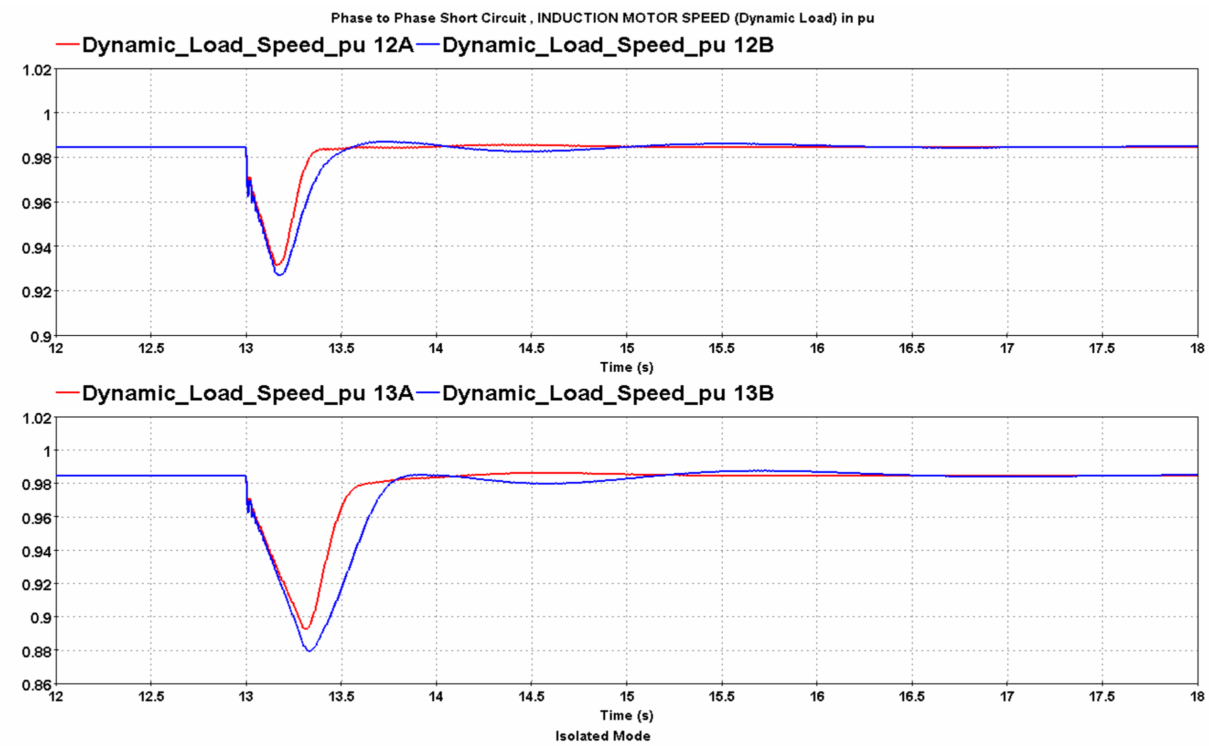

Figure 3.7.2-4: Dynamic load speed (Isolated mode - 2P short circuit)

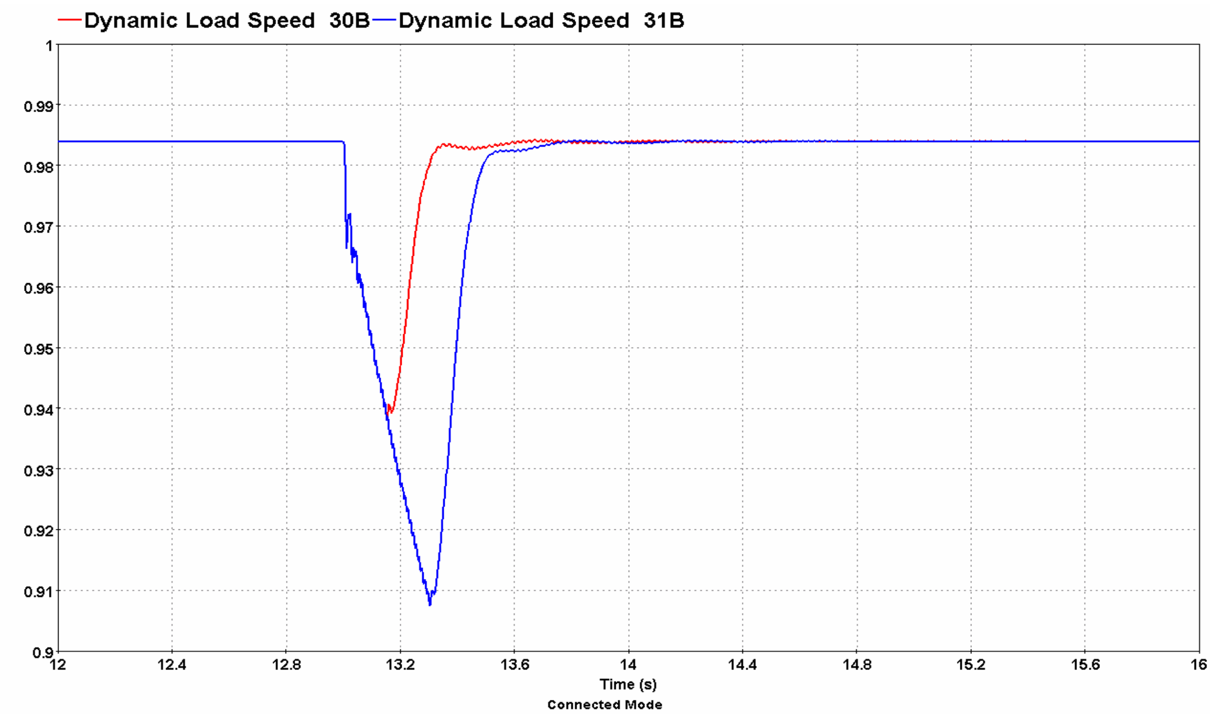

Figure 3.7.2-5: Dynamic load speed (Connected mode - 2P short circuit)

Figure 3.7.2-4 and Figure 3.7.2-5: The same remarks as in 3P are available here; except that for this short circuit, even for the supposed worst case (13B), the speed recovers very fast.

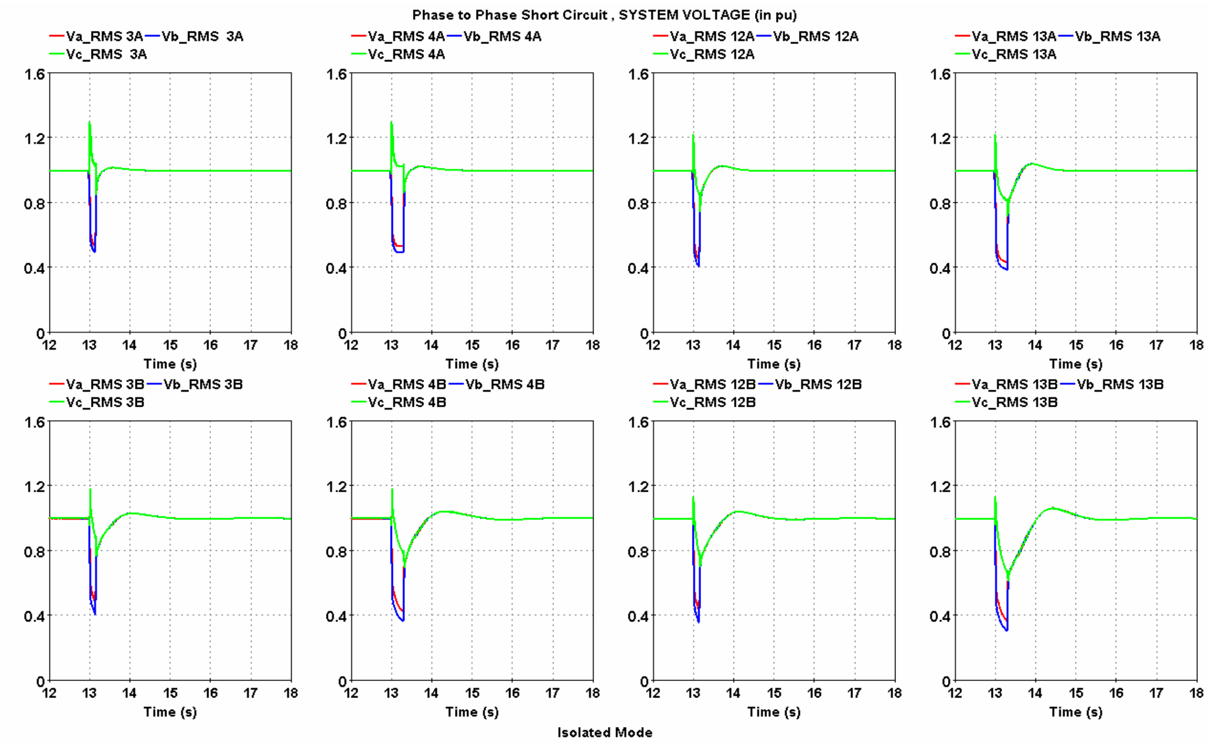

Figure 3.7.2-6: Voltage (Isolated mode - 2P short circuit)

Figure 3.7.2-6:

- The two faulted phases voltages drop to almost 0.4 pu.
- In case of need of the reactive power (if the WF is connected and the motor loads are considered), the phase C voltage drops lower.
- The Voltages recover to normal value very fast

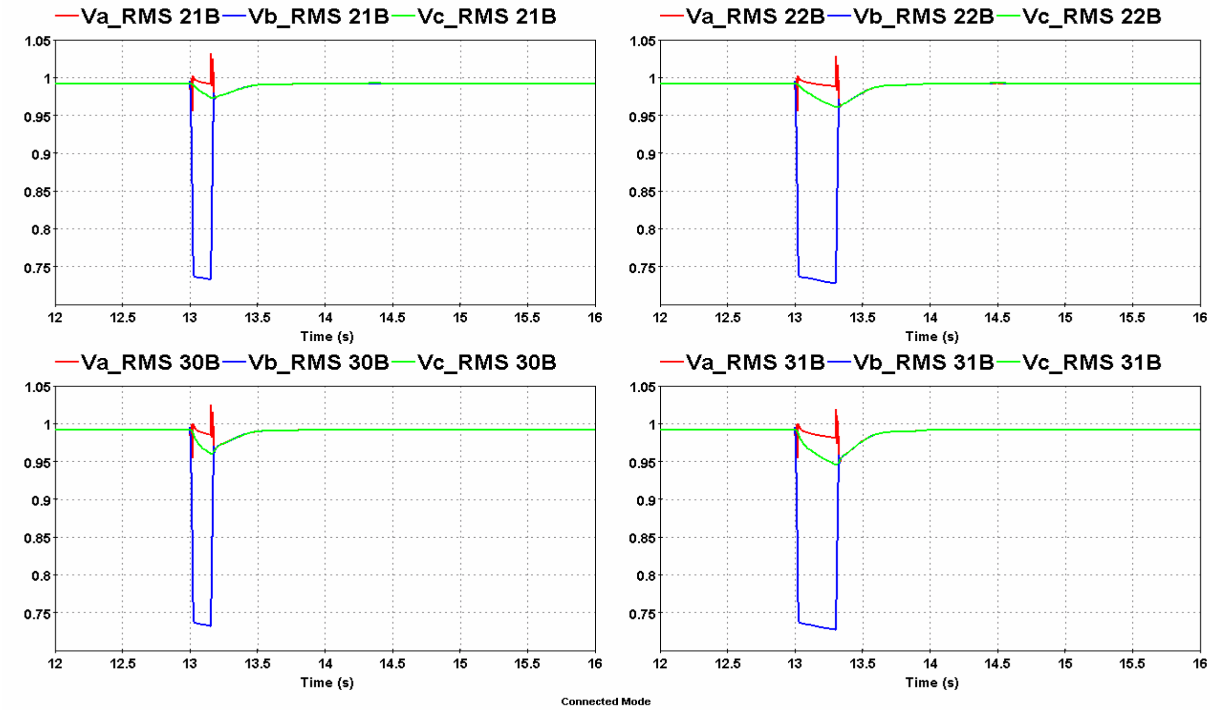

Figure 3.7.2-7: Voltage (Connected mode - 2P short circuit)

Figure 3.7.2-7:

- The B phase voltage falls to 0.75 pu.
- A & C phase voltages don't vary as B phase voltages.
- The Voltages recover to normal value very fast.

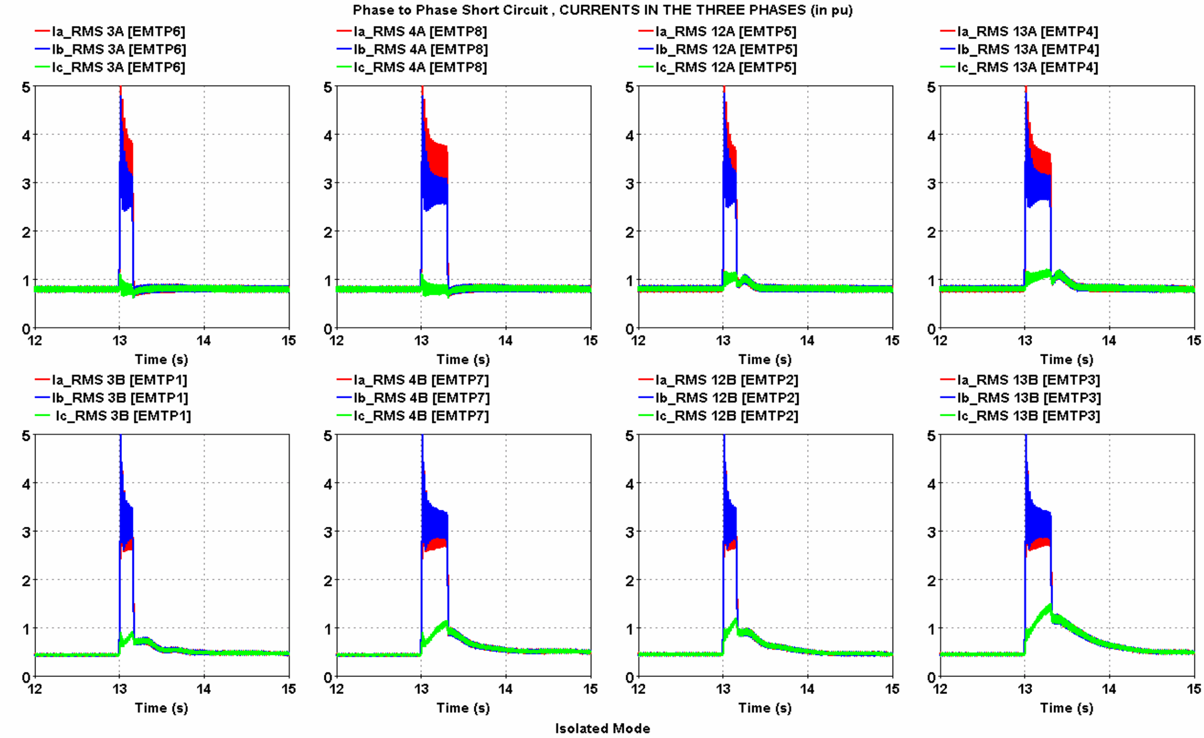

Figure 3.7.2-8: Current (Isolated mode - 2P short circuit)

Figure 3.7.2-8: The currents in faulted phases vary between 3 to 4 pu.

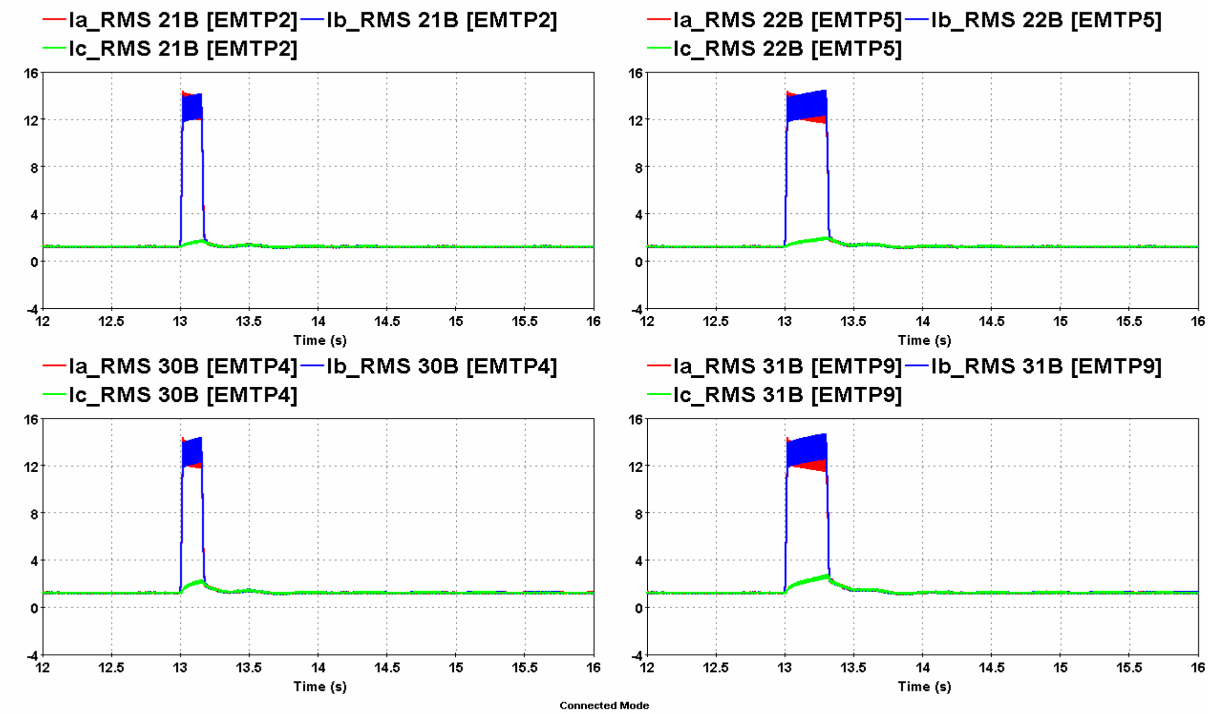

Figure 3.7.2-9: Current (Connected mode - 2P short circuit)

Figure 3.7.2-9: The currents in faulted phases vary between 12 to 14 pu.

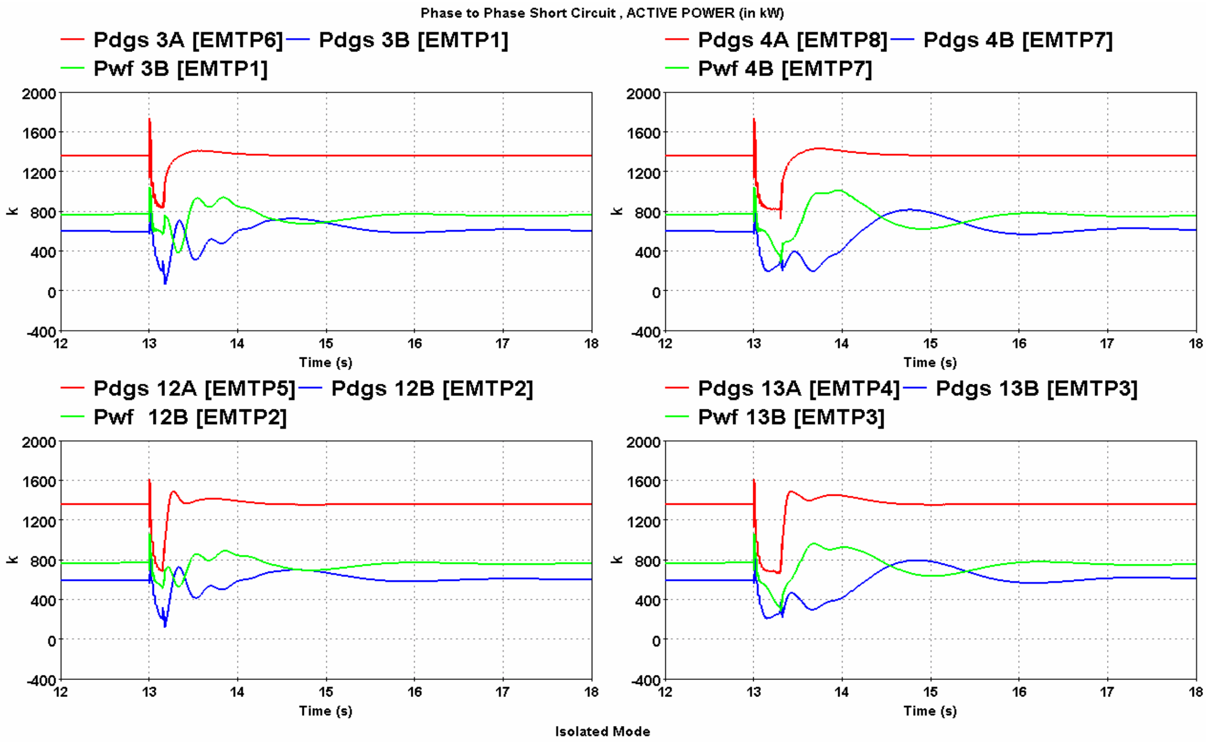

Figure 3.7.2-10: Active power (Isolated mode - 2P short circuit)

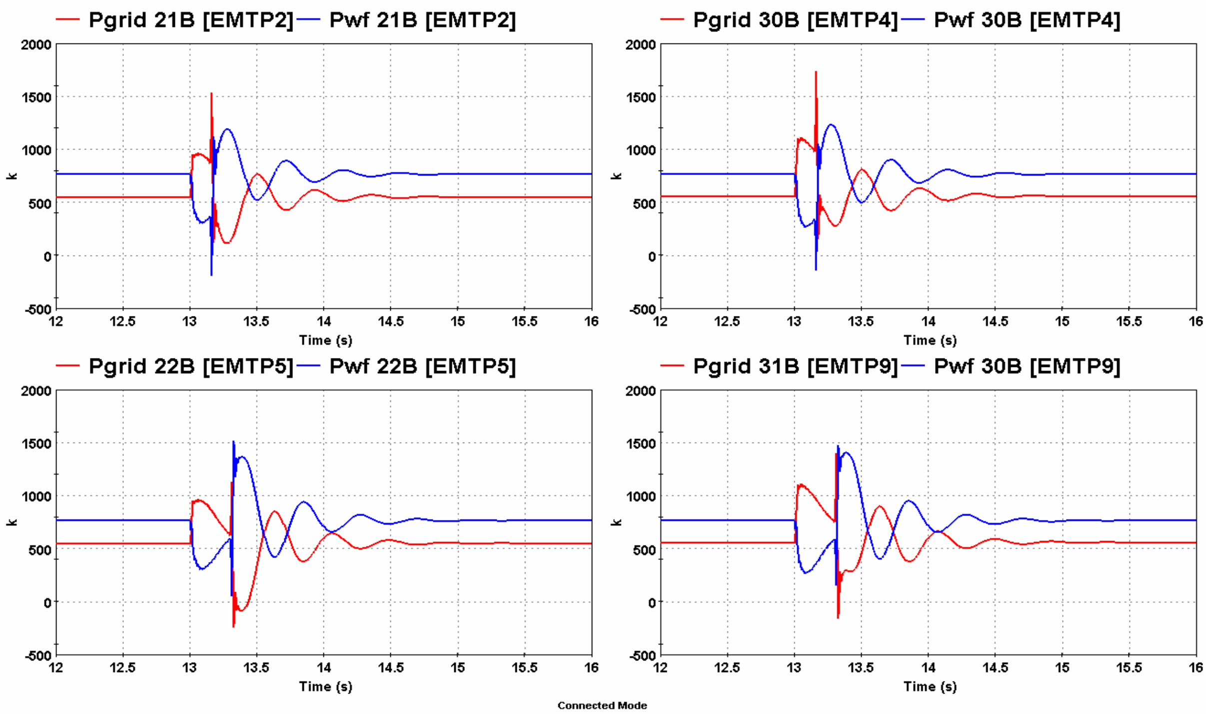

Figure 3.7.2-11: Active power (Connected mode - 2P short circuit)

Figure 3.7.2-10 and Figure 3.7.2-11:

- When the short circuit occurs, the WF active power doesn't fall to almost 0 in isolated case like PPP short circuit.
- The other remarks on PPP case are available here.

3.7.3. Phase to ground (PN) short circuit

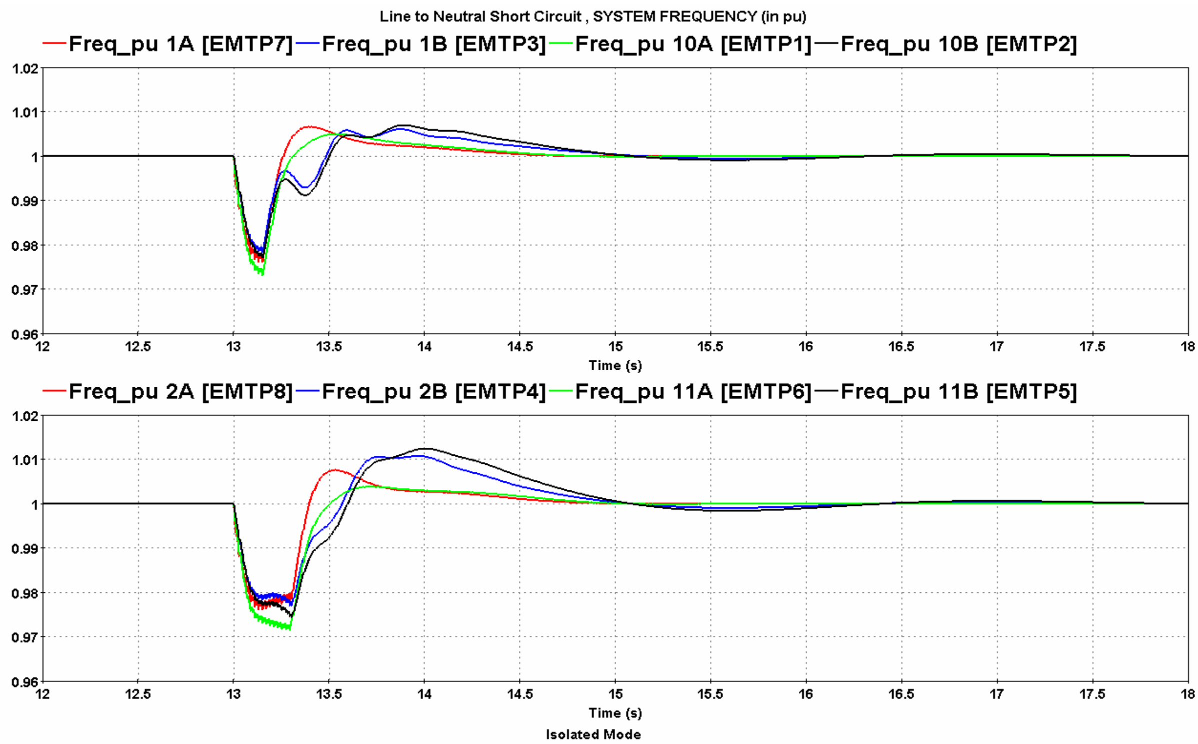

Figure 3.7.3-1: System frequency (Isolated mode - PN short circuit)

Figure 3.7.3-1:

- The transient is shorter than in 2P and 3P short circuits.
- The frequency excursions stay in reasonable proportions.

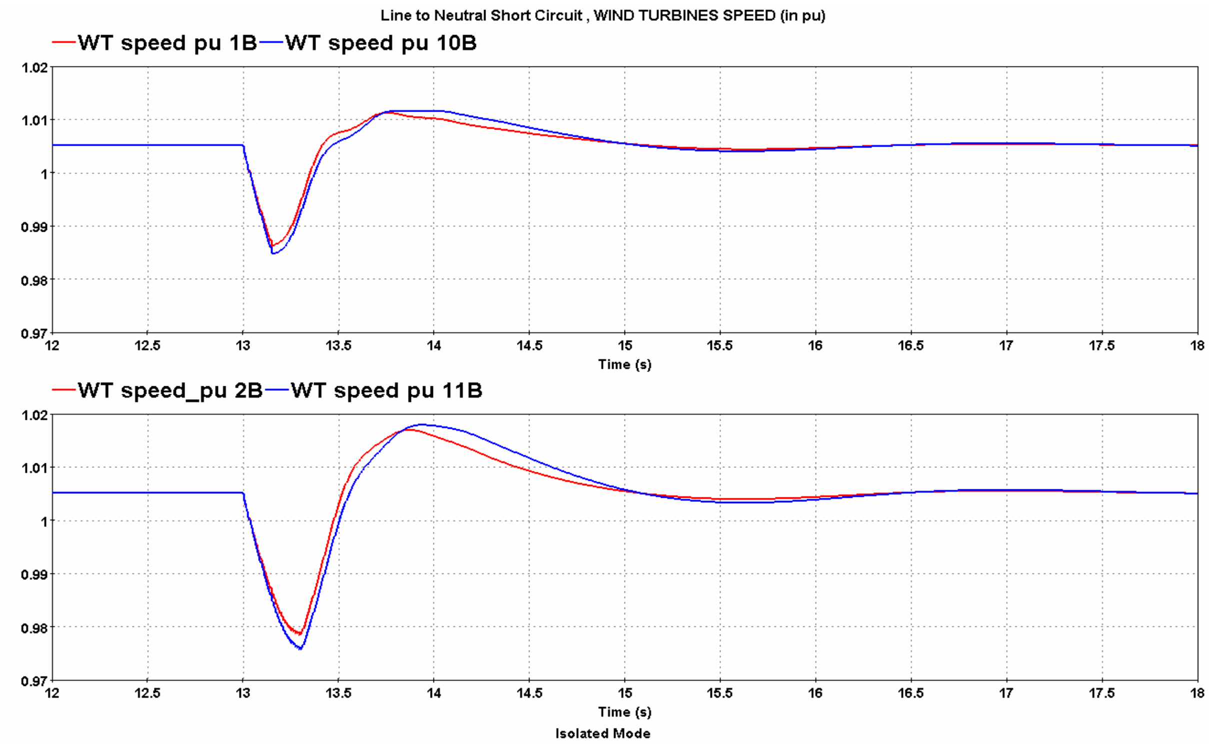

Figure 3.7.3-2: WTG Speed (Isolated mode - PN short circuit)

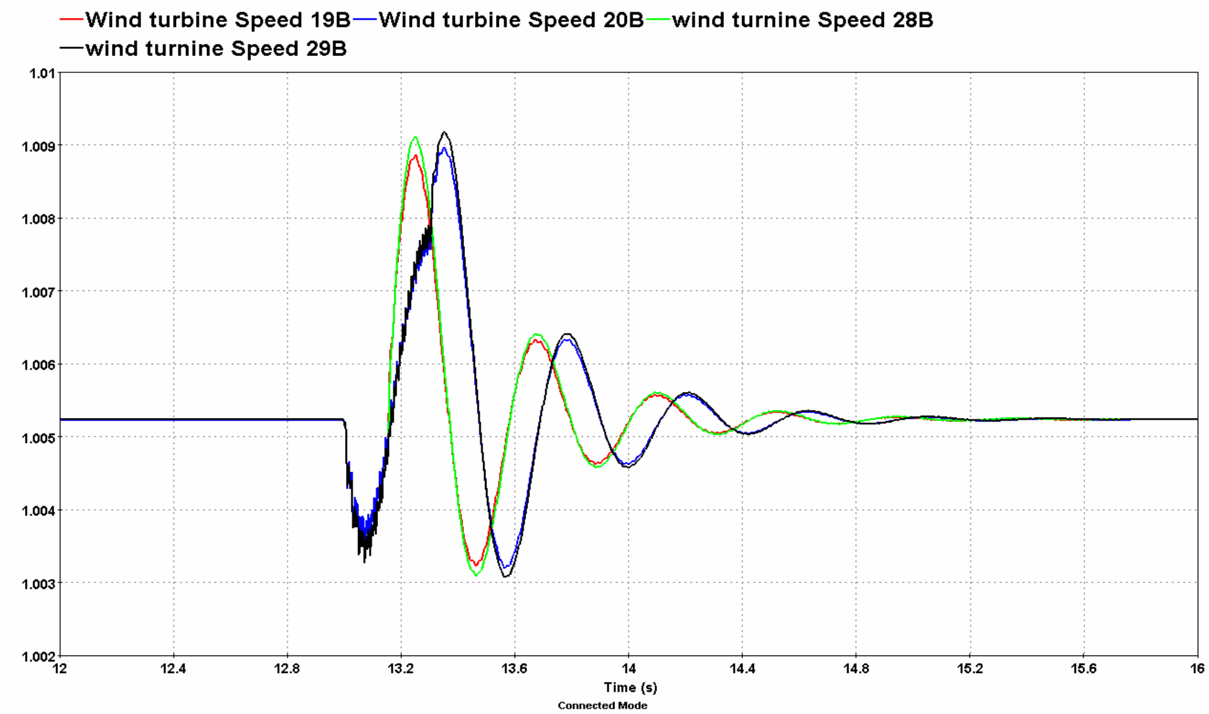

Figure 3.7.3-3: WTG speed (Connected mode - PN short circuit)

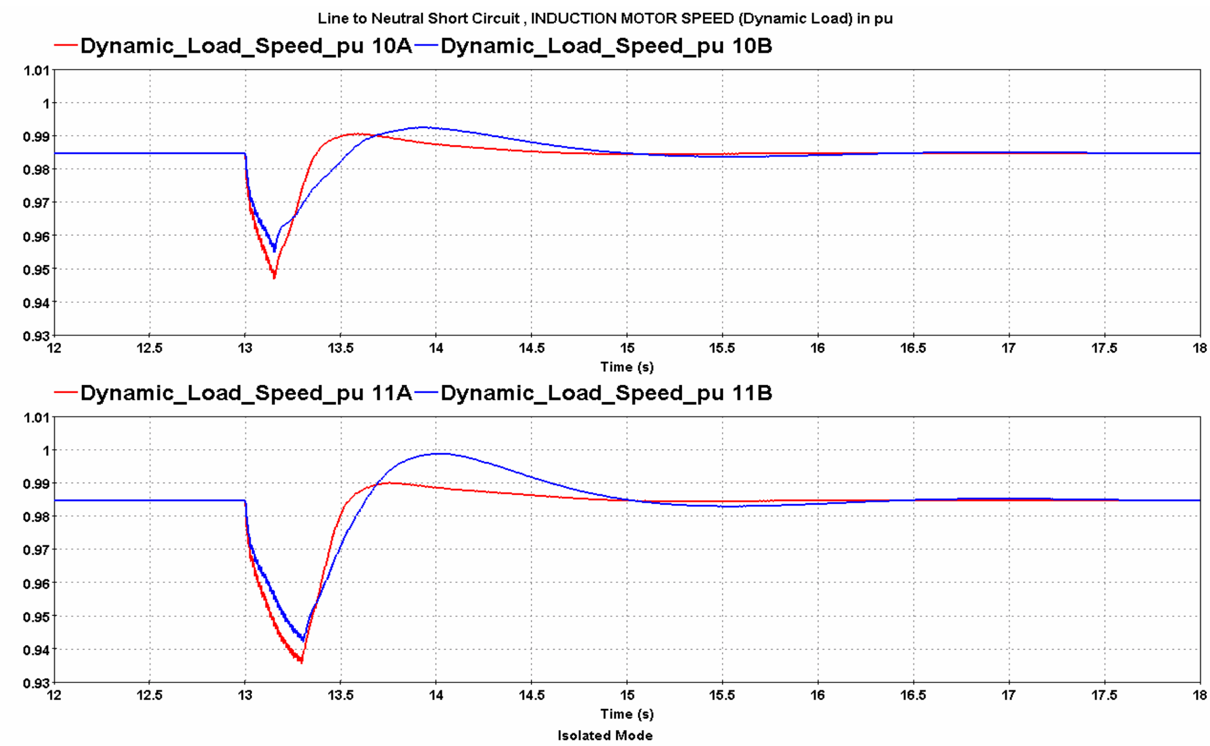

Figure 3.7.3-4: Dynamic load speed (Isolated mode - PN short circuit)

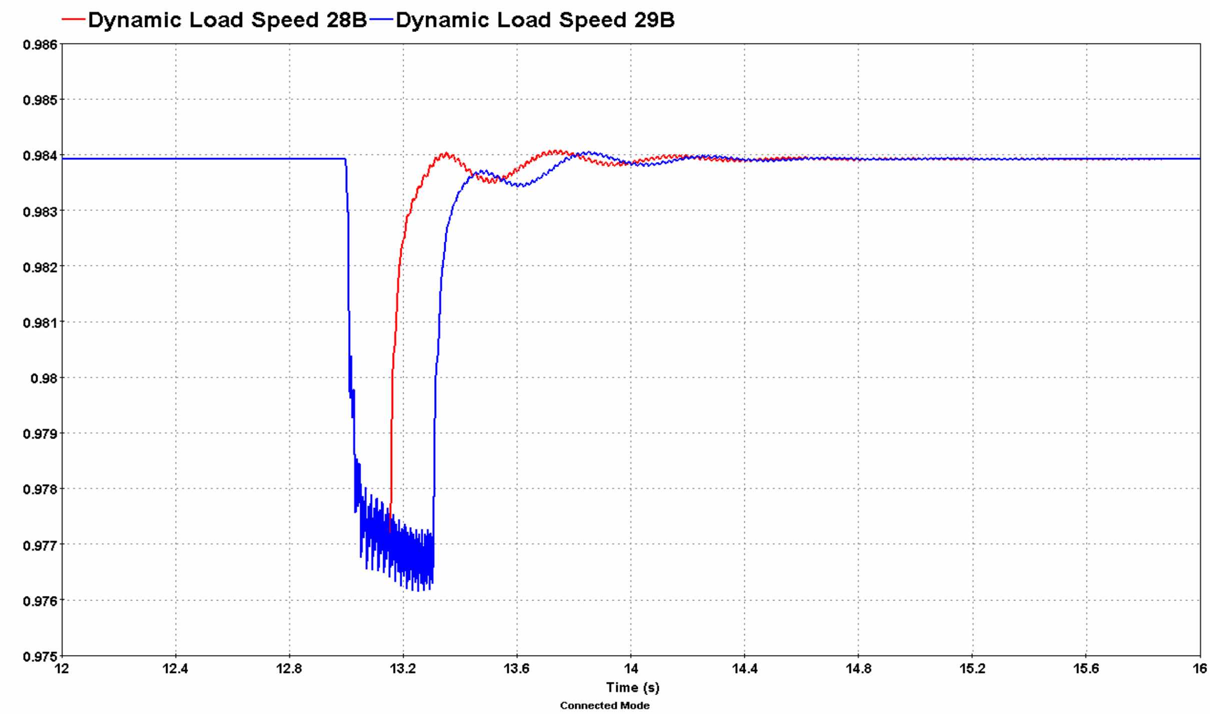

Figure 3.7.3-5: Dynamic load speed (Connected mode - PN short circuit)

Figure 3.7.3-2, Figure 3.7.3-3, Figure 3.7.3-4 and Figure 3.7.3-5:

- In line to ground short circuit we see a major difference with previous cases.
- The wind turbines decelerate and the behaviour of the motor loads is very different in connected mode

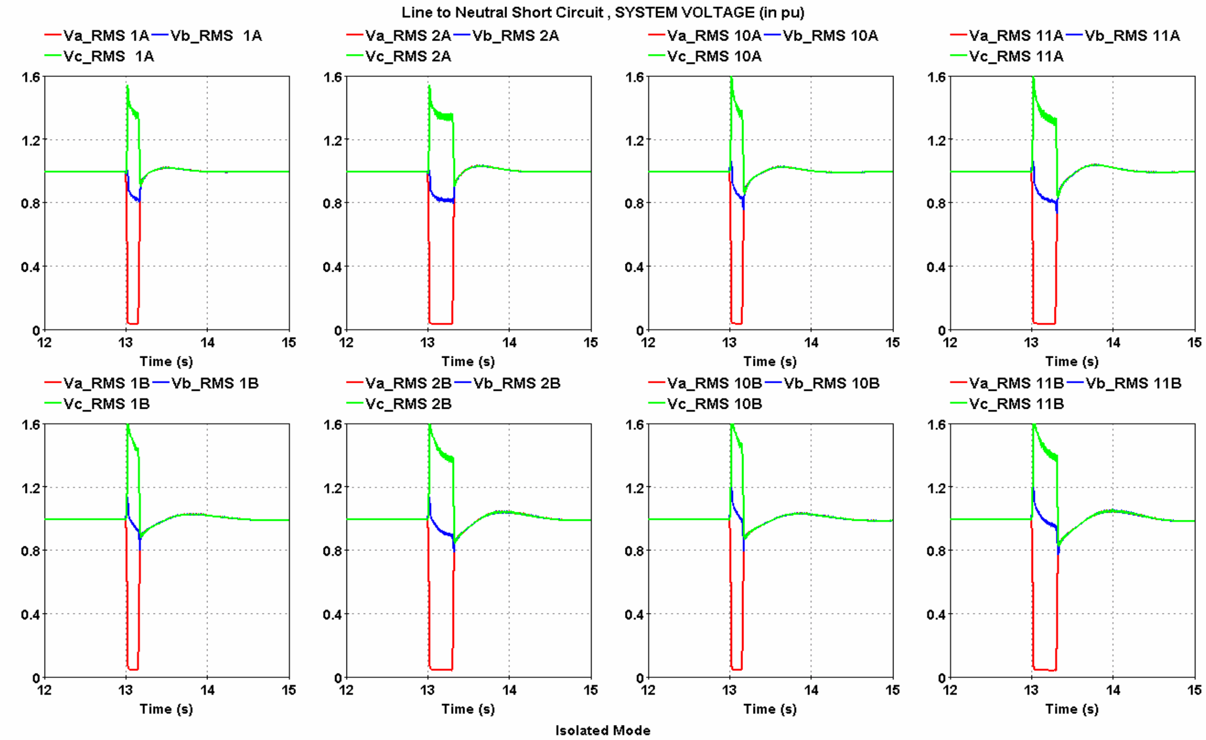

Figure 3.7.3-6: Voltage (Isolated mode - PN short circuit)

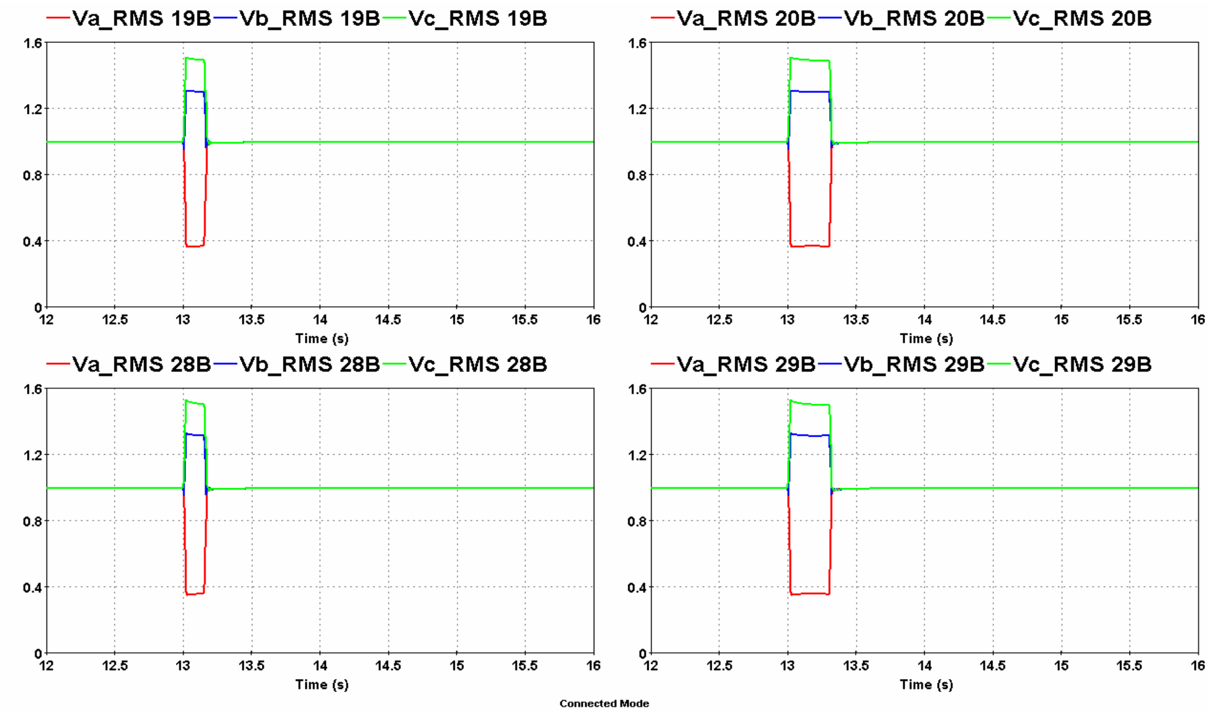

Figure 3.7.3-7: Voltage (Connected mode - PN short circuit)

Figure 3.7.3-6 and Figure 3.7.3-7:

- The voltage recovers faster than 2P and 3P short circuits.
- C phase voltage rises considerably in both modes.
- B phase voltage rises in connected mode.

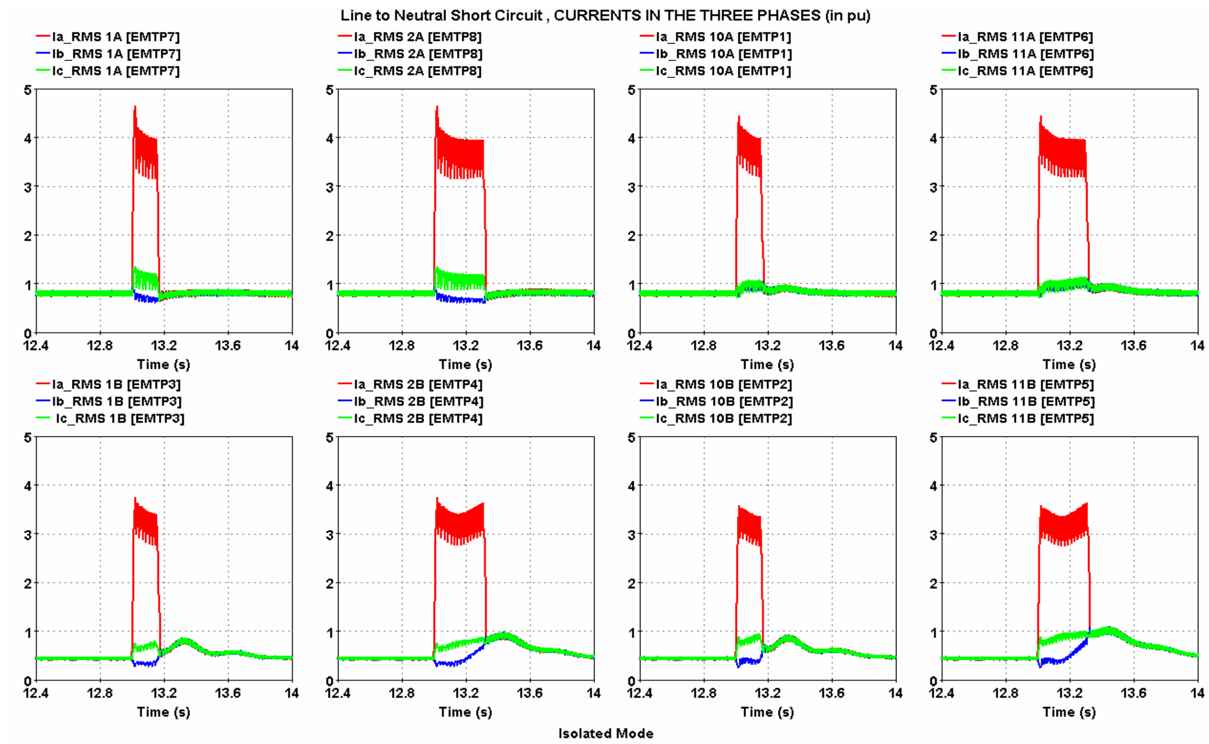

Figure 3.7.3-8: Current (Isolated mode - PN short circuit)

Figure 3.7.3-8: The current in the faulted phase (A) reaches 4 pu.

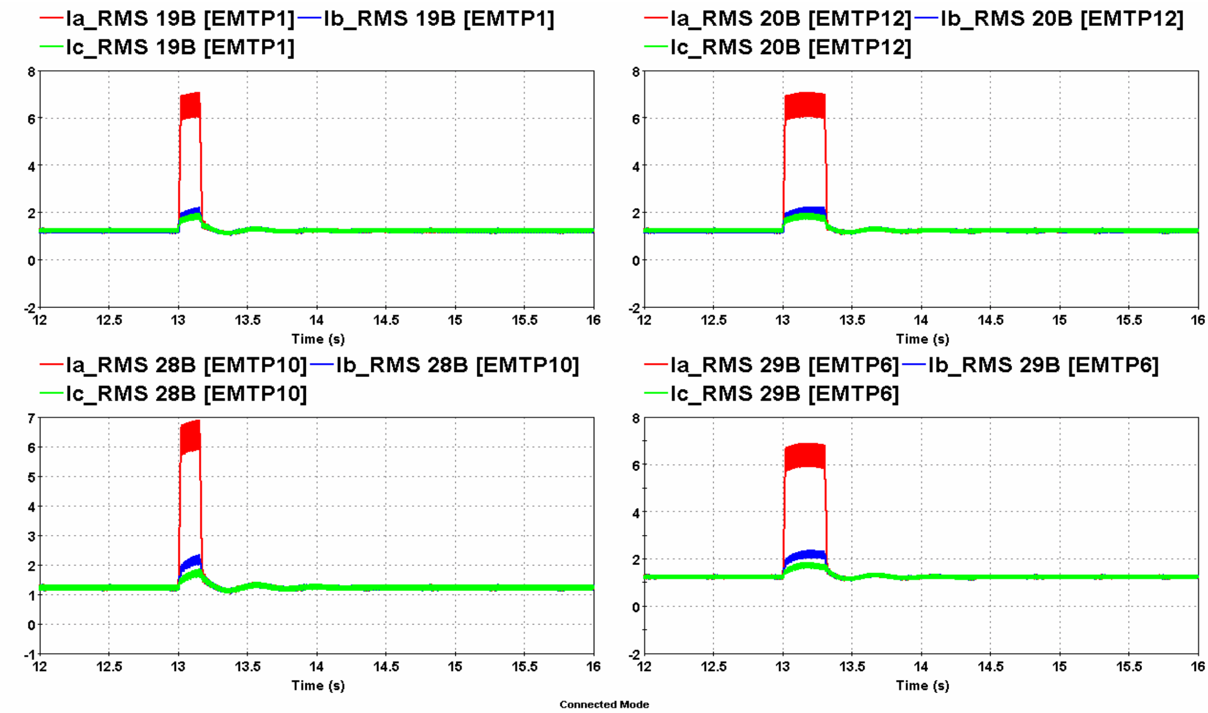

Figure 3.7.3-9: Current (Connected mode - PN short circuit)

Figure 3.7.3-9: The current in the faulted phase (A) reaches 6 pu.

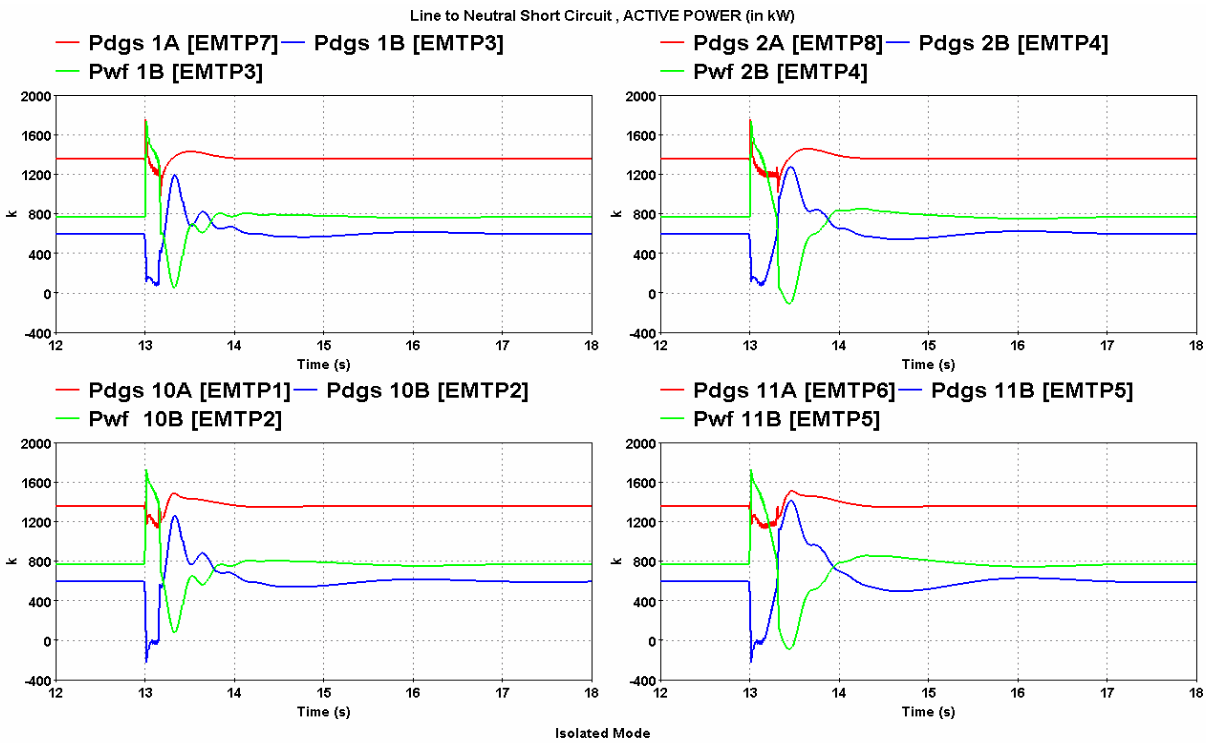

Figure 3.7.3-10: Active power (Isolated mode - PN short circuit)

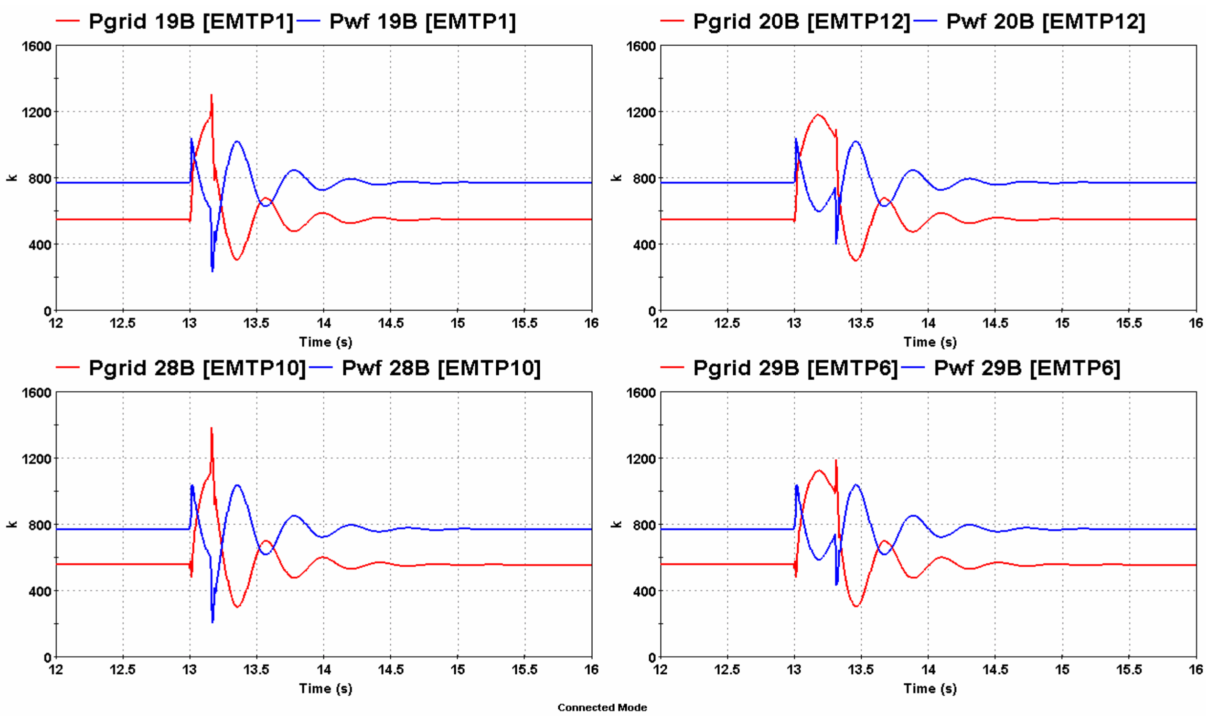

Figure 3.7.3-11: Active power (Connected mode - PN short circuit)

Figure 3.7.3-10 and Figure 3.7.3-11: The same remarks for pp short circuit are available here.

3.7.4. Incidents on the WF

<u>Wind Farm Disconnection</u>

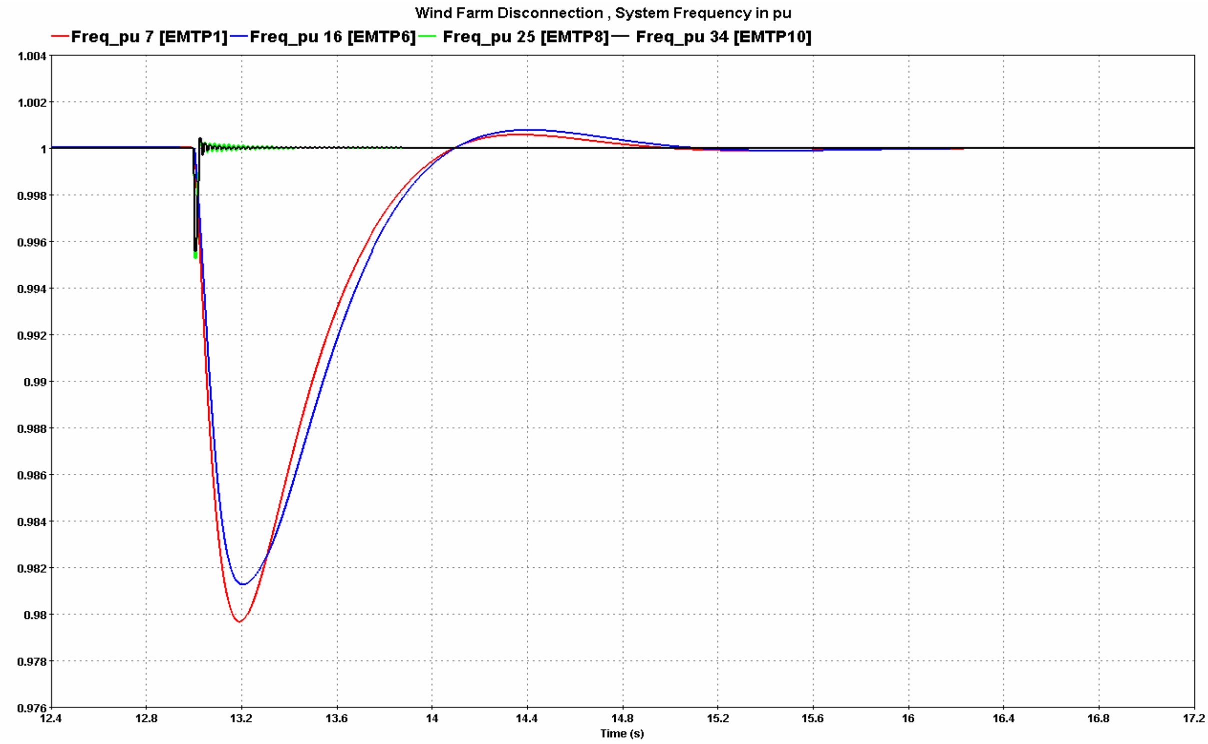

Figure 3.7.4-1: System frequency (Isolated and connected modes - WF disconnection)

Figure 3.7.4-1: The sudden unbalance between production and consumption when the WF is disconnected creates a 2% frequency excursion.

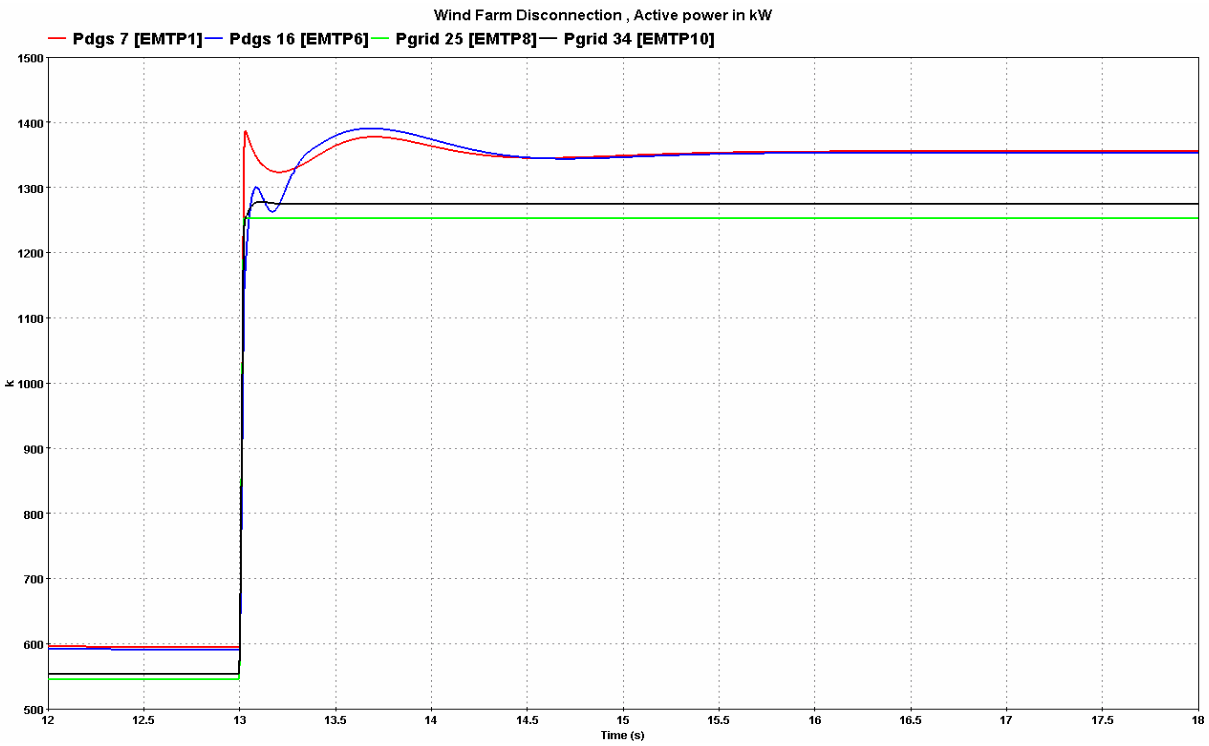

Figure 3.7.4-2: Active power (Isolated and connected modes - WF disconnection)

Figure 3.7.4-2: No relevant or critical situation was detected in that case: All parameters behaved normally without any excessive results.

<u>Wind Farm Connection</u>

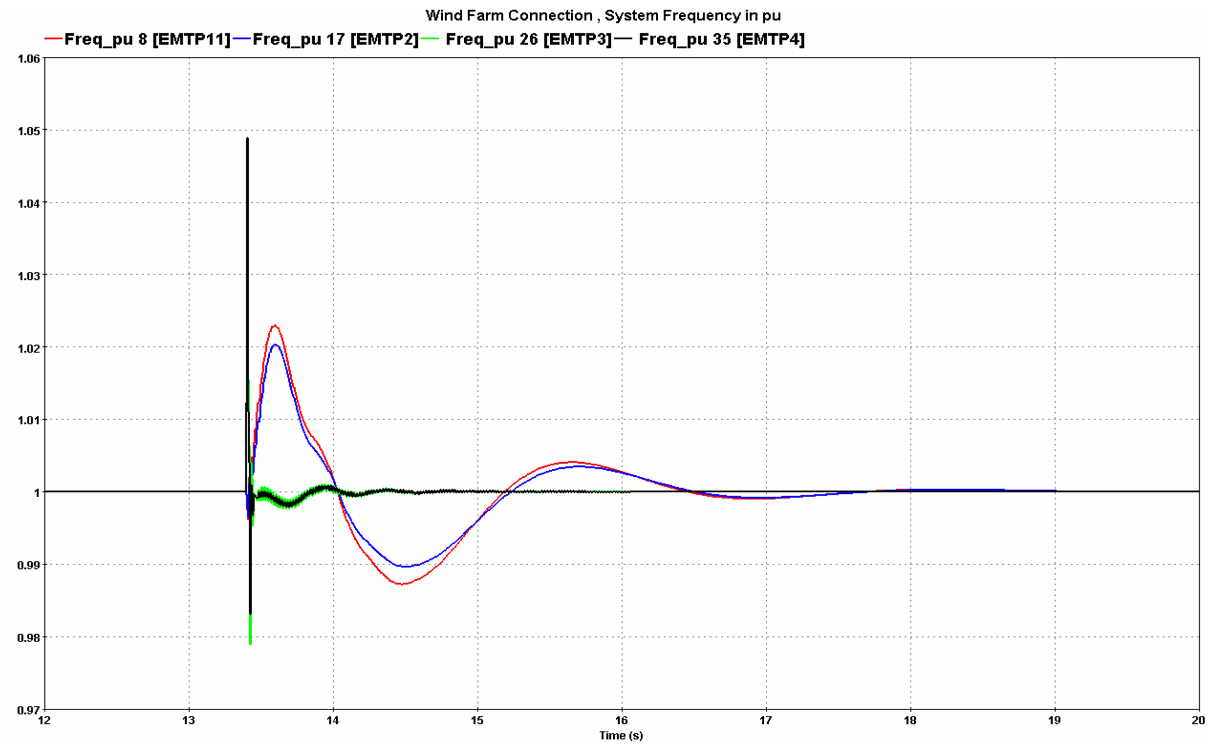

Figure 3.7.4-3: System frequency (Isolated and connected modes - WF connection)

Figure 3.7.4-3: In this case, the connection of the wind farm creates the opposite unbalance between the production and the consumption than in disconnection case.

The frequency rises till 1.02 pu.

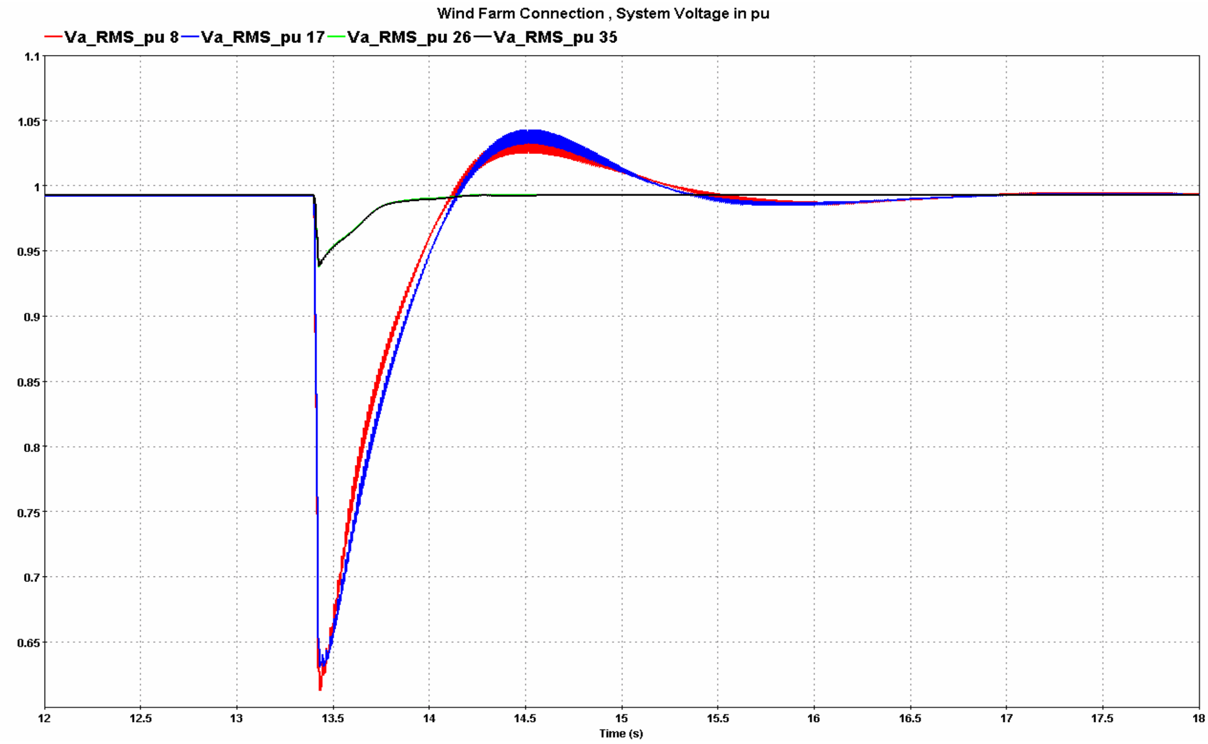

Figure 3.7.4-4: Voltage (Isolated and connected modes - WF connection)

Figure 3.7.4-4: The voltage dip is big because the whole wind turbines are connected at the same time. The duration is however very short (< 100ms). It is more advisable to connect the WTGs separately.

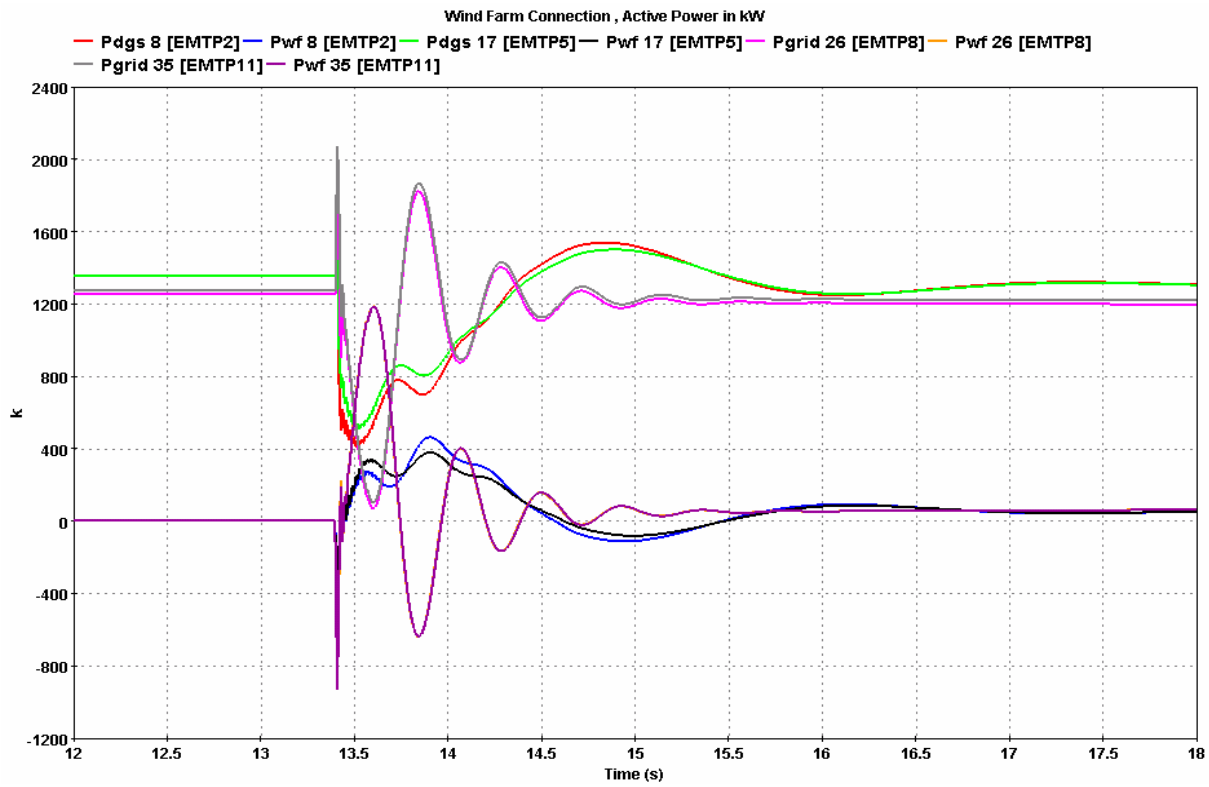

Figure 3.7.4-5: Active power (Isolated and connected modes - WF connection)

Wind Speed Variation

Wind is a quite rapidly fluctuating prime mover. In our case (constant speed turbines), prime mover fluctuations are directly translated into output power fluctuations because there is no buffer between mechanical input and electrical output (Figure 3.7.4-6).

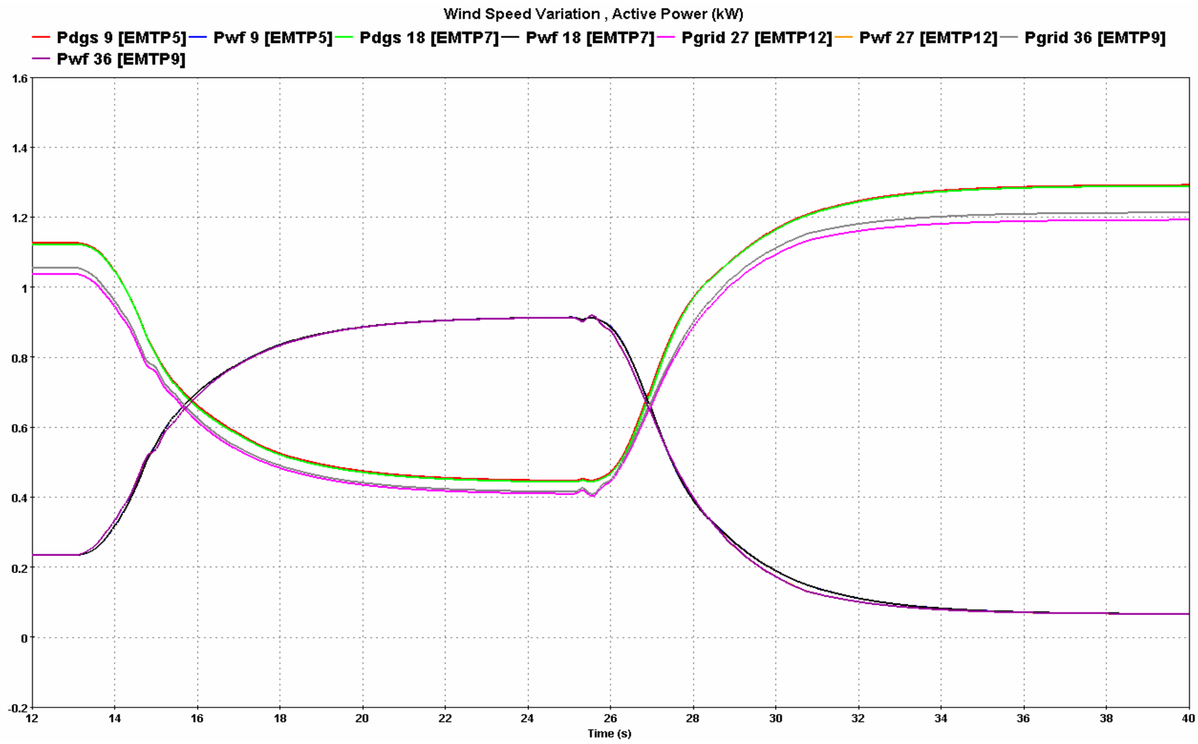

Figure 3.7.4-6: Active power (Isolated and connected modes - Wind speed variation)

For the three kinds of incidents on the wind farm, we see that the machines speeds variations are very small. The stress on these machines is less serious than in the previous simulations (short circuit).

3.8. Conclusions

The simulations were performed with severe situations in both isolated and connected mode: direct short circuit (3 phase, 2 phase, phase to ground fault) and with a quite big wind power penetration (50%).

The results show a global good stability of the microgrid if respecting critical default clearing time (in our system modelling, it is around 0.3s). The transient amplitudes are reasonable and the duration lasts up to 5 s and the frequency stays in good interval.

The grid is strength enough to face some the variation on the wind farm.

The protection strategy must take into account these transients and particularly the currents in sound phase during short circuit that can be very high.

3.9. Glossary

SC	Short Circuit
WT	Wind Turbine
WF	Wind farm
AVR	Automatic Voltage Regulator
DGS	Diesel GenSet

3.10. Bibliography

[1] P. M. Anderson, A. A. Fouad, “Power system control and stability”, volume 1, IOWA state university press, AMES, IOWA, U.S.A publications. 1977

[2] G.S. Stavrakakis, G.N. Kariniotakis," A general simulation algorithm for the accurate assessment of isolated diesel-wind turbine systems interaction", IEEE transactions on energy conversion, Vol. 10, No. 3, Sept., pp 577-590

[3] Reza, M.; Schavemaker, P.H.; Slootweg, J.G.; Kling, W.L.; van der Sluis, L , “Impacts of distributed generation penetration levels on power systems transient stability”

[4] Power Engineering Society General Meeting, 2004. IEEE 6-10 June 2004 Page(s):2150 - 2155 Vol.2

[5] Slootweg, J.G.; Kling, W.L." Is the answer blowing in the wind Power and Energy Magazine, IEEE Volume 1, Issue 6, Nov-Dec 2003 Page(s):26 - 33

[6] Fesquet, F.; Juston, P.; Garzulino, I." Impact and limitation of wind power generation in an island power system” Power Tech Conference Proceedings, 2003 IEEE Bologna , Volume 3, 23-26 June 2003 Page(s):7 pp. Vol.3

3.11. Annex A

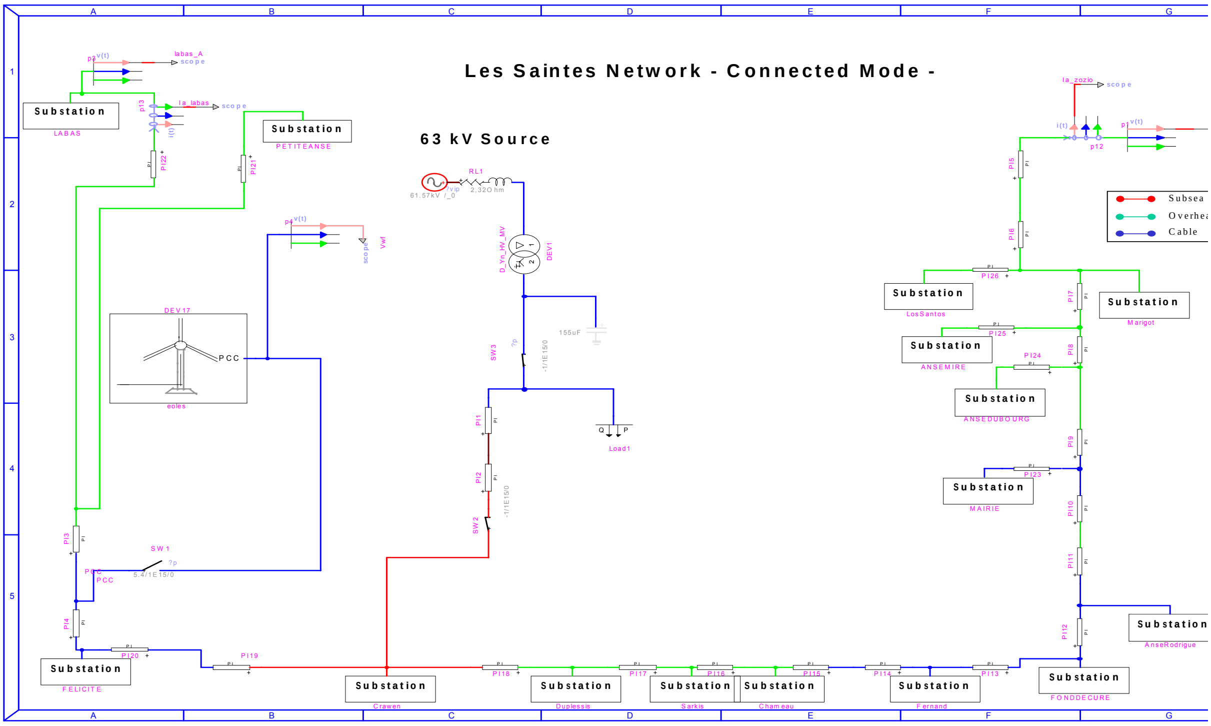

Figure 3.7.4-1: Les Saintes network (Connected mode)

3.12. Annex B

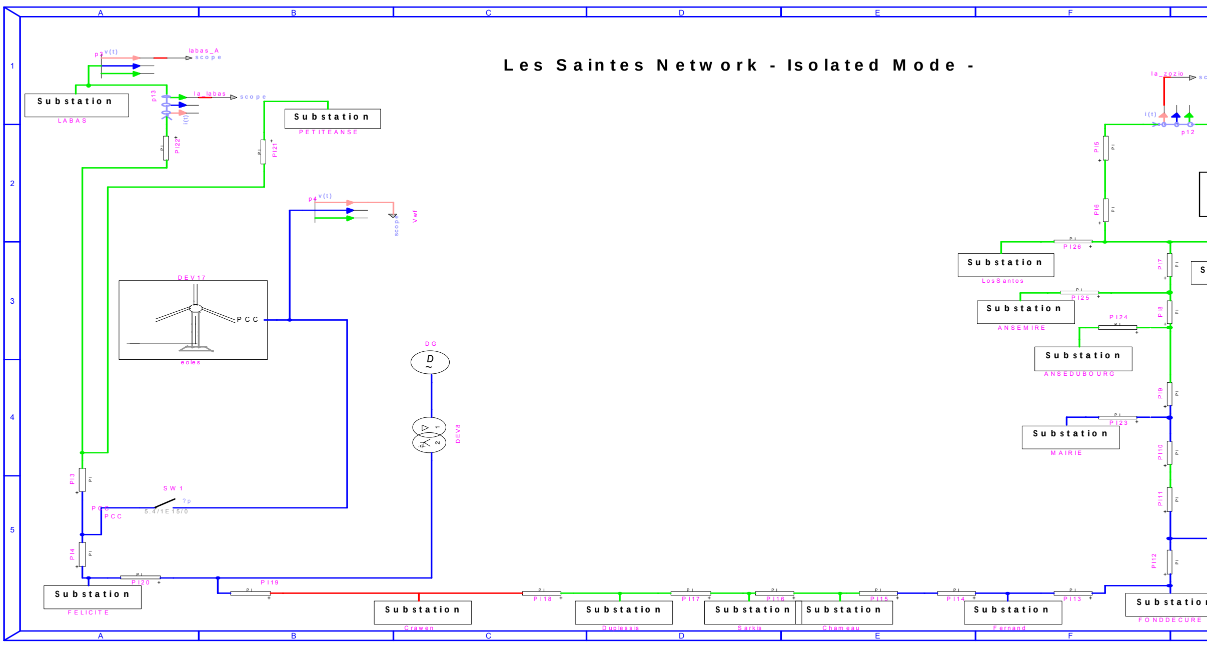

Figure 3.7.4-1: Les Saintes network (Isolated mode)

3.13. Annex C

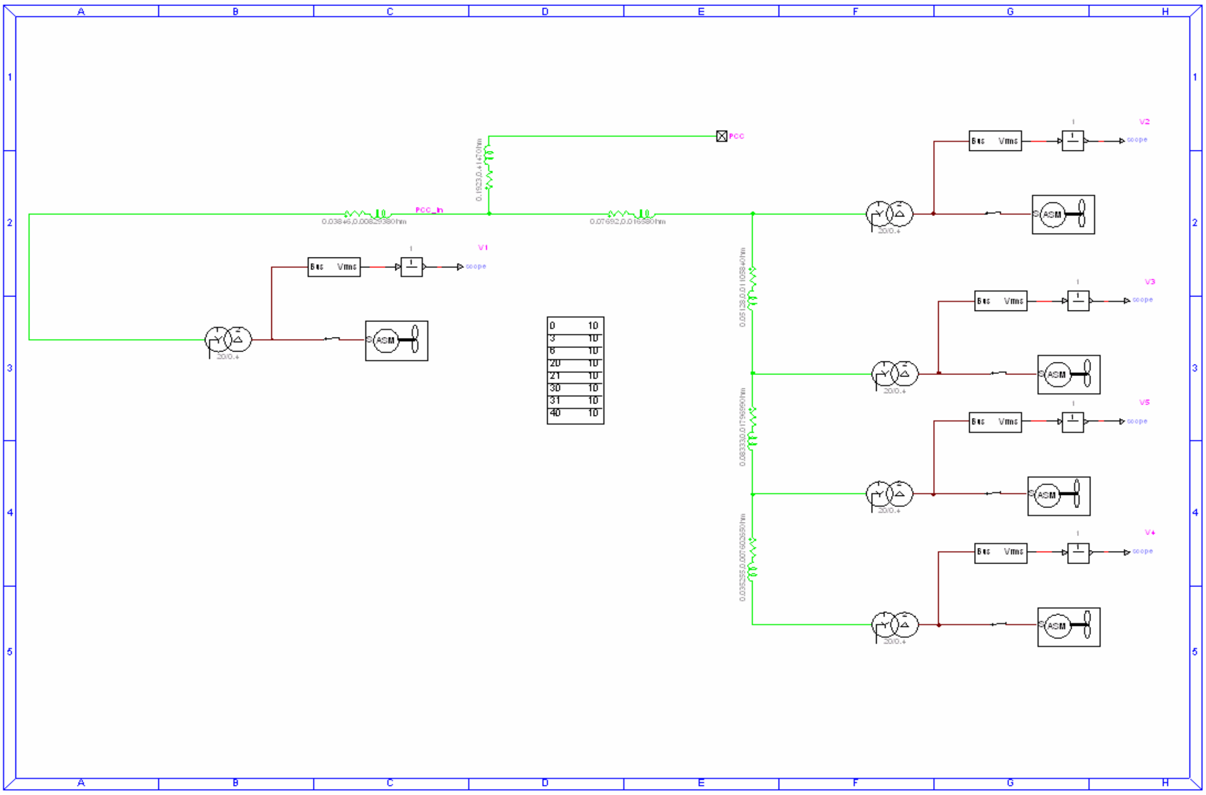

Figure 3.7.4-1: Wind Farm

3.14. Annex D

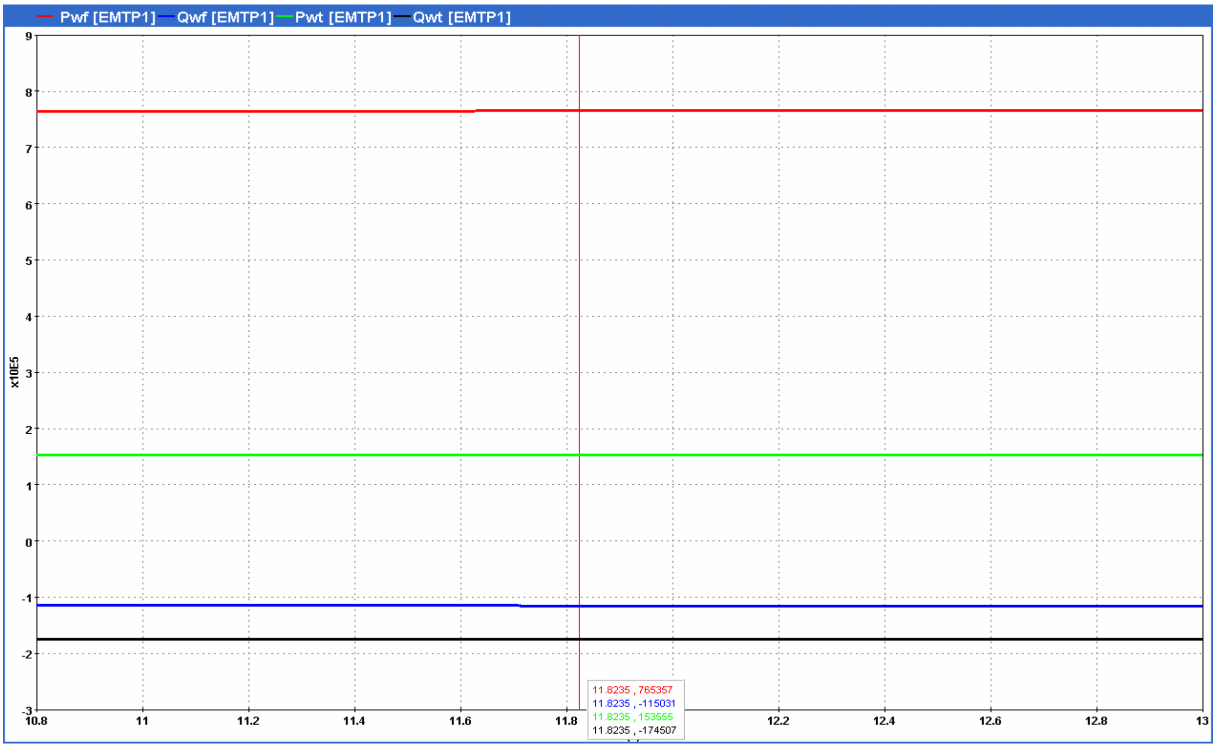

Figure 3.7.4-1: EMTP results

4. Case Study: Portuguese Low Voltage Network

4.1. Introduction

The main objective of this document is to analyse the steady state and dynamic behaviour of a study case Low Voltage (LV) network, located in Portugal [1].

4.2. The Portuguese Study Case Low Voltage Network

The Portuguese study case LV network comprises a micro-cogeneration system based on a microturbine (MT), which generates electric power and heat in a Natural Gas (NG) station. Details on the electrical data and consumers' characterisation can be found in [1]. A potential operation scheme is depicted in Figure 4.2-1, where is possible to observe the distribution transformer (PTD), the microturbine plant and an LV feeder with its electrical loads. The consumers are mainly of the industrial, residential and agricultural type [1]. In a near future it is expected that photovoltaic panels (PV) may be installed in some customers (C3, C12, and C14).

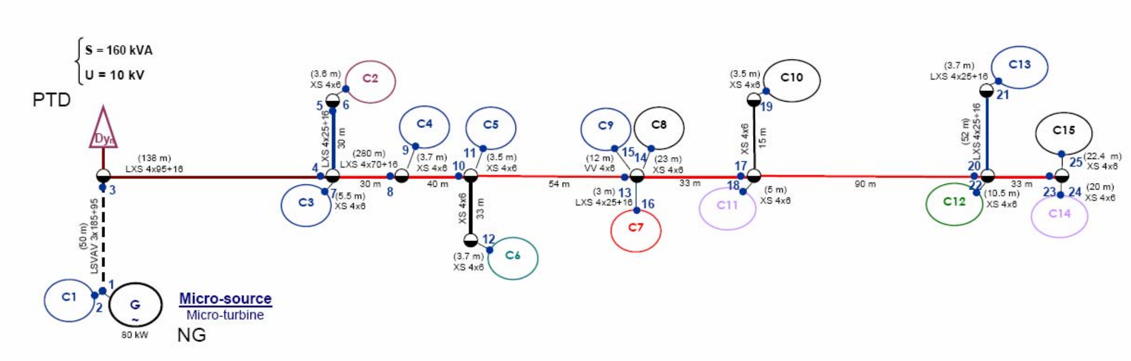

Figure 4.2-1: EDP LV study case network

Considering or not the inclusion of the PV in a near future and regarding the specific characteristics of this micro-cogeneration system [1], two operation scenarios can be defined for this electrical grid:

- Normal Interconnected Mode: the LV distribution system is interconnected with the upstream MV network and the microturbine is running on full power, and the corresponding electric power produced is consumed locally in the LV grid and the remaining power is exported to the MV network;

- Autonomous Operation Mode: due to planned or unplanned situations (maintenance needs, faults) in the upstream MV network, the LV system can be operated autonomously (islanded operation). In this case, microturbine production will be continuously adapted to the LV grid load. For the next years it is also expected that the microturbine will have the capacity to supply all LV consumers represented in Figure 4.2-1 [1].

EDP has performed several tests on this electrical system and the main measurements recorded are presented in [2]. One of the test performed consisted on moving to islanded operation. Initially the microturbine is operating at full power and then the loss of mains is tested. In the actual micro-cogeneneration plant, the microturbine feeds only a small protected load (C1) during islanded conditions. Due to the normal operation plan defined to the microturbine, an imbalance of at least 50 % of the microturbine rated power is foreseen between generated power and LV grid load. Recorded measurements can be found in [2] for imbalances of about 90 to 95 %, which lead to very high over-voltages (around 1.6 pu) and with a significant time duration. These over-voltages may damage LV loads and it will be desirable to smooth the transitions to autonomous operation by installing a storage device in the LV side of the distribution transformer. In this case, a loss of mains detection will lead to the islanding of the LV system and the Voltage Source Inverter (VSI) associated with the storage device will ensure that the microturbine will be always operating in grid-connected mode (in this operation mode, the microturbine static converter will act as a current source). A local load-frequency control function should be installed in the microturbine in order to control its active power production according to load variations and to maintain the MicroGrid frequency within tight limits. Primary voltage and frequency control are performed by the VSI. Details on this control approach can be found in [3].

4.3. Simulation Platform

In this chapter, the study case LV network used for simulation purposes and the corresponding simulation platforms under the *MatLab*® *Simulink*® environment are presented. The system under analysis was transposed to the simulation platform under the

MatLab® Simulink® environment developed for Work Package D, as can be seen in Figure 4.3-1.

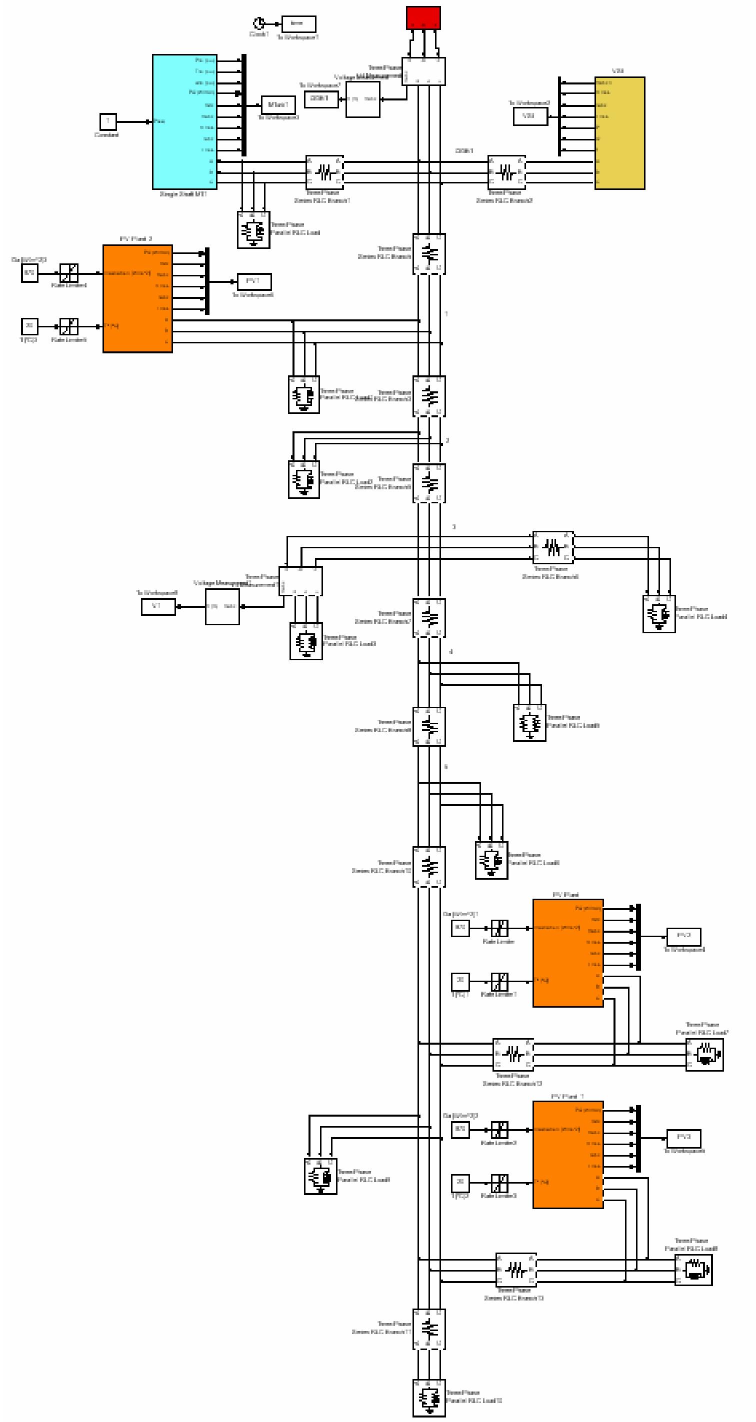

Figure 4.3-1: EDP LV study case network under the *MatLab® Simulink®* environment

Adequate dynamic models for the microturbine, PV generators, storage devices and power electric interfaces were developed and used. Details on modelling issues can be found in [3].

4.4. Steady State Analysis

In order to evaluate the steady state behaviour of the study case network, a power flow algorithm was used. The tool used for the power-flow calculation was *MatPower*®, a toolbox for *MatLab*®.

The network scheme used is the one presented in Figure 4.2-1.

A steady state analysis was performed for two scenarios: Scenario 1 included an islanded operation, with the microturbine feeding the MicroGrid loads; scenario 2 included also an islanded operation, with the MicroGrid loads being fed by the microturbine and by 3 PV generators. The main objective of this analysis is to compare the behaviour of the MicroGrid in terms of voltage profiles and power losses.

	Losses (%)	
	P	Q
Scenario 1	2.16	3.35
Scenario 2	1.42	1.79

Table 4.4-1: Power losses in the two scenarios considered

From Table 4.4-1, it can be seen that there is a small reduction in both active and reactive power losses in the case of the inclusion of dispersed PV generators. The PV generators help to minimize the losses by generating active and reactive powers locally.

Also, the PV generators included also contribute to voltage control since they inject reactive power with a power factor of 0.93.

In terms of voltage levels, the second scenario presents a maximum improvement of 1.44 % when compared to the first scenario. All voltages are well within acceptable limits for both scenarios.

4.5. Dynamic Analysis

The dynamic behaviour of the Portuguese study case LV network, including a MT and three PV generators, was evaluated after disconnecting the MV network for the scenario described in Section 4.2. The *MatLab® Simulink®* simulation platform shown in Figure 4.3-1 was used. In this scenario the MicroGrid is exporting 39.4 – j11.6 kVA to the upstream MV network, with a local generation of 88.3 + j8.8 kVA and MicroGrid load of 48.9 + j20.4 kVA.

The disconnection of the MV network occurs at t = 10s. The main results are shown in the following figures.

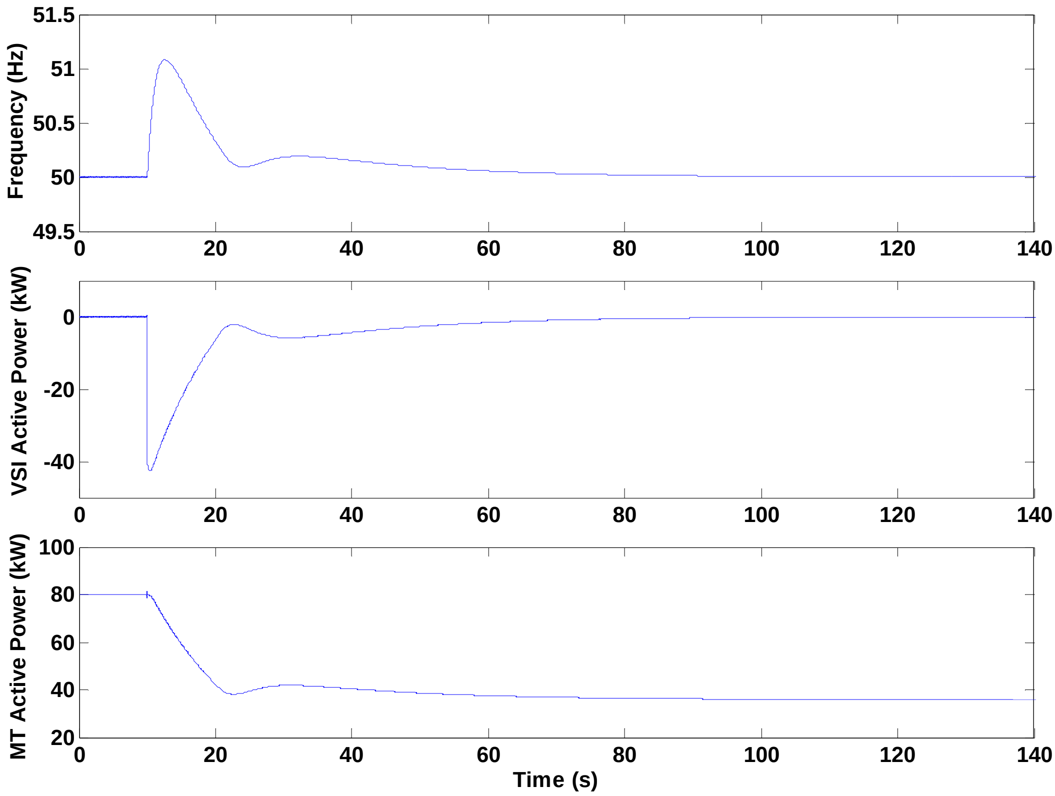

Figure 4.5-1: MicroGrid frequency and microsources' active power

As can be observed in Figure 4.5-1, the high imbalance between MicroGrid load and generation is quickly compensated by the VSI coupled with the storage device, which absorbs the excess of power produced in the MT, while a secondary control reduces MT active power production in order to match local load and maintain frequency around the nominal value of 50 Hz.

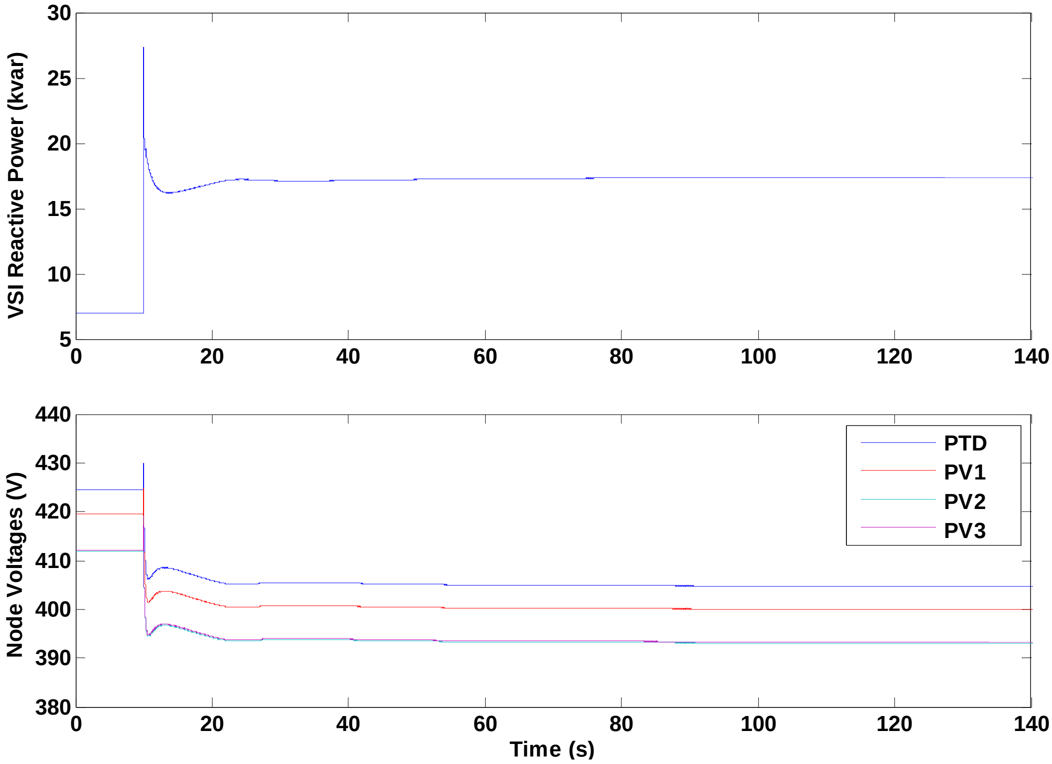

Figure 4.5-2: VSI reactive power and voltages in the secondary side of the PTD and PV units

The VSI is responsible for controlling voltage in the islanded MicroGrid. The presence of the VSI smoothes the transition to islanded operation and no significant overvoltages are observed.

4.6. Conclusions

In this report the steady state and dynamic stability studies for the EDP Portuguese study case LV network are described.

Regarding the steady state analysis, no significant system operation improvements are achieved, because the main microsource (the microturbine) is installed at the beginning of the feeder and the power production at the PV generators is quite low.

The suggestion of installing a storage device at the LV side of the distribution transformer appears to be interesting in order to smooth the transition to islanded operation, as proved by the results obtained for the MicroGrid dynamic behaviour.

4.7. References

[1] J. Oyarzábal, et al, DI1 – Electrical and RES Data Collection, MicroGrids project deliverable, 2005

[2] Amorim, Integration of a Microturbine in a Low Voltage Grid – Monitoring Results, MicroGrids draft report for WPI, 2004

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5. Case Study: Spanish Medium Voltage Network

5.1. Introduction

Existing transmission and distribution networks were originally designed and sized having in mind the existing loading situation and the expected load growth over a given time horizon. The connection of Distributed Energy Resources (DER) into these distribution networks can make them exceed their physical and safety limits. For this reason, it is necessary to study the influence of this kind of generation on the different parameters of the network. On the other hand, load and generation profile changes lack of smoothing effects given the reduced sample size.

This study is focused on the analysis of line loading and voltage profile from a stochastic point of view. For this purpose, Monte Carlo simulations are performed. In each simulation the power flow for a determined operating condition of the system is calculated.

Two case studies characterised by different types of distributed generators are considered. Each case is analysed for distinct DER penetration and DER dispersion levels.

- DER penetration represents the ratio between the total rated power of all connected DER to the system and the peak load demand of the day.
- DER dispersion is the ratio between the number of DER connected to the system and the total number of load buses in the network.

The results will allow the identification of which of the mentioned parameters (line loading or voltage magnitude) is the most limiting factor when introducing DER.

5.2. Modelling

5.2.1. Monte Carlo Simulations

The objective consists in analyzing the influence of a determined amount of DER connected to the network on line loading and on the voltage profile.

In the study, different kinds of variables are involved. Some of them are deterministic because they take predictable values. This is the case of the DER dispersion level, the DER penetration level or the type of distributed generators. However, other variables such as generation location, load demand or DER output are uncertain and they take random values given by probability distributions. If we wanted to do a deterministic analysis of all possible states of the system, it would be practically impossible and it would require an enormous computational effort.

To simplify the problem, Monte Carlo Simulations have been employed [1], [2], [3] and [4]. The Monte Carlo Simulations are a repeated process using random values that obtains deterministic solutions to a given problem. The main issue is to define the number of simulations required to obtain accurate results. In order to adjust the value of this parameter, some test with different number of simulations were carried out. After the analysis it was concluded that 500 simulations are enough to obtain a good solution.

Each simulation consists in calculating a power flow on a fixed operating condition of the system characterised by different sets of values of the following parameters:

- DER dispersion level
- DER penetration level.
- Type of DER.
- Load demand.
- Generation location.
- Generation output.

5.2.2. Study network

In order to carry out the analysis, a real Spanish Medium Voltage Network of 30 kV has been chosen as a test system. It is a meshed network exploited in a radial configuration containing 23 buses and 18 loads. The customers connected are mainly commercial although there is an industrial load placed on bus 23. The one-line diagram is given in Figure 5-1:

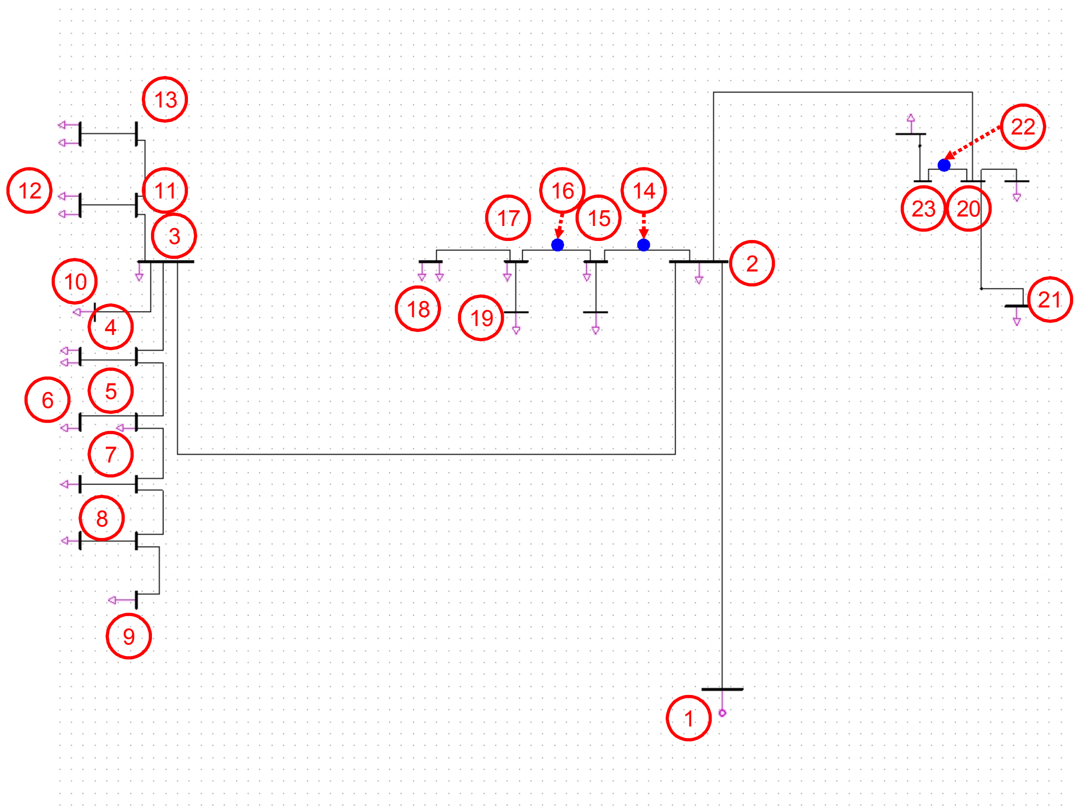

Figure 5-1 Spanish Medium Voltage Network

The network is composed of two radial feeders that have a common starting point, the bus 1 where the slack generator is placed.

The following tables show the power flow results on the base case corresponding to the peak load demand.

BUS DATA						
Bus	**Voltage**		**Generation**		**Load**	
#	Mag (pu)	Ang (deg)	P (MW)	Q (MVAr)	P (MW)	Q (MVAr)
1	1,0000	0,000	11,67	5,62	-	-
2	0,9961	-0,056	-	-	0,096	0,046
3	0,9948	-0,076	-	-	0,018	0,009
4	0,9947	-0,077	-	-	0,783	0,376
5	0,9946	-0,077	-	-	0,121	0,058
6	0,9946	-0,077	-	-	0,078	0,038
7	0,9946	-0,078	-	-	0,181	0,087
8	0,9946	-0,079	-	-	0,844	0,405
9	0,9946	-0,079	-	-	0,119	0,057
10	0,9947	-0,076	-	-	0,734	0,352
11	0,9947	-0,077	-	-	-	-

BUS DATA						
Bus	**Voltage**		**Generation**		**Load**	
#	Mag (pu)	Ang (deg)	P (MW)	Q (MVAr)	P (MW)	Q (MVAr)
12	0,9947	-0,077	-	-	0,874	0,420
13	0,9946	-0,078	-	-	0,874	0,420
14	0,9959	-0,059	-	-	-	-
15	0,9959	-0,060	-	-	0,280	0,135
16	0,9957	-0,062	-	-	-	-
17	0,9957	-0,063	-	-	0,594	0,285
18	0,9957	-0,063	-	-	0,970	0,465
19	0,9957	-0,063	-	-	0,495	0,237
20	0,9960	-0,058	-	-	0,130	0,062
21	0,9960	-0,058	-	-	0,031	0,015
22	0,9956	-0,063	-	-	-	-
23	0,9956	-0,064	-	-	4,399	2,111

Table 5-1 Base case PF results under peak conditions - Node data

BRANCH DATA							
From	**To**	**From bus injection**		**To bus injection**		**Losses**	
Bus	Bus	P (MW)	Q (MVAr)	P (MW)	Q (MVAr)	P (MW)	Q (MVAr)
1	2	11,67	5,62	-11,63	-5,58	0,040	0,033
2	3	4,63	2,23	-4,63	-2,22	0,005	0,005
3	4	2,13	1,02	-2,13	-1,02	0,000	0,000
4	5	1,34	0,64	-1,34	-0,64	0,000	0,000
5	6	0,08	0,04	-0,08	-0,04	0,000	0,000
5	7	1,14	0,55	-1,14	-0,55	0,000	0,000
7	8	0,96	0,46	-0,96	-0,46	0,000	0,000
8	9	0,12	0,06	-0,12	-0,06	0,000	0,000
3	10	0,73	0,35	-0,73	-0,35	0,000	0,000
3	11	1,75	0,84	-1,75	-0,84	0,000	0,000
11	12	0,87	0,42	-0,87	-0,42	0,000	0,000
11	13	0,87	0,42	-0,87	-0,42	0,000	0,000
2	14	2,34	1,12	-2,34	-1,12	0,000	0,000
14	15	2,34	1,12	-2,34	-1,12	0,000	0,000
15	16	2,06	0,99	-2,06	-0,99	0,000	0,000
16	17	2,06	0,99	-2,06	-0,99	0,000	0,000
17	18	0,97	0,47	-0,97	-0,47	0,000	0,000
17	19	0,49	0,24	-0,49	-0,24	0,000	0,000
2	20	4,56	2,19	-4,56	-2,19	0,001	0,000
20	21	0,03	0,01	-0,03	-0,01	0,000	0,000
20	22	4,40	2,11	-4,40	-2,11	0,001	0,001
22	23	4,40	2,11	-4,40	-2,11	0,000	0,000

Table 5-2 Base case PF under peak conditions - Branch data

Table 5-1 shows the voltage magnitude obtained at each bus of the network. The calculation has been done taking the bus 1 as reference and giving it a voltage equal to 1.

Looking at the results it can be observed that the maximum voltage drops are approximately 0.5 % and they occur at feeder end nodes. The voltage profile has been graphically represented in Figure 5-2.

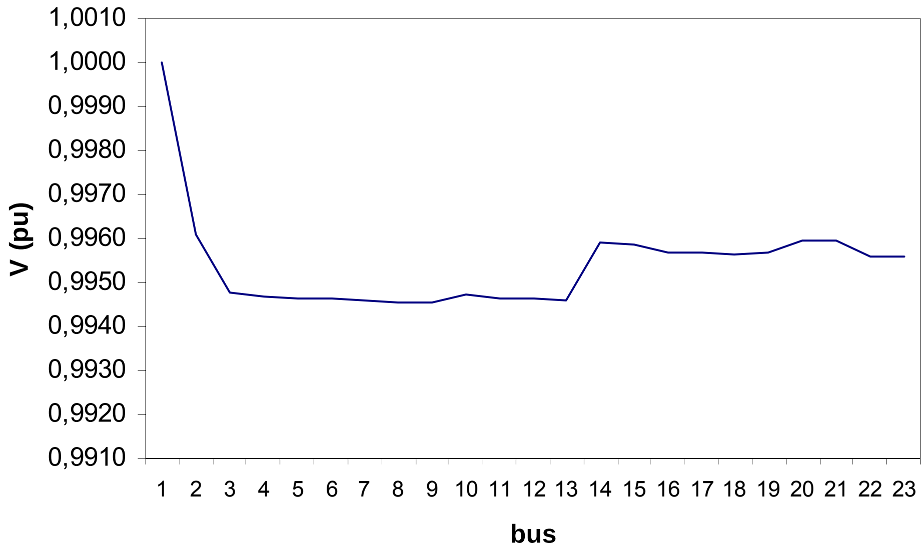

Figure 5-2 Base case voltage profile

5.2.3. Load demand curves

Load demand curves provide the forecasted power consumption at each load bus for each time interval of the day and they have been obtained from real historical data of a weekday of May 2004. Figure 5-3 shows the profile of the aggregated load demand curve employed in this study.

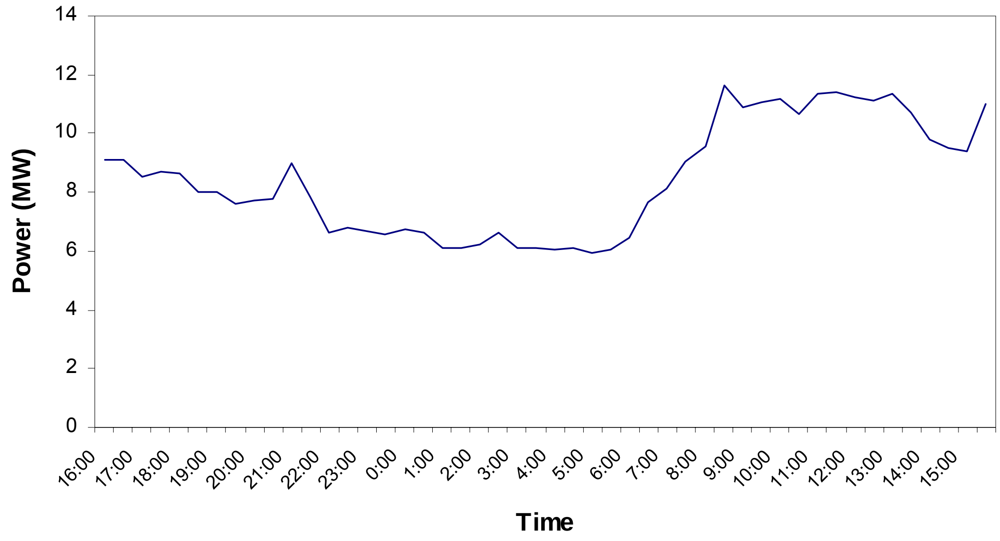

Figure 5-3 Load demand curve

5.2.4. Uncertainty modelling

Some of the parameters of the system, such as forecasted load demand, DER locations, DER outputs… are uncertain, that is, they take random values that can be modelled using probability distributions. The most frequently used probability distributions are the following:

- Uniform distribution.
- Normal distribution.
- Triangular distribution.

A detailed description of each of them is given below.

5.2.4.1. Uniform distribution

An uniform distribution is one for which the probability of occurrence is the same for all values of x on an interval (a,b) and zero elsewhere [4].

The probability density function for the uniform distribution is:

$$f(x) = \begin{cases} \dfrac{1}{b-a} & a \le x \le b \\ 0 & elsewhere \end{cases}$$

Figure 5-4 shows a plot of the probability density function [6]:

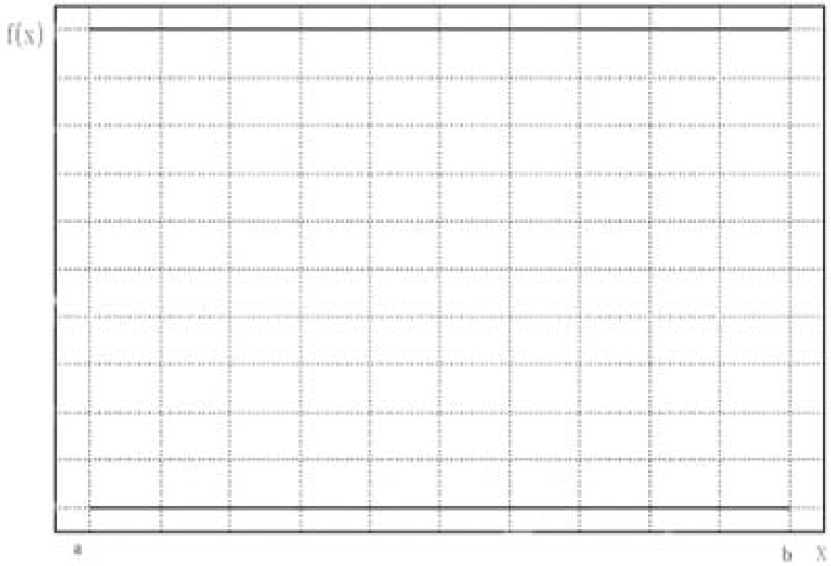

Figure 5-4 Uniform distribution

This probability distribution has been employed to locate distributed generators along the network. That is, the chances of a generator to be placed on a given bus are equal across all buses.

5.2.4.2. Normal distribution

The normal distribution is appropriated when values are expected to cluster disproportionately near the most probable value. This distribution requires to provide an estimation of the most probable value (the mean) and the standard deviation [4].

The probability density function is:

$$f(x) = \frac{1}{\sqrt{2\pi\sigma^2}} e^{\frac{-(x-\mu)^2}{2\sigma^2}}$$

where:

μ: mean

σ: standard deviation

The graphical representation [6] is given in Figure 5-5:

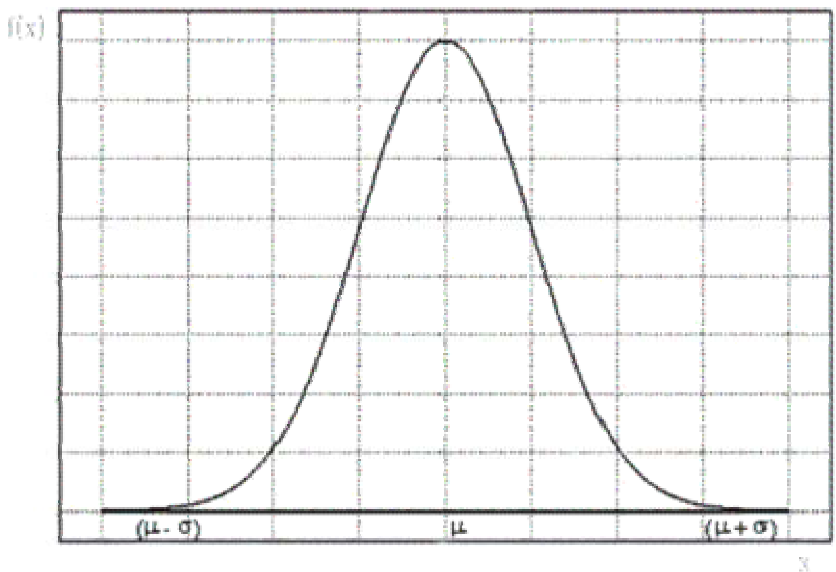

Figure 5-5 Normal distribution

By definition during 68% of the time the values are between (μ-σ) and (μ+σ). But if the range (μ-3σ) and (μ+3σ) is considered, this percentage reaches the 99.73%.

For a given value of accuracy, the standard deviation can be calculated as follows:

$$3\sigma = \mu \frac{accuracy}{100} \rightarrow \sigma = \mu \frac{accuracy}{300}$$

This distribution has been used to model the uncertainties in forecasted commercial power demand and the output of CHP units.

5.2.4.3. Triangular distribution

The triangular distribution is similar to the normal distribution but it requires only the range (a and c) and the most probable value (b) as parameters [4].

The probability density function is:

$$f(x) = \begin{cases} \dfrac{2(x-a)}{(c-a)(b-a)} & a \le x \le b \\ \dfrac{2}{(c-a)(c-b)} & b \le x \le c \end{cases}$$

Figure 5-6 shows a graphical representation of the probability density function [6]:

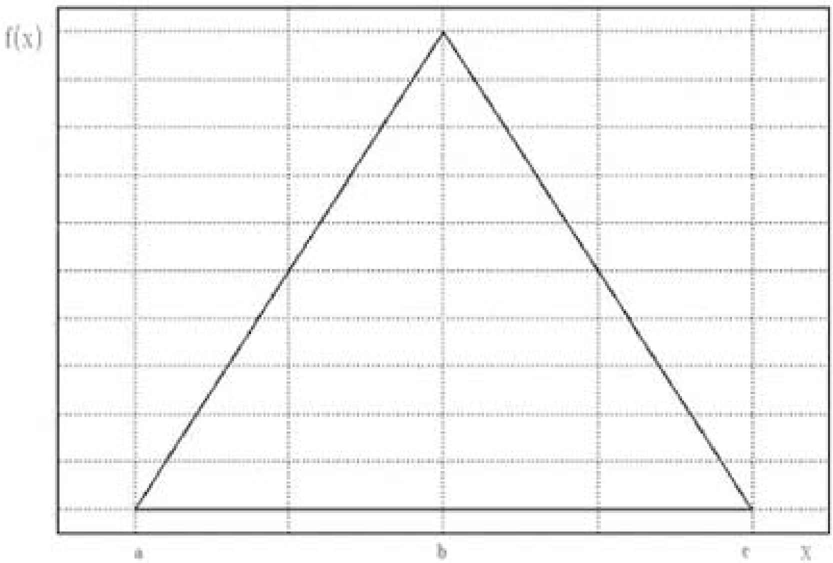

Figure 5-6 Triangular distribution

This distribution has been employed to take into account the randomness of the industrial loads.

5.3. Case studies

5.3.1. Introduction

Distributed generation connected to the distribution network causes an impact on it that can affect to the network operation, planning and provoke economic losses because the network was not designed taking into consideration this kind of generation.

In order to study the influence of DER penetration on line loading and on the voltage profile two case studies with different DER technologies have been considered. In the first one CHP penetration is studied as an example of controllable generation. In the second one Wind Turbines that represent an intermittent generation are analysed.

The study has been performed for a whole day supposing that it is divided in 48 time intervals, that is, one for each half an hour.

For each time interval, five hundred Monte Carlo Simulations have been carried out. In each simulation, the power flow for a determined operating condition of the system is calculated. These conditions are characterised by different values of load demand, type of DER, DER location and DER outputs.

The definition of the previous operating conditions of the system depends on the case study and they are explained in the following sections.

5.3.2. Case 1: CHP

Nowadays, the total installed capacity of combined heat and power plants (CHP) is growing very fast due to the possibility of recovering and using the waste heat that allows a higher efficiency. In addition to this, the governments are supporting this kind of generation, so in a short term, the CHP technology could be widely integrated. In this case study the penetration based on CHP has been analysed.

The modelling of the case requires the definition of the hourly demand curves for each load bus of the system and the characteristics of the distributed generators.

5.3.2.1. Load modelling

Load demand curves have been obtained from real historical data of a weekday of May 2004.

Randomness for the commercial and the industrial load demands has been modelled with normal and triangular probability distributions respectively. It has been assumed that the accuracy in both cases is equal to 100%, so the necessary parameters for each distribution are the following:

Normal distribution:

$$\mu = \text{load demand}$$
$$\sigma = \mu \frac{\text{accuracy}}{300} = \mu \frac{100}{300} = \frac{\mu}{3} = \frac{\text{load demand}}{3}$$

Triangular distribution:

$$a = b - \frac{accuracy}{100} b = b - \frac{100}{100} b = 0$$
$$b = \text{load demand}$$
$$c = b + \frac{accuracy}{100} b = b + \frac{100}{100} b = 2b$$

5.3.2.2. DER modelling

The power output curves for combined heat and power plants (CHP) have been calculated as a function of the energy price curve. Generators produce their maximum when the price reaches the higher value. The remaining outputs are calculated proportionally.

For this purpose, historical hourly data have been chosen. Data corresponding to this curve has been taken from the “Operador del mercado iberico de energía – Polo Español, S.A.” [9] and they are given in Table 5-3. It should be noted that higher prices are found in the evening due to be a winter day.

Date	Time	Price (cent/kWh)
11/05/2004	16:00	2,700
11/05/2004	17:00	2,700
11/05/2004	18:00	2,700
11/05/2004	19:00	2,330
11/05/2004	20:00	2,330
11/05/2004	21:00	2,012
11/05/2004	22:00	3,000
11/05/2004	23:00	2,300
11/05/2004	0:00	1,617
12/05/2004	1:00	2,207
12/05/2004	2:00	2,000
12/05/2004	3:00	1,804
12/05/2004	4:00	1,773
12/05/2004	5:00	1,705
12/05/2004	6:00	1,803
12/05/2004	7:00	2,007
12/05/2004	8:00	2,217
12/05/2004	9:00	2,183
12/05/2004	10:00	2,357
12/05/2004	11:00	2,467
12/05/2004	12:00	2,357
12/05/2004	13:00	2,357
12/05/2004	14:00	2,147
12/05/2004	15:00	1,468

Table 5-3 Energy price curve

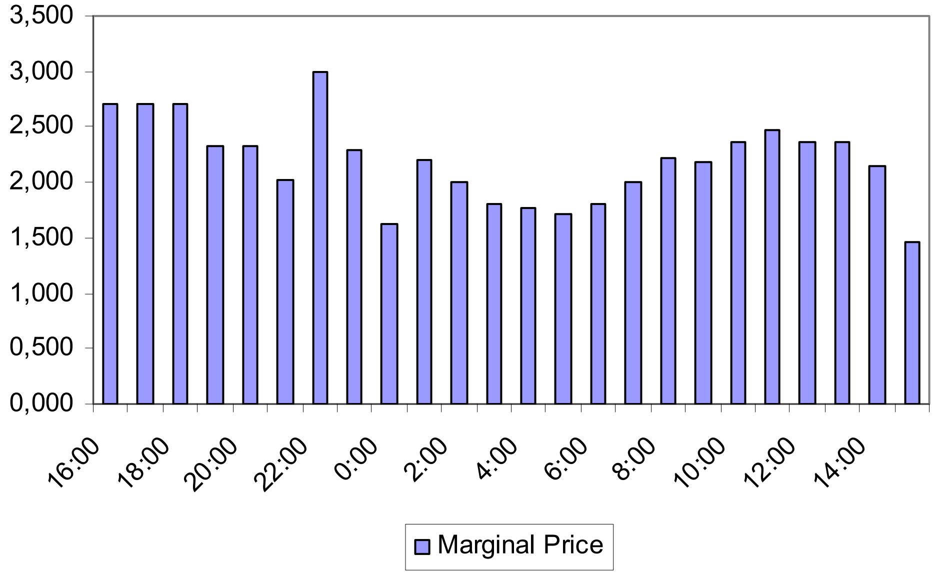

Figure 5-7 Energy price curve

The peak generation of each individual CHP has been obtained as a function of the DER penetration level using the following formula:

$$\%\text{DER penetration} = \frac{\text{total MVA DER}}{S_{max}} \cdot 100 = \frac{\text{DER output} \cdot \text{number of DER}}{S_{max}} \cdot 100 \rightarrow$$

$$\text{DER output} = \frac{\%\text{DER penetration} \cdot S_{max}}{\text{number of DER} \cdot 100}$$

Where the number of distributed generators is given by the DER dispersion level and the S_{max} represents the apparent power at the time of the day of peak demand.

The peak power output corresponds to the generation at the time of the day of maximum energy price. The remaining values of the generation curve are obtained following the energy price curve profile in a similar manner.

The power output calculated with the formula represents the maximum power of the CHP, so the real value of generation will be a bit smaller. Besides, the required generation depends on the heat demand that is uncertain. For this reason, there is also an uncertainty on the generation outputs that has been simulated modifying the values of the generation curve with a normal distribution of 50% of accuracy.

The location of distributed generators has been identified by generating a random sequence of n integers, (n is the number of buses in the system). This sequence represents the buses at which a distributed generator will be placed.

5.3.2.3. Analysed scenarios

Three different dispersion levels have been considered: 4.3% (1 DER), 52% (12 DER) and 100% (23 DER). The last one corresponds to the case in which all buses have a distributed generator.

For each dispersion level, 31 penetration levels between 5 and 500% have been studied.

Two real examples that can be used as reference to define the penetration level are the following:

Example 1: For a magnitude of the voltage of 30 kV, the “Special System producers regulation” [5] says that the recommended maximum power to be connected to the system is 8 MVA. As the peak load demand for the Spanish Medium Voltage test network is 12.9 MVA, the DER penetration percentage would be approximately the 60%.

Example 2: A Wind Farm placed in Vizcaya (Spain) is composed of 30 wind turbines of 850 kW connected to a 30 kV network so it has an installed power of 25.5 MW. This is equivalent to a 200% of DER penetration.

5.3.2.4. Solving process

This section presents an overview of the general procedure used in this work to carry out the mentioned study. A description of the required input data, the processing and the output data obtained is given.

5.3.2.4.1. Input data

The necessary inputs are the following:

- Number of Monte Carlo Simulations: five hundred simulations are performed.
- Network topology: it is defined by bus and line data. A real Spanish Medium Voltage Network has been chosen as a test system.
- Demand curves: they provide the forecasted hourly load demand for each bus of the network.

- Energy price curve: it represents the hourly price of the energy at the market. This data is necessary to obtain the power output curves of the generators.

5.3.2.4.2. Processing

The computational algorithm is the following:

- Step 1: Read input data.
- Step 2: Define an initial DER dispersion level.
- Step 3: Define an initial DER penetration level.
- Step 4: Take the first time interval of the day.
- Step 5: Run the Monte Carlo Simulations that consist in defining load and distributed generators data that are generated randomly and solve the power flows.
- Step 6: Take the next time interval and return to the step 5. This process is repeated for every time interval of the day.
- Step 7: Increment DER penetration level and return to step 4. Do this while the maximum penetration level is not reached.
- Step 8: Store and analyse the results obtained for the dispersion level under study.
- Step 9: Increment DER dispersion level and return to step 3. Repeat this process until the maximum dispersion level is reached.
- Step 10: After having studied all the scenarios, a processing of the results is carried out.

Figure 5-8 summarises this method:

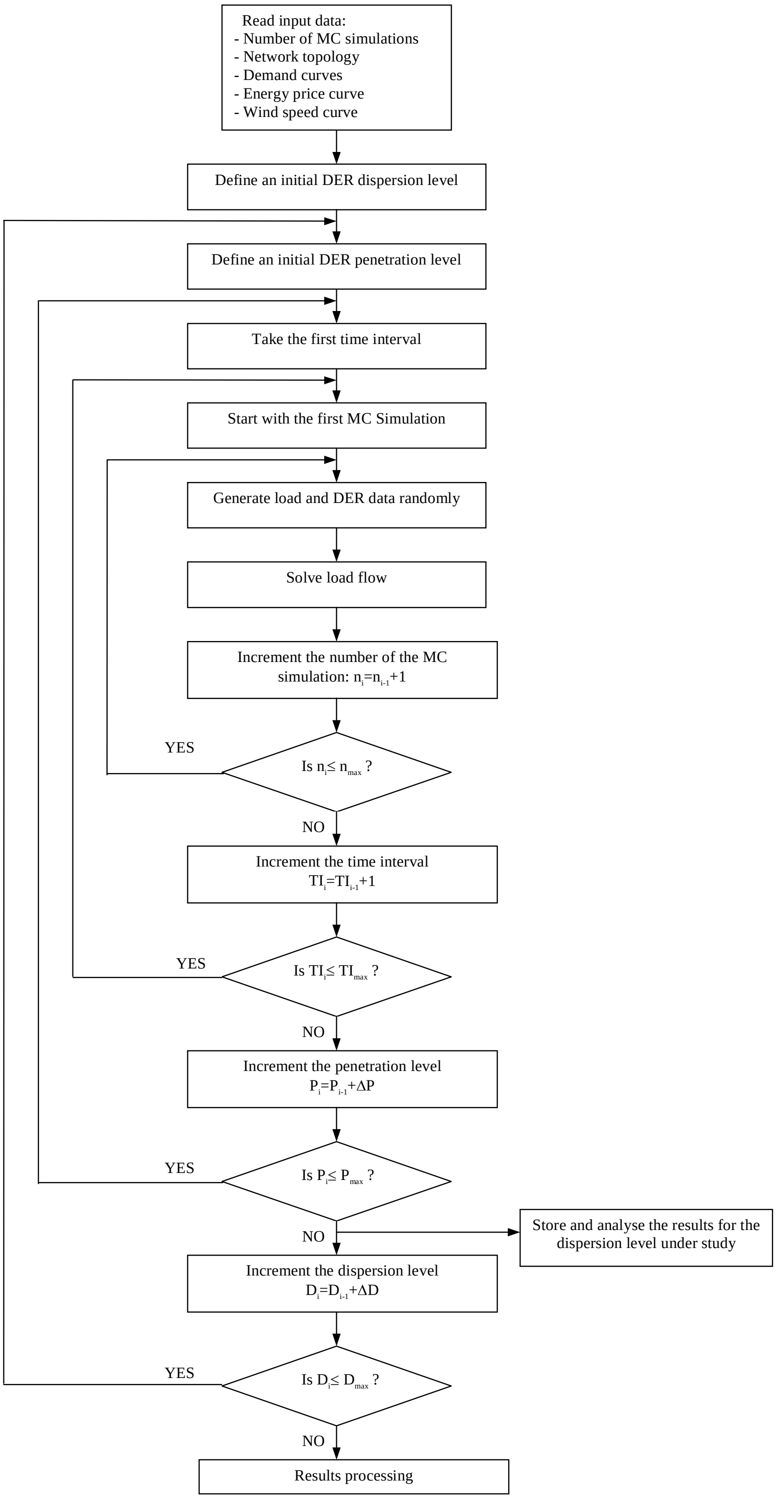

Figure 5-8 Flowchart of the resolution process

Where:

D_i = dispersion level.

P_i = penetration level.

TI_i = time interval.

n_i = number of the Monte Carlo simulation that is being run.

n_{max} = the maximum number of Monte Carlo Simulations (500).

TI_{max} = the maximum number of time intervals (48).

P_{max} = the maximum penetration level considered (500%).

D_{max} = the maximum dispersion level considered (100%).

5.3.2.4.3. Output data

The previous process allows gathering data for the generation of different graphics in relation to line loadings and voltage profiles.

<u>Line loading results</u>

Different graphics that represent the bad cases probability as a function of the DER penetration for a given dispersion level are obtained. A bad case is a simulation where at least one line of the network is overloaded. So the previous percentage can be defined as the ratio between the total number of bad cases for all simulations of the day and the total simulations performed:

$$\text{bad cases probability}\,(\%) = \frac{\sum \text{bad cases}}{\text{number of time intervals} \cdot \text{number of MC simulations}} \cdot 100$$

In addition to this, a three dimensional graphic that represents the probability for each line of the network to be overloaded as a function of the penetration level is obtained for each dispersion level. This percentage is considered for the whole day, so the calculation has been done using the following formula:

$$\text{overload probability of line}_{ij}\,(\%) = \frac{\text{number of cases where the line}_{ij}\text{ is overloaded}}{\text{number of time intervals} \cdot \text{number of MC simulations}} \cdot 100$$

Voltage results

As in the previous analysis, different graphics that show the bad cases probability as a function of the DER penetration level are obtained. Now a bad case defines a simulation where at least one of the buses exceeds its voltage limit.

5.3.2.5. Results

5.3.2.5.1. Line loading results

Table 5-4 shows the bad cases probabilities obtained for 4.3% (1 DER), 52% (12 DER) and 100% (23 DER) dispersion levels respectively. These results have been graphically represented in the Figure 5-9.

It can be noted that the probability of one bad case is 1 / (48*500)*100 = 0.004%. This value has been obtained for the dispersion level 1 and the penetration level 170 and it means that there is only one simulation in the whole day where at least one line of the network is overloaded.

% Penetration	Dispersion (number of DER)		
	1	12	23
5	0	0	0
25	0	0	0
50	0	0	0
70	0	0	0
80	0	0	0
90	0	0	0
100	0	0	0
110	0	0	0
120	0	0	0
130	0	0	0
140	0	0	0
150	0	0	0
160	0	0	0
170	0,004	0	0
180	0,050	0	0
190	0,125	0	0
200	0,317	0	0
210	0,825	0	0
220	1,329	0	0
230	2,479	0	0
240	3,821	0	0
250	5,838	0	0
260	8,504	0	0
270	11,104	0,008	0
280	14,367	0,050	0,029
290	18,650	0,238	0,121
300	22,796	0,688	0,467
350	46,063	5,708	5,388
400	65,942	18,267	17,946
450	80,208	40,171	40,042
500	89,108	65,467	65,817

Table 5-4 Results of CHP penetration

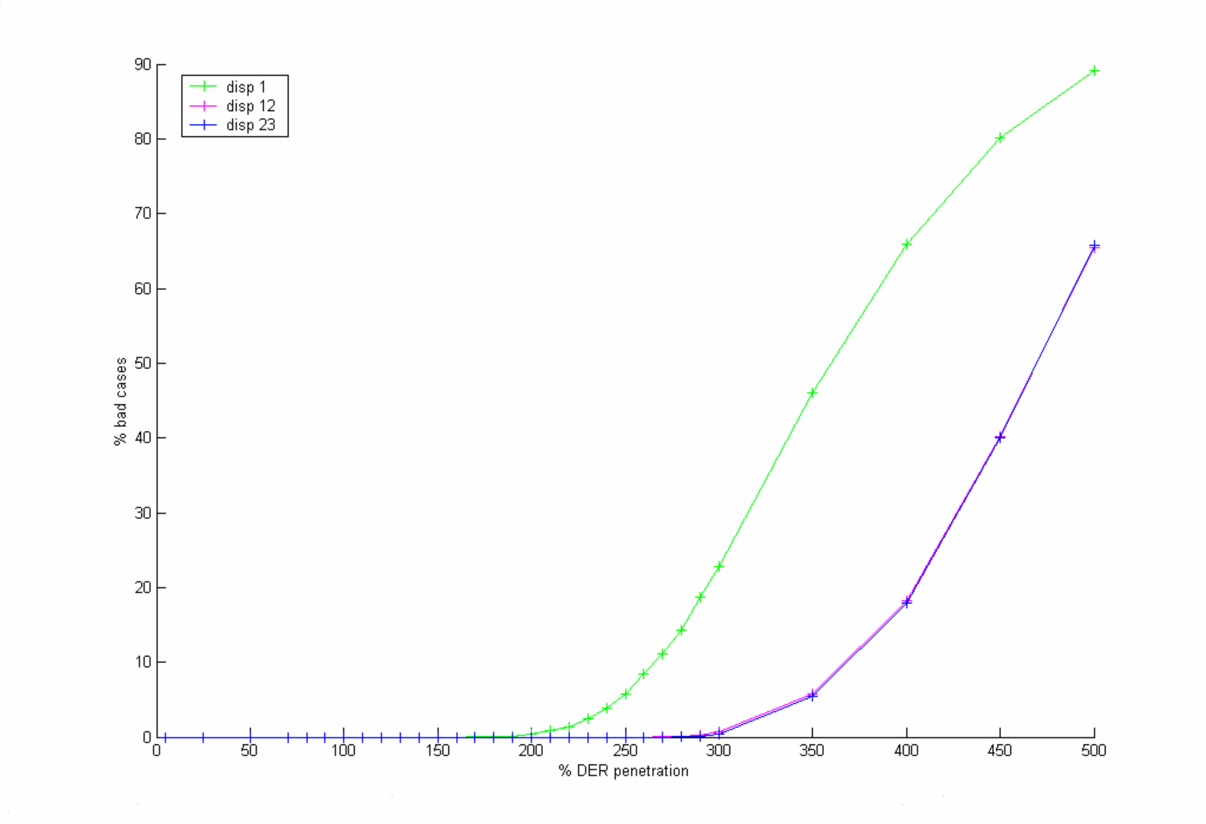

Figure 5-9 Results of CHP penetration

Before analysing the conclusions it has to be taken into account a very important issue regarding the definition of the DER penetration level.

In a radial network it can be defined a penetration level for the whole system or it can be obtained a different penetration level for each radial feeder of the network. This can be illustrated with the example given in Figure 5-10:

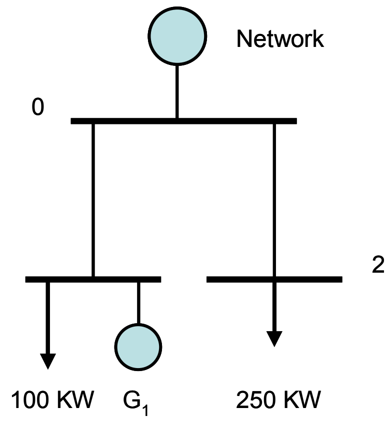

Figure 5-10 Example of radial network

This network is composed of two radial feeders that have a common starting point, the bus 0 where the network equivalent is placed. The loads on each feeder are 100 KW and 250 KW respectively. If a distributed generator providing 250 KW is placed on the bus 1, the global penetration level is the following:

$$\%\text{penetration}_{\text{global}} = \frac{250}{350} \cdot 100 \approx 70\%$$

However, the penetration levels corresponding to each radial feeder are:

$$\%\text{penetration}_{\text{feeder 1}} = \frac{250}{100} \cdot 100 = 250\%$$

$$\%\text{penetration}_{\text{feeder 2}} = \frac{250}{250} \cdot 100 = 100\%$$

In this study the global penetration level has been considered.

Looking at Figure 5-9 it can be concluded that the probability of bad cases increases with the penetration level for all dispersion levels. This occurs because an increase in the penetration level provokes an increase in the generation output that can cause overloads on the lines.

It can be seen too, that the penetration level for which the curves start to have values different from zero increases as the dispersion level increases due to the bigger distribution of the generation along the buses. This makes the power flows of the lines smaller and consequently the overload probability decreases.

If we compare the three curves we can see that the values corresponding to the dispersion level 1 are clearly bigger than the corresponding to the other dispersion levels for the same penetration percentage. Besides, the curves for dispersion levels higher than 1 are very close. In order to explain this fact, it is necessary to take into account that it is a radial network and therefore the maximum power flows always occur upstream of the buses where distributed generators are located. For the dispersion level 1, all the power output is supplied by only one generator and consequently there is a high probability to overload the upstream branches. However, higher dispersion levels also imply smaller units distributed between all involved branches. In this case, connected loads consume part of the generation locally reducing the power to be exported and thus reducing branch loading on the root feeders.

For each dispersion level considered, the following graphics provide the probability for each line of the network to be overloaded as a function of the penetration level:

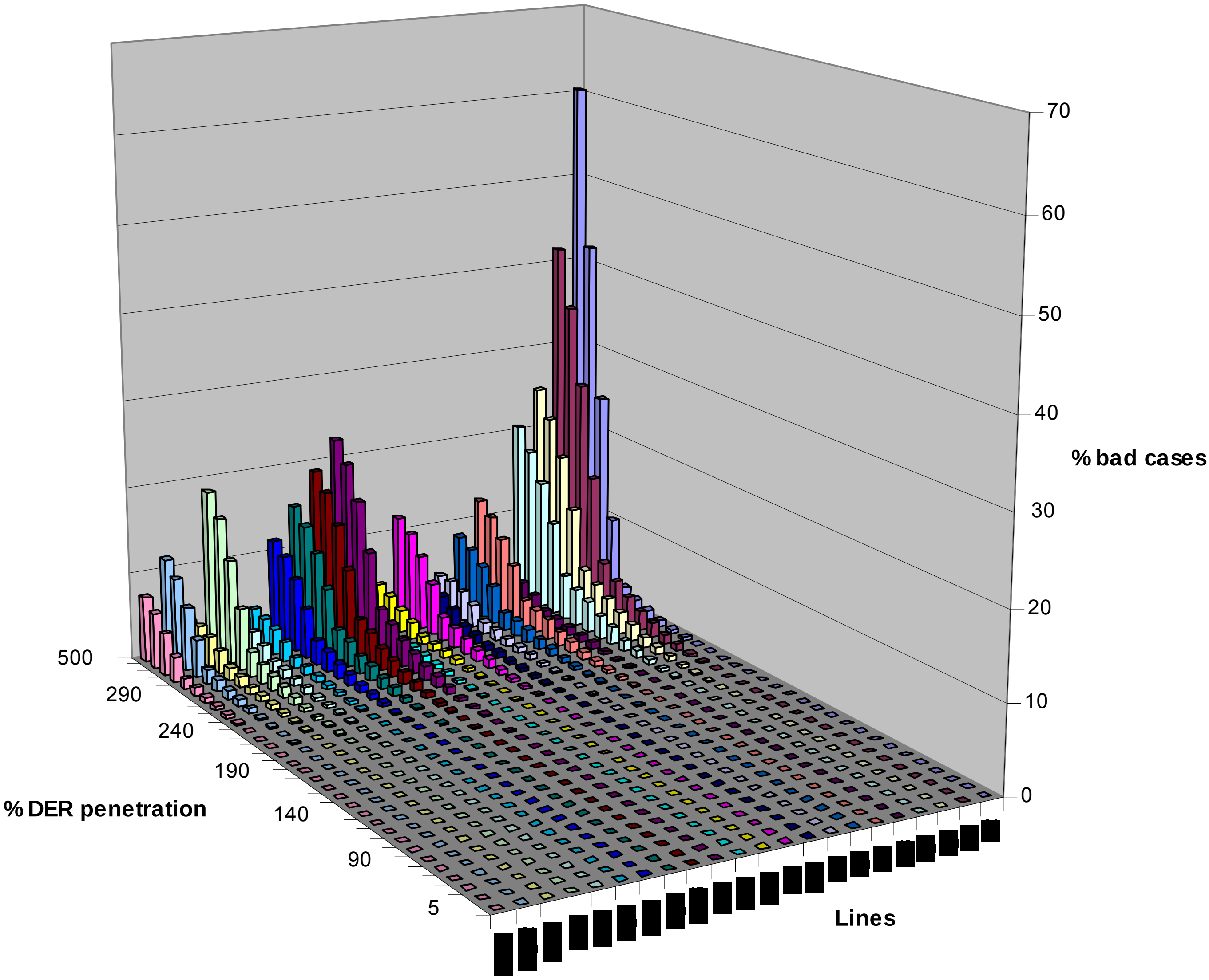

Figure 5-11 Line overloads - CHP (Dispersion level 1)

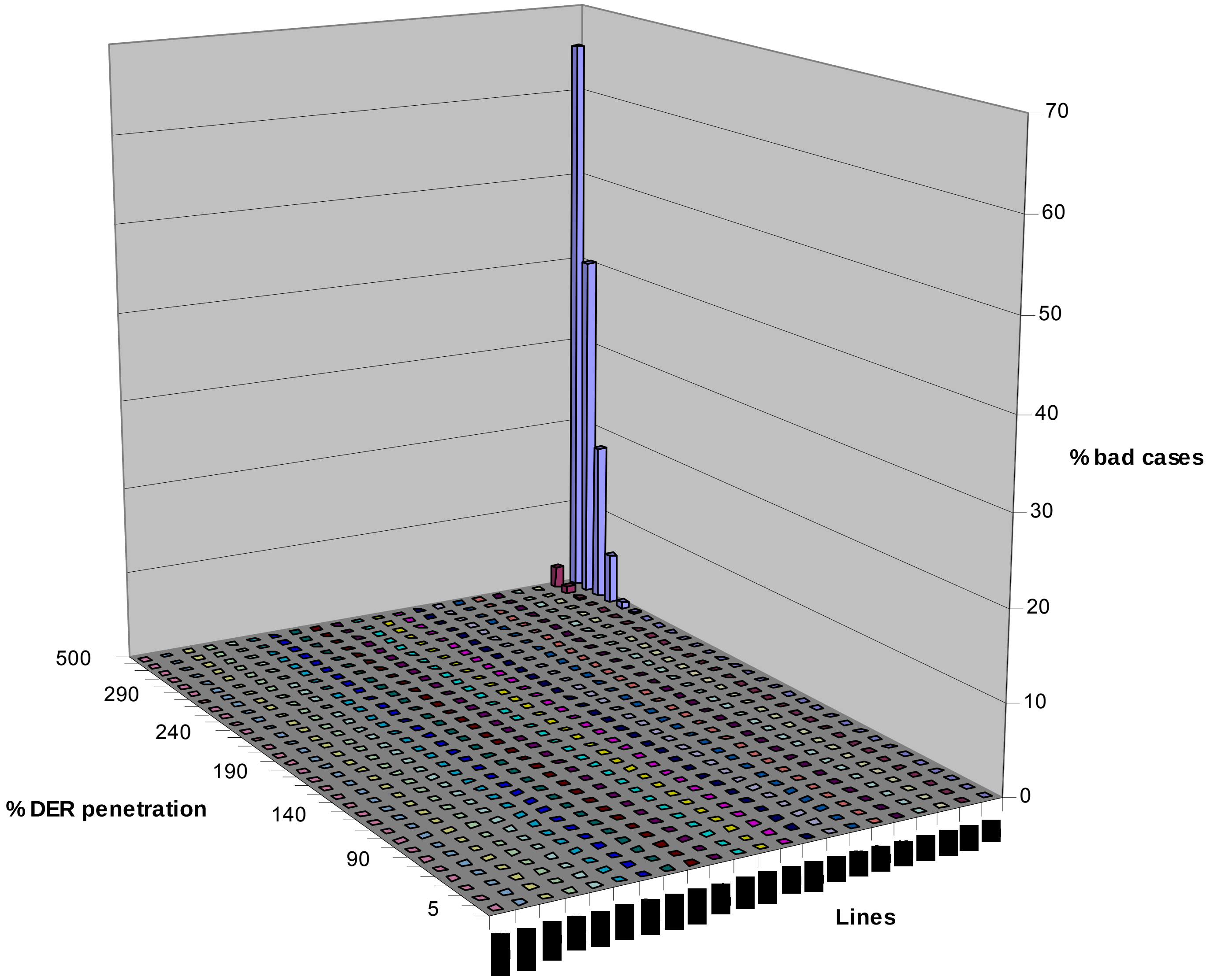

Figure 5-12 Line overloads - CHP (Dispersion level 12)

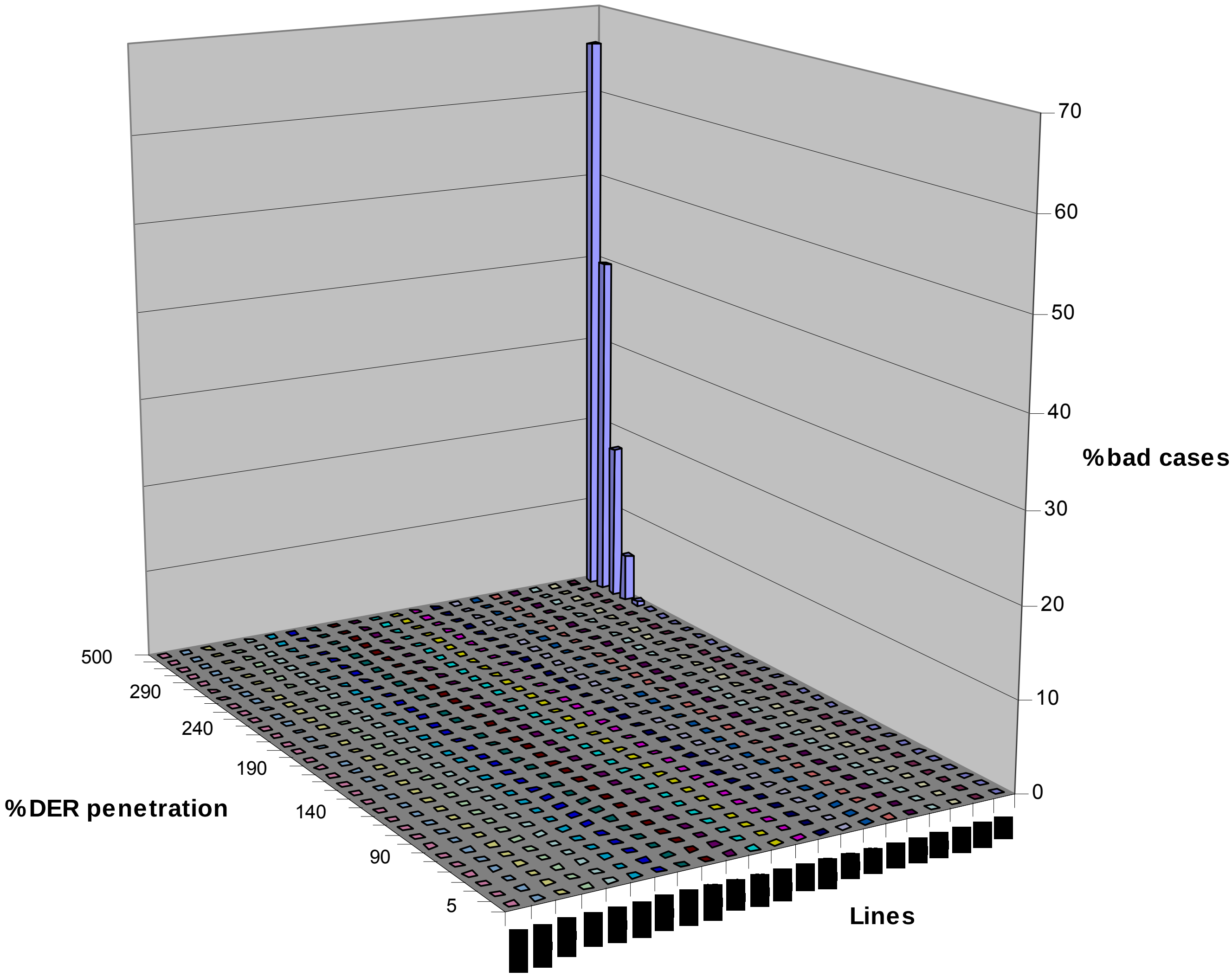

Figure 5-13 Line overloads - CHP (Dispersion level 23)

Looking at Figure 5-11 it can be seen that there are no overloaded lines until the 170% of penetration. After this point, the upstream lines are the first in becoming overloaded and their overload probability increases when the penetration level increases.

It can be seen too, that the overload probability of line 2-3 is bigger than the probability of line 2-4 because its radial feeder is composed of more buses and therefore the probability to have a distributed generator is bigger.

Besides, it can be observed that the overload probabilities of feeder end branches are very small because the only way of overloading them is placing a distributed generator behind them producing a power output bigger than their ratings and the probability of occurrence of this situation is not very high.

If we look at Figure 5-12 and Figure 5-13 we can see that the behaviour of the system is very similar in both cases. If we compare these results with the obtained for dispersion level 1, we can conclude that the bigger the dispersion level is, the smaller the amount of overloaded lines is. This occurs because the generated power is more uniformly distributed along the buses and therefore the power flows of the lines are smaller for the same DER penetration.

It can be seen too, that the most limiting line when introducing DER is the 1-2 because it is placed upstream and consequently its power flow is bigger than the others.

5.3.2.5.2. Voltage results

Figure 5-14 shows the voltage bad cases probability obtained for this case study:

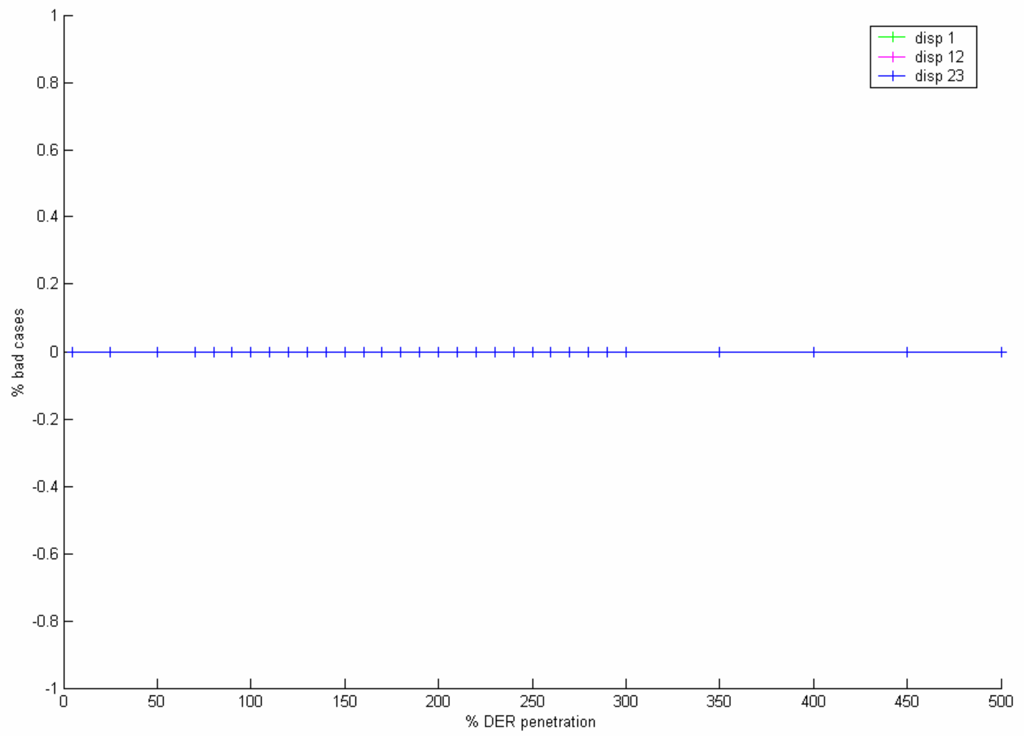

Figure 5-14 Voltage results of CHP penetration

It can be seen that the voltage value never exceeds its limit for the considered dispersion levels. This is due to the small resistances and lengths of the lines that make the system have very small voltage drops. As it was seen in Figure 5-2, the maximum voltage drop of the base case is 0.5%. If it is supposed that the acceptable voltage limit is ±5%, it would be necessary a penetration level near the 1500% to exceed it. For this reason, it can be concluded that the ratings of the lines are more limiting than the voltage magnitude when introducing DER for low values of the penetration level.

5.3.3. Case 2: Wind turbines

Due to environmental reasons and to promotion mechanism to increase renewable generation, wind turbine technology is expected to grow notably in the next years. In this case study wind turbines integration has been analysed.

Wind turbines represent an example of non controllable generation in contrast to the CHP units where market prices guide generation outputs.

5.3.3.1. Load modelling

Load modelling is the same as in the previous case study.

5.3.3.2. DER modelling

Generator output curves are obtained with the following procedure:

a) Define a wind speed curve

Take a historical wind speed curve data of a winter day. Wind speed measurements of Valkenburg in the Netherlands have been considered [9]. It has been chosen the 2002/02/19 day whose data is given in Table 5-5:

Time	Wind speed (m/s)
1	9,2
2	9,9
3	11
4	11
5	11,3
6	12,3
7	13,3
8	14,3
9	14,3
10	13,3
11	10,5
12	9,2
13	9,2
14	9,5
15	7,2
16	7,2
17	5,1
18	3,3
19	3,5
20	5,5
21	7,7
22	11
23	12,1
24	13,2

Table 5-5 Wind speed curve

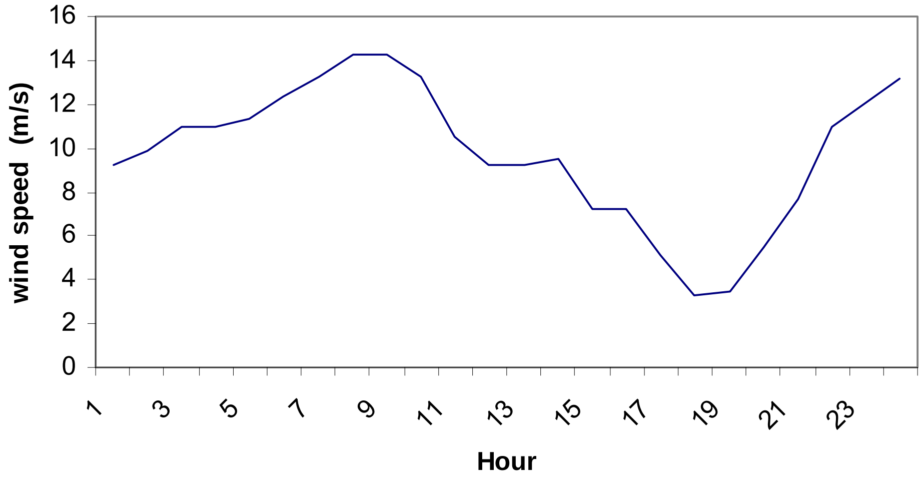

Figure 5-15 Wind speed curve

b) Model wind speed uncertainty

There are two common wind distributions used to make energy calculations for wind turbines: the Weibull distribution and a variant of the Weibull called the Rayleigh distribution that is thought to be more accurate at sites with high average wind speed [7]. In this work, the last one has been considered.

The general formula for the probability density function is:

$$f(x) = \frac{x}{\sigma^2} e^{\frac{-x^2}{2\sigma}}$$

where

σ: mean

The graphical representation [6] is given in Figure 5-16:

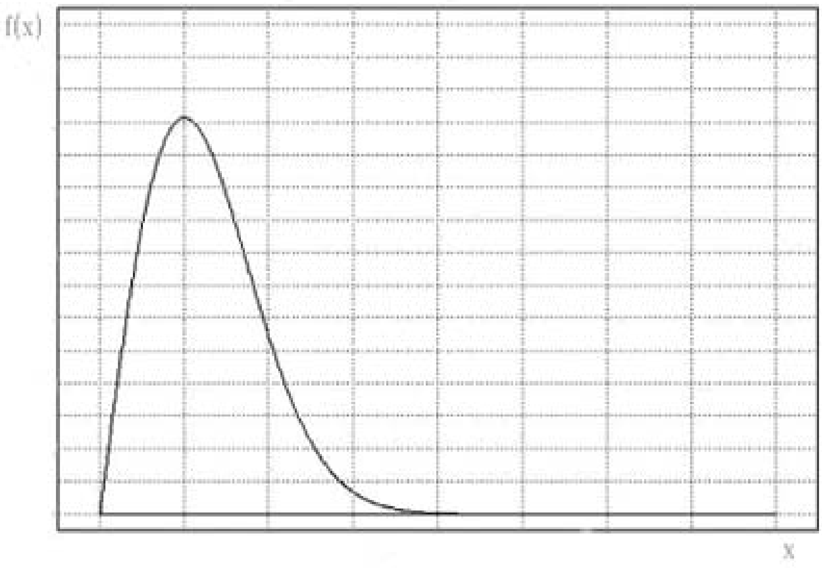

Figure 5-16 Rayleigh distribution

The stochastic nature of wind speed has been modelled generating a random number with a Rayleigh's distribution with mean equal to the average speed of wind.

c) Obtain power outputs

With the hourly value of wind speed, the output power generated by wind turbines is estimated using manufacturer's power curves. These curves represent the power output as a function of the wind speed and they can be approximated to linear functions:

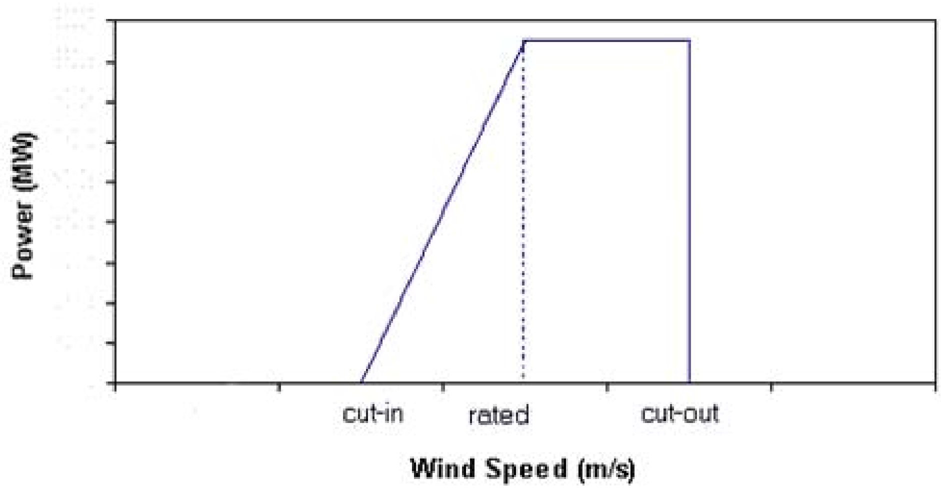

Figure 5-17 Wind Speed (m/s)

Where:

- Cut-in wind speed: it is the wind speed at which the turbine begins to produce power.
- Rated: it is the wind speed at which the turbine produces its maximum performance.
- Cut out wind speed: it is the wind speed at which the turbine is shut down to protect it from damage.

These curves have different values of the previous parameters for each machine because they depend on the power ranges and the manufacturer. Anyway, they are usually very similar, so it has been considered that they all take the following values irrespectively from the wind generator size:

- cut-in wind speed: 3 m/s.
- rated wind speed: 13 m/s.
- cut-out wind speed: 21 m/s.

The power obtained from the DER penetration level represents the rated power:

$$\%\text{DER penetration} = \frac{\text{rated power} \cdot \text{number of DER}}{S_{max}} \cdot 100 \rightarrow$$

$$\text{rated power} = \frac{\%\text{ DER penetration} \cdot \text{S}_{max}}{\text{number of DER} \cdot 100}$$

5.3.3.3. Analysed scenarios

Three different dispersion levels are considered: 21.79% (5 DER), 52% (12 DER) and 100% (23 DER).

It has not been studied the integration of only one distributed generator as in the previous case because wind turbines that provide so much power do not exist. Nowadays, the maximum power output of the existing wind turbines is 2 MVA which is not enough to provide the required generation for relatively high penetration levels.

It has to be noted that it is not possible the real implementation of all the scenarios studied due to the previous reason but this fact has been obviated in order to carry out a theoretical analysis. For example, if we consider a dispersion level of 5 and a penetration level of 500, and taking into account that the peak load demand of the system is 12.9 MVA, each distributed generator should provide 12.9 MVA while the bigger units commercially available only reach up to 2MVA. Another example of this issue occurs for a dispersion level of 12 and a penetration level of 300 in which each unit should generate 3.2 MVA.

For each dispersion level, 31 penetration levels between 5 and 500% are studied.

5.3.3.4. Solving process

The process of resolution is the same as in the previous case study. There is only a small difference in the required input data because it is necessary to provide the wind speed curve instead of the energy price curve. This curve gives the hourly potential wind speed in m/s.

5.3.3.5. Results

5.3.3.5.1. Line loading results

Table 5-6 shows the bad cases probabilities obtained for 21.79% (5 DER), 52% (12 DER) and 100% (23 DER) dispersion levels respectively. These results have been graphically represented in the Figure 5-18:

%Penetration	Dispersion (number of DER)		
	5	12	23
5	0	0	0
25	0	0	0
50	0	0	0
70	0	0	0
80	0	0	0
90	0	0	0
100	0	0	0
110	0	0	0
120	0	0	0
130	0	0	0
140	0	0	0
150	0	0	0
160	0	0	0
170	0	0	0
180	0	0	0
190	0,017	0	0
200	0,071	0,004	0
210	0,200	0,000	0
220	0,708	0,029	0
230	1,471	0,096	0
240	2,567	0,246	0,008
250	3,821	0,579	0,063
260	5,829	1,354	0,196
270	8,271	2,138	0,588
280	10,667	3,658	1,283
290	12,800	5,358	2,325
300	16,167	7,958	4,288
350	32,179	25,458	21,738
400	46,600	44,492	44,988
450	57,888	60,317	63,754
500	66,000	70,792	75,146

Table 5-6 Results of wind turbines penetration

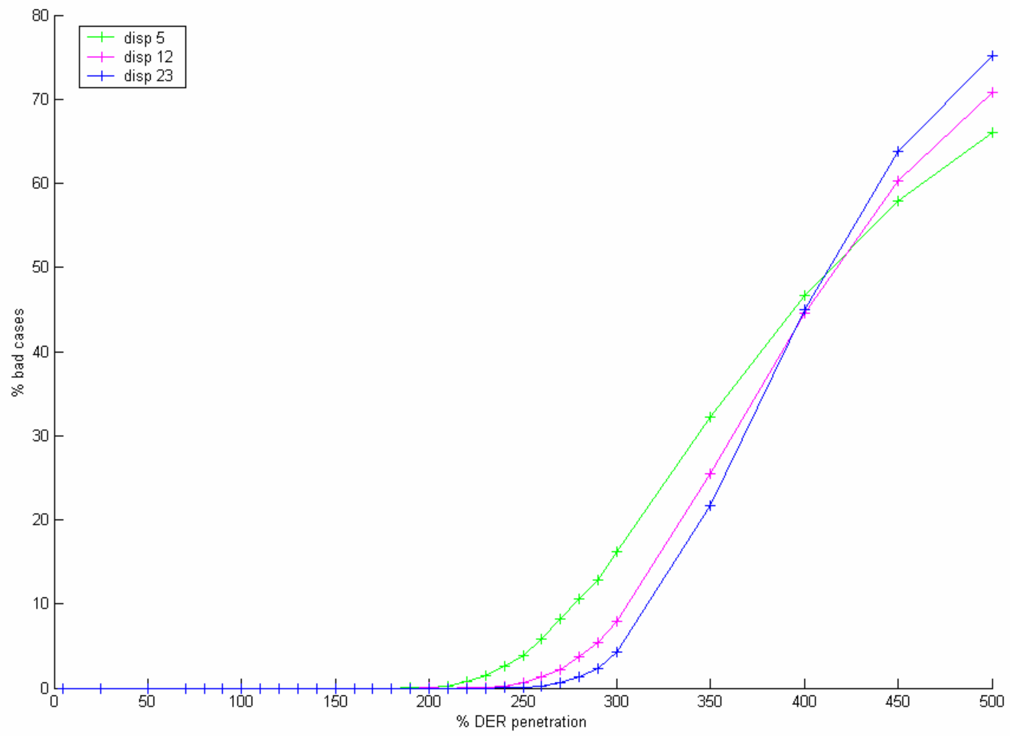

Figure 5-18 Results of wind turbines penetration

Looking at Figure 5-18 it can be seen that the probability of bad cases increases as the penetration level increases. Besides the obtained results for all dispersion levels are very similar because the lines that exceed their limits are always the same and they are the upstream branches such as 1-2, 2-3…

The penetration levels for which the curves start to have values different from zero increases with the dispersion level because of the bigger distribution of the generation along the buses.

The bad cases probabilities obtained are bigger than the corresponding to the CHP units. This happens due to the randomness of the power outputs of the generators defined in this case study while in the CPH case power outputs follow a similar shape to load profiles.

For each dispersion level considered, the following graphics provide the probability for each line of the network to be overloaded as a function of the penetration level:

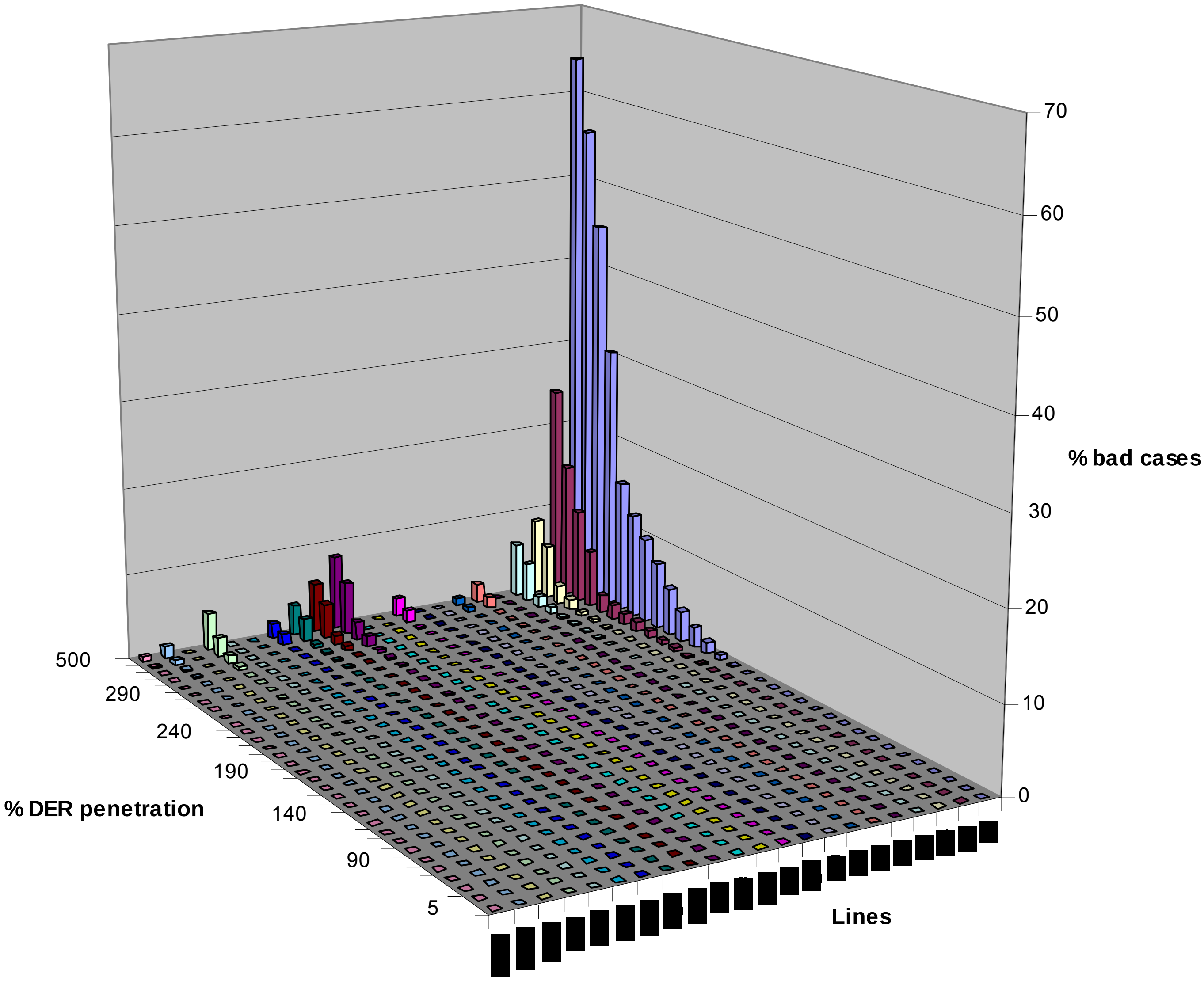

Figure 5-19 Line overloads - Wind turbines (Dispersion level 5)

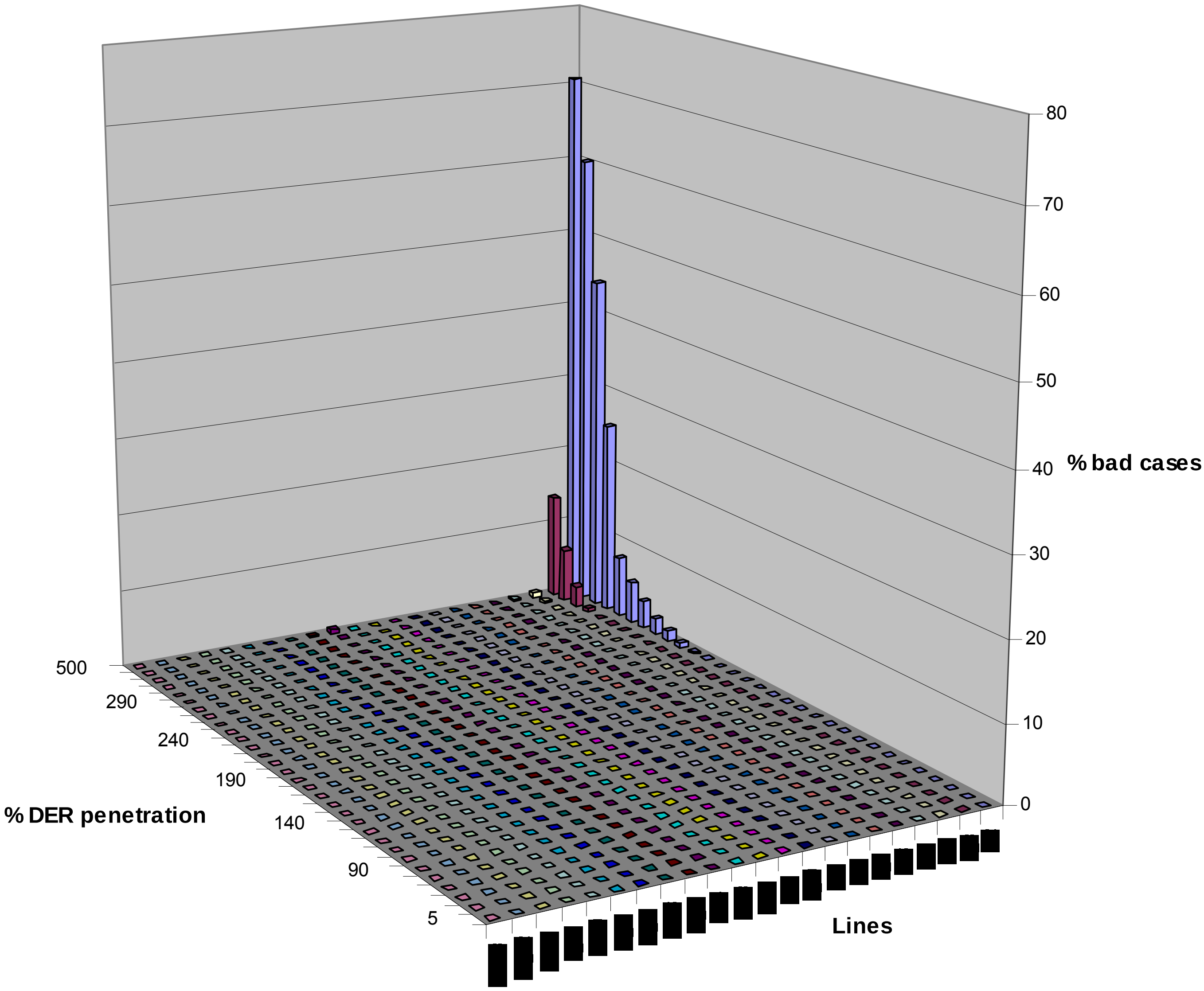

Figure 5-20 Line overloads - Wind turbines (Dispersion level 12)

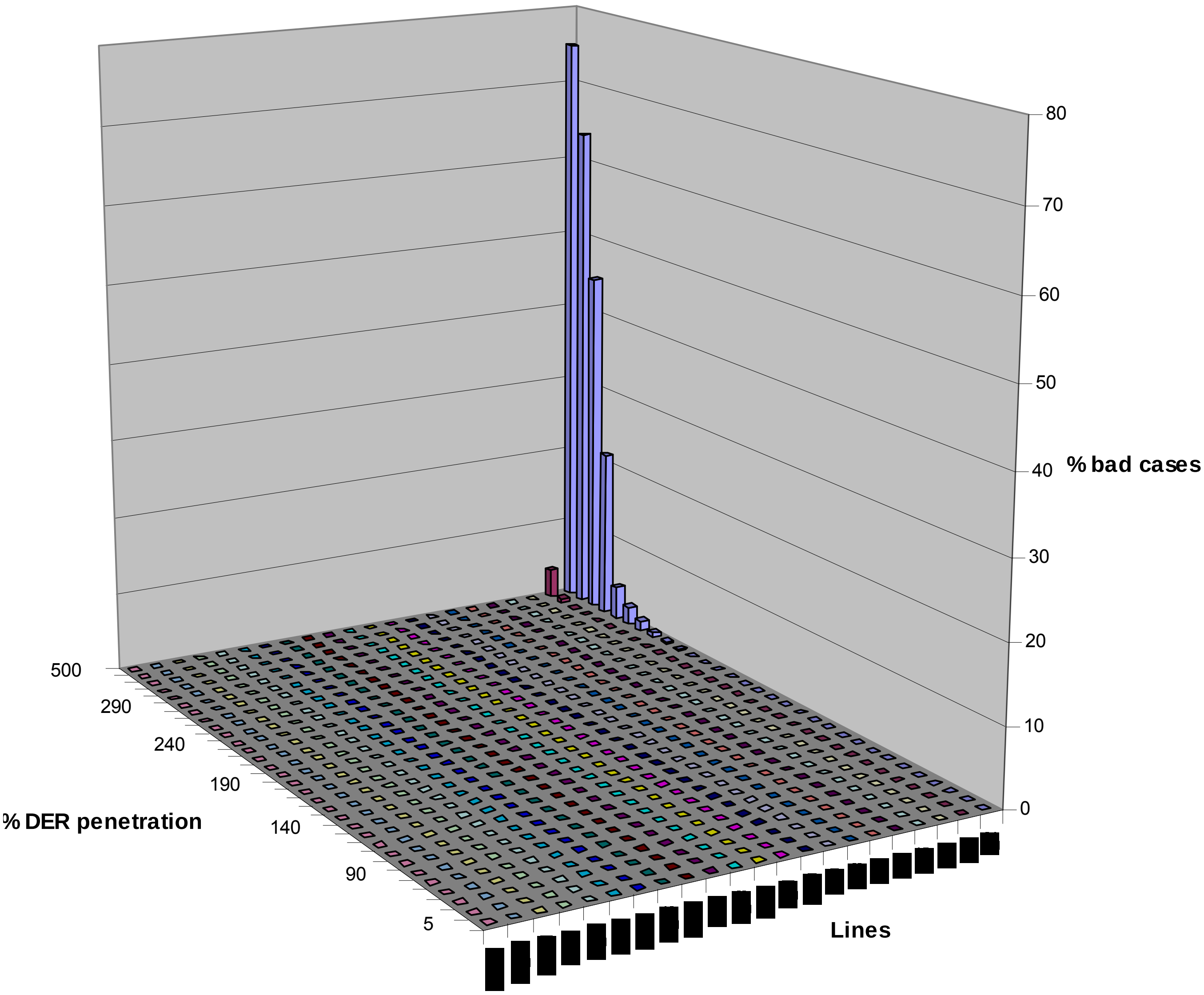

Figure 5-21 Line overloads - Wind turbines (Dispersion level 23)

Looking at Figure 5-19, Figure 5-20 and Figure 5-21 it can be concluded that the behaviour of the system for the different dispersion levels is very similar.

The most important difference between them is that the required penetration level to overload the lines increases as the number of distributed generators increases. This occurs because the generated power is more uniformly distributed along the buses and therefore the power flows of the lines are smaller. Besides, the upstream branches are always the most limiting ones.

The results are very similar to the results obtained in the previous case study (CHP).

5.3.3.5.2. Voltage results

Figure 5-22 shows the voltage bad cases probability obtained for this case study:

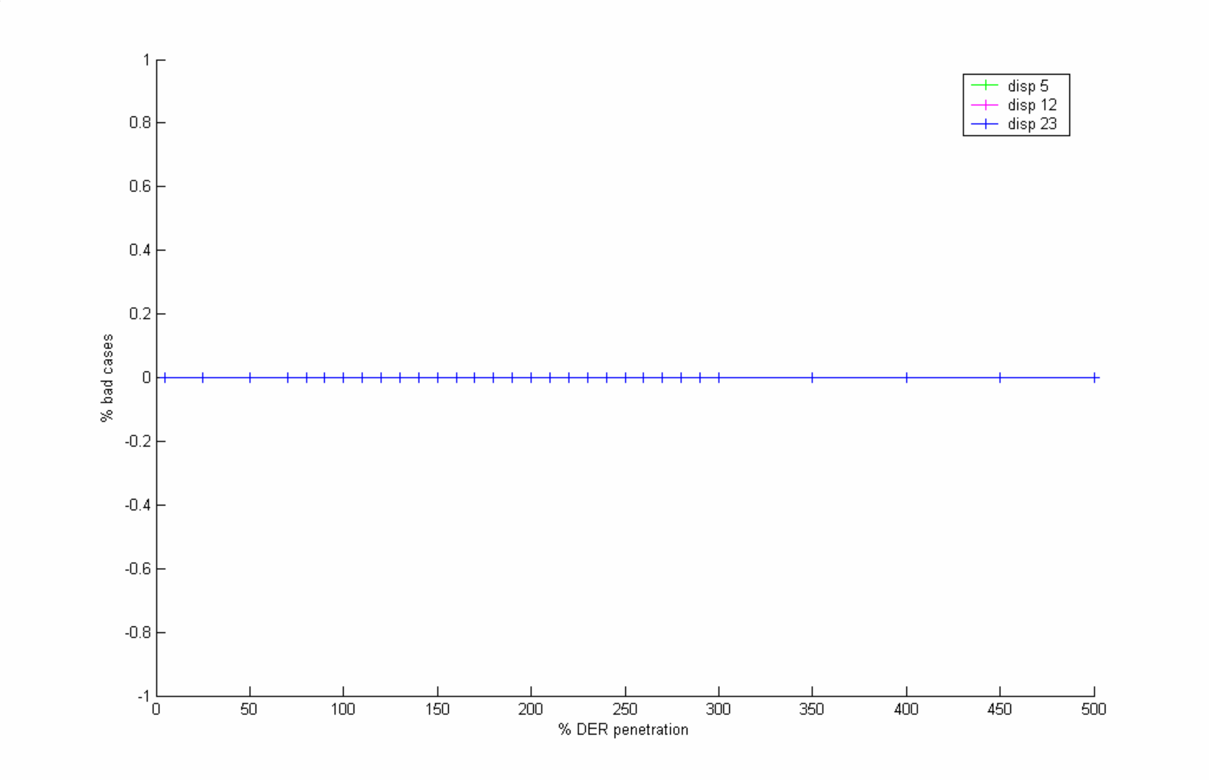

Figure 5-22 Voltage results of wind turbines penetration

The same as in the previous case study, the voltage value never exceeds its limit for the dispersion levels studied. This is due to the small resistances and lengths of the lines that make the system have very small voltage drops. So, it can be concluded that the ratings of the lines are more limiting than the voltage magnitude for low values of the penetration level.

5.4. Conclusions

In this work, a study of line loading and voltage profile from a stochastic point of view has been developed. Five hundred Monte Carlo simulations have been performed in order to study the impact of DER on the previous parameters.

For this purpose, two case studies characterised by different type of distributed generators have been considered: CHP and Wind turbines.

In the first case the power outputs provided by the generators are obtained as a function of the energy price at the market. In the second one, they depend on the wind speed curve.

If we compare the line loading results of both case studies, it can be concluded that the probability of overloads increases as the penetration level increases.

The bigger difference between both cases is on the overload probabilities. The obtained values for wind turbines are bigger than the corresponding to CHP. This occurs because of the high randomness of the power outputs of the generators defined in that case study.

It has been seen too that the voltage values are always between limits. This is due to the configuration of the network that is composed of lines of small resistances and lengths that make it have small voltage drops.

So, it can be concluded that the ratings of the lines are more limiting than the voltage magnitude for low values of the penetration level.

5.5. References

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6. Case study: Dynamic behaviour of hybrid power system on an isolated network

6.1. Abstract

A hybrid power system on Les Saintes island network has been modelled and simulated with EMTP-RV software in islanded mode. Les Saintes consists of 2 islands, Terre-de-Bas and Terre-de-Haut, that form a single network due to a sub-sea cable. This hybrid power system is composed of a 20 kV network with a 2.4 MW wind farm (8 asynchronous wind turbines), a 1.6 MW diesel generator, a storage system (represented by a power injector) and loads (0.76 to 1.5 MW).

The dynamic behaviour has been investigated in 3 different configurations: diesel power system; diesel and wind turbines power system; diesel and wind farm system with a storage device (power injector). Various events were considered, such as generation connection or disconnection, short circuits (1, 2 or 3-phase ; at generation connecting point or on the MV network), load variations (in particular loss of the sub-sea cable connecting Terre-de-Bas and Terre-de-Haut)…

With the diesel / wind power system, the 2 main issues are load/generation balance and behaviour on a short circuit. Concerning the first issue, the transient imbalances between load and generation are correctly compensated by the high-performance diesel genset, provided that the level of wind penetration is compatible with the minimum acceptable power output of the diesel, even during wind or load variations. Concerning the second issue, the system remains stable if the diesel unit can cover the reactive power requested by the asynchronous wind turbines after the short circuit. With the configuration studied, the wind turbines lose stability in case of a 500 ms 3-phase short circuit at the diesel unit terminal or on a MV node. It should be noted that they remain stable in case of a 500 ms 3-phase fault occurring at the wind farm connecting point.

With the diesel / storage / wind power system, the aim of the simulation cases chosen is to assess if the storage system enables to cope with a loss of a generator, either the wind farm or the diesel unit. With the hypothesis considered, the situation is back to normal operation after an acceptable transient state, which depends strongly on the voltage and frequency control of the diesel unit and the storage system.

This study must be considered as a preliminary one and further investigation would be necessary to implement such a hybrid power system.

6.2. Executive summary

Les Saintes are part of La Guadeloupe archipelago, a French oversea department. These 2 little islands, Terre-de-Bas and Terre-de-Haut, are generally connected to Basse-Terre, a bigger island. Nevertheless, if the sub-sea cable is out of order, they will be operated in an islanded mode. That is why they are considered as a case study in Microgrids project.

Nevertheless, the present available generation mix on the islands consists only of emergency diesel units, which are not supposed to run all the year long. Operating Les Saintes as a microgrid would require replacing them. That is the hypothesis that is used in this study.

The case study considers a hybrid power system composed of Les Saintes 20 kV network with a 2.4 MW wind farm (8 asynchronous wind turbines), a 1.6 MW diesel generator, a storage system (represented as a power injector) and loads (0.76 to 1.5 MW). It has been modelled in isolated mode and simulated with EMTP-RV software. The diesel generator was equipped with high-performance controls (governor and voltage control).

This report describes the model the generators considered and analyses their behaviour under various disturbances such as:

- connection/disconnection of diesel,
- disconnection of loads,
- connection/disconnection of wind turbines,
- changes of wind power, gusts,
- 1, 2 or 3 phase short-circuit,
- shutdown of wind turbine generators,
- shutdown of diesel generator… .

The dynamic behaviour for three configurations of the power system has been investigated:

- diesel power system,
- diesel and wind turbines power system,
- diesel and wind turbines with storage device (power injector).

6.2.1. Main results and conclusions

6.2.1.1. Diesel power system

In all cases studied, the diesel is able to recover its normal operation after the clearing of the disturbances (short-circuits, disconnection of loads…).

The diesel generator maintains the balance of active and reactive power on the network thanks to its governor and voltage regulator.

6.2.1.2. Wind farm and diesel system power

The wind/diesel power system is stable in response to different types of disturbances: connection/disconnection of diesel, connection/disconnection of wind turbines, gusts, 1, 2 or 3-phase short-circuits. It recovers its normal operation after clearing of experimental disturbances. The diesel generator remains synchronized with the network.

- Concerning load/generation balance, the transient imbalances between load and generation are correctly compensated by the diesel genset, provided that the level of wind penetration is compatible with the minimum acceptable power output of the diesel, even during wind or load variations. Difficulties may occur when wind power increases due to wind speed variations, or when the load decreases. It should be highlighted that the simulation results do not take protection devices into account, and focuses on the stability of the generation means. With this approach, it appears that the wind turbine power can reach and even exceed by a few kW the power required by the loads. In this case, the diesel generator becomes a synchronous motor and ensures the voltage and frequency regulation (wind power tries to drive the diesel generator). It should be checked whether it would be temporarily acceptable, and which actions should be taken to bring the system back to a normal situation. The case of a sudden load disconnection (loss of the sub-sea cable between Terre-de-Bas and Terre-de-Haut) is the most constraining one concerning this issue. In this case, as the wind output power exceeds the power absorbed by the suddenly reduced loads, the diesel loses control of its rotor speed. In fact, the excess energy from the wind power tries to drive diesel engine which tends to accelerate the rotor speed too much.
- Concerning the behaviour on a short circuit, the system remain stable if the diesel unit can cover the reactive power required by the asynchronous wind turbines after the short circuit. With the configuration studied, the wind turbines lose stability in case of a 500 ms 3-phase short circuit at the Diesel unit or on a MV node. It should be noted that they remain stable in case of such a fault at the wind farm level, as this case is more favourable to the ability of the Diesel unit to generate reactive power.

To conclude, the wind/diesel power system is dynamically stable, even in extreme operation conditions (for instance gusts, high wind power penetration…), except in 2 cases: three phase short-circuit of duration 500 ms or oversized wind turbines in comparison to the loads, making the diesel operate as a motor (negative power output of diesel). In all the other situations or cases studied, the diesel is able to follow the variations of local load and wind generation. It should be reminded that protections are not taken into account in these case studies.

6.2.1.3. Wind farm and diesel system with energy storage system (power injector)

In this configuration, the objective of the study was to analyse the behaviour of the wind-diesel hybrid system if a storage system is available to compensate instantaneously the loss of a generation mean (wind farm or diesel unit). In the cases studied, the storage device (power injector) compensates correctly the lack of power due to diesel or wind turbines shutdown (active and reactive power…), and the global behaviour of the system during the transient is satisfactory (the system remains stable).

Note: in the simulation, the central controller, that would coordinate the operation of the generation units (wind turbines and diesel) and of the storage system, is not represented.

6.2.2. Comments on the results

Globally, the behaviour of this microgrid based on Les Saintes is satisfactory. The governor and voltage control of the diesel unit play a mayor role concerning this issue. It is even strengthened by the fact that the diesel unit is much bigger than the load, so that its control capabilities are rather large in comparison with the constraints. The difficulty associated with this size is the diesel unit minimal acceptable active power output that limits wind power penetration. When the diesel unit is disconnected, the storage device (represented by a power injector) plays this role.

Nevertheless, it should be reminded that several aspects have not been taken into account in this study. First, the protection devices are not represented. In particular, in some cases, the diesel unit behave temporarily as a synchronous motor. It should be checked whether such a behaviour is acceptable or if there are protection devices, which disconnect automatically the generation unit in this case. Secondly, power quality aspects are not considered in this study.

We would also like to remind that the case studies are based on Les Saintes network, but do not correspond exactly to the present power system, in particular concerning the generation means.

6.2.3. Recommendations for further studies

Some limitations highlighted by the present study could be examined with the following guidelines:

- The diesel unit minimal acceptable active power output : this technical constraint is reached in several cases and limits the wind power penetration. Another scenario should be considered with several smaller diesel units that would also require a central controller to manage the different units.
- The storage system representation: the simplified model as a power injector does not allow undertaking a study of transient responses to short-circuits. A more thorough study would require modeling the energy storage system in detail (e.g. device storage, inverter and control).

Moreover, complementary points should be studied concerning the storage issues. In the context of Les Saintes, when the weather is windy, the storage system would give the frequency reference for the asynchronous wind turbines, and perform the voltage and frequency control, so that all the thermal units could be off. Its size in power (MVA) and energy (MWh) should be adapted to the following specifications:

- its control capability should be adapted to the normal load and wind variations;
- when the wind farm output decreases suddenly due to the wind conditions, it should be able to feed the loads until a thermal unit could be connected;
- when the wind turbines disconnect because of a fault, it should be able to feed the loads until the wind turbine are back to normal operation after the fault clearance;
- it could solve partly the difficulties linked with the diesel unit minimal acceptable active power output, as it could store active power to support the diesel generation.

Lastly, it would be interesting to investigate power quality aspects and economic aspects, in particular concerning the storage system.

6.2.4. Keywords

Renewable energy, Wind energy, Wind farm, Diesel energy, Energy storage, Stability, Simulation with EMTP-RV, Induction machine, Hybrid system, Dynamic system of energy, Transient fault response, Unsymmetrical faults

6.3. Introduction and study objectives

Microgrids are part of a European project, which aims at developing the concepts and the tools allowing optimised operation of network, with decentralized production. The objective of this Work Package (WP) is to assess the performance of systems on study cases. A hybrid power system with a wind farm, a diesel genset and storage devices has been modelled with EMTP-RV (ElectroMagnetic Transients Program Revised Version).

Different types of disturbances:

- changes of wind power,
- shutdown of diesel,
- shutdown of wind farm,
- short-circuits, …

have been simulated on the isolated network in order to analyse the dynamic behaviour of hybrid power systems.

6.4. Description of power system

The purpose of this section is to describe the network of "Les Saintes" islands, particularly its modelling and data.

In normal operation, the network of "Les Saintes" is connected to the power system of "Guadeloupe" island (200 MW at peak load and 120 MW at light load) by a submarine cable and HV/MV in parallel transformers. Thus, the power is imported from the main island of the Guadeloupe archipelago to Ile Les Saintes. In case of disconnection of submarine cable, the island "Les Saintes" operates in isolated mode (autonomous energy system) [1].

The power system network studied is composed with:

- lines and cables,
- decentralized production (wind farm and diesel genset),
- storage system (power injector).

Some of the characteristics of "Les Saintes" network are:

- 1.5 MW and 0.55 MVAR (peak load),
- 0.76 MW and 0.26 MVAR (light load),
- 1.1 MW and 0.4 MVAR (average assumption).

Generators (generation sources):

- wind farm (8 wind turbines: 8*300 kW rated active power with 20/ms wind speed - connected to the network between T-Felicite and Z-Labas),
- diesel (1.6 MW rated active power - connected to Centrale),
- power injector (connected to wind turbine terminals or wind farm terminals).

So, three types of power generation: wind, diesel and power injector can supply the loads at Les Saintes.

6.4.1. Network

The distribution network of "Les Saintes" is composed of nodes: Low Voltage (LV: 400 V), Medium Voltage (MV: 20 kV) and High Voltage (HV: 63 kV). The network is set out in the following figure:

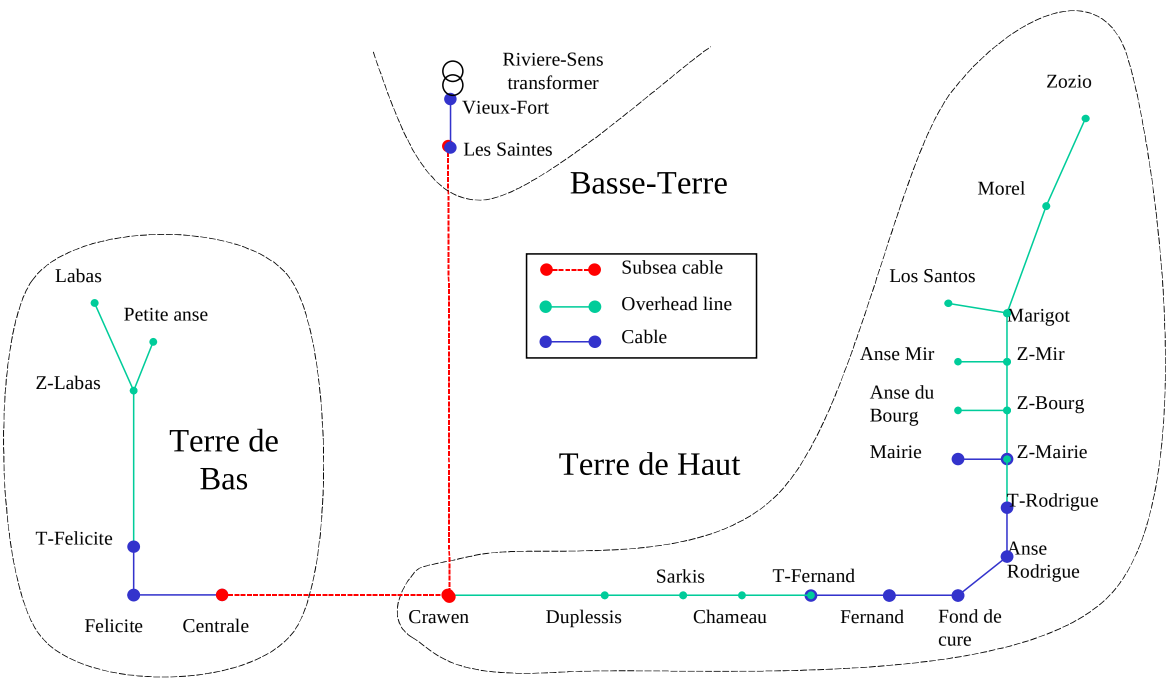

Figure 6.4.1-1: One-line diagram of "Les Saintes"

6.4.2. Substations and nodes

The network is divided into 3 sub-networks : Terre de Bas, Basse-Terre and Terre de Haut. There are 18 substations : Centrale, Labas, Petite Anse, Felicite (substations of Terre de Bas), Mairie, Fond de Cure, Fernand, Anse Rodrigue, Anse Bourg, Anse Mir, Marigot, Los Santos, Morel, Zozio, Sarki, Crawen (connexion point to island Terre de Haut) Duplessis, Chameau (substation of Terre de Haut) and Vieux Fort (substation Basse de Terre) (see

Figure 6.4.1-1). References [1] and [2] give more details on the components and their characteristics.

6.4.3. Lines and cables

The network is composed of a submarine cable (sub-sea) and underground cable (cable) or overhead line (OHL). The modelling lines and cables are based on the generic multiphase PI branch (Figure 6.4.3-1). The cable segments are modelled as resistive R, inductive L and capacitive C (π-links model). The lengths and impedances of the cables and lines are given in the document [2].

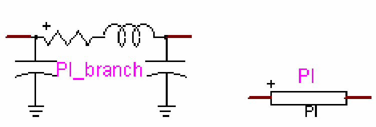

Figure 6.4.3-1: PI line 3 phase (model EMTP-RV)

6.4.4. Load modelling

The load models are traditionally classified into two categories: static models and dynamic models. In our study, static loads are used. They are modelled by a RLC circuit (active power $P \geq 0$, reactive power $Q \geq 0$ or ≤ 0, Voltage $V > 0$). The loads are directly connected to 20 kV substations.

6.4.5. Wind turbine generator

The system of conversion of wind energy transforms the energy present in the blown wind into electricity. It is an induction generator which converts the power captured by the wind turbine into electrical power. Electrical power is transmitted to the grid by the stator winding. The pitch angle is controlled in order to limit the generator power output to its nominal value in case of high wind speeds.

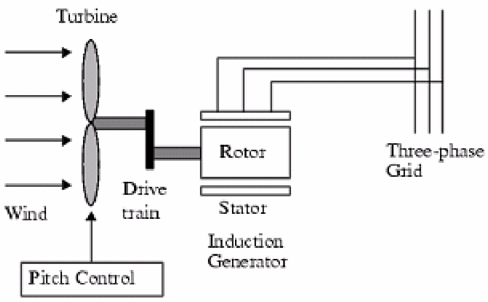

Figure 6.4.5-1: Physical diagram of wind turbine

6.4.5.1. Wind turbine model

A wind turbine provides the torque to the generator through a mechanical and electrical system. The wind power depends on the wind speed and the angular velocity of the rotor.

Wind turbine aerodynamic characteristics [3]:

- cut-in wind speed (minimal wind speed) v_d= 4.5 m/s,
- rated wind speed (rated wind speed) v_n= 20 m/s,
- cut-out wind speed (maximal wind speed) v_m= 25 m/s.

The modelling of the wind turbine and pitch control is presented in appendix 1.

6.4.5.2. Wind generator model

The electrical generator transforms mechanical energy into electrical energy. In this study, the wind generator is based on an induction generator (classical asynchronous machine). The asynchronous generator (wind turbine) is connected directly to the grid (LV network). The data is drawn from [3] and [4].

- Rated apparent power S_n= 357 kVA
- Rated active power P_n= 300 kW,
- Rated voltage U_n= 400 V
- Rated power factor Cos φ = 0.84 (at full load)
- Rotor speed Ns= 1500 tr/mn,
- Frequency f= 50 Hz, number of poles p= 4,
- Rated slip g= 0.5%, N_n= 1507.5 tr/mn.

NB: the wind farm is equipped with 8 wind turbines, 300 kW nominal power each, i.e. the nominal wind power installed capacity reaches 2.4 MW.

The electrical parameters of the asynchronous generator are given in Table 6.4.5-1, [1], [4].

Table 6.4.5-1: Data: the squirrel cage induction (MAS)

Rotor type	Single squirrel cage	d-axis linkage inductance Lmd	3.13 pu
Rated power	300 kW	q-axis linkage inductance Lmq	3.1.3 pu

Stator winding connection	Wye grounded
Nominal slip	0.5%
Stator resistance Rs	0.0074 pu
Stator leakage inductance Lls	0.107 pu

Rotor resistance Rr1	0.0063 pu
Rotor leakage inductance Lir1	0.14 pu
Moment of inertia J [5]	50 kg.m^2
Inertia constant H(s) $H = \frac{1}{2 * S_n} * J\omega^2$	2.5 s

Note: the shaft system includes 1 mass (single mass). So, the mechanical model or equation is: $J * \frac{d\omega_m}{dt} + D * \omega_m = T_e - T_{turbine}$. with:

- J: moment of inertia of rotating turbine-generator mass,
- ω_m: mechanical speed,
- D: damping coefficient for viscous and wind friction,
- $T_{turbine}$: torque input to turbine,
- T_e: electromagnetic torque of the generator.

6.4.5.3. Capacitor bank (compensating capacitors)

An asynchronous machine (generator) needs a reactive power when it is in operation (power factor of generator Cos φ < 1). Each asynchronous machine reactive power consumption is compensated by capacitor bank of 85 kVAR connected to Low Voltage (400 V) network (C= 4.8 mF - Wye coupled for a nominal power of P_n= 300 kW, wind speed= 20 m/s and with a power factor about 0.95).

6.4.5.4. Transformer grid connection (LV/MV: 400 V/21 000 V)

Wind turbines are connected to the MV (Medium Voltage) network through a step-up LV/MV transformer. The characteristics of the transformers are given in Table 6.4.5-2:

Table 6.4.5-2: Transformers LV/MV: Parameters [1] and [2]

Number of transformers	8
Rated power	315 kVA
Vector group (coupling)	Dyn11

Rated transformer ratio	52,5/1	
Coupling	Wye	
Winding resistance R	0.007 pu	

Rated voltage HV-side	21 kV	Winding inductance X	0.07 pu	
Rated voltage LV-side	400 V	Winding impedance on winding 1	0.9	

Note: in our study, the reactive power consumed by the transformer has been neglected.

6.4.6. Diesel genset

The data of the diesel generator and diesel-control (voltage and speed regulators) is presented in this section.

6.4.6.1. Diesel Genset

The diesel is modelled by a synchronous generator with electrical and mechanical characteristics as follows:

Table 6.4.6-1: Synchronous machine parameters (diesel genset) [typical values from literature]

Machine Type	Synchronous	d-axis transient reactance X'd	0.255 pu
Rated apparent power	2 MVA	q-axis transient reactance X'q	0.53 pu
Rated active power	1.6 MW	d-axis sub-transient reactance X''d	0.177 pu
Frequency	50 Hz	q-axis sub-transient reactance X''q	0.213 pu
Field current (no laod)	20 A	d-axis transient time constant (open) T'd0	6.09 s
Number of poles	4	q-axis transient time constant (open) T'q0	0.002 s
Nominal speed	1500 tr/min	d-axis sub-transient time constant (open) T''d0	0.05 s
Armature winding connection	Wye Grounded	q-axis sub-transient time constant (open) T''q0	0.1 s
Armature resistance Ra	0.002 pu	Inertia constant H	1 s
d-axis reactance Xd	1.06 pu	Moment of inertia J	112.5 kg.m^2
q-axis reactance Xq	0.6 pu		

Note: the shaft system includes 1 mass (j in kg.m^2: aggregate moment inertia turbine, generator and exciter).

6.4.6.2. Voltage and speed regulators

The diesel generator control, i.e. the speed and voltage regulators is provided by Armines [6], reference [7]. The exciter and automatic voltage regulator and speed control block diagram are shown in Figure 6.4.6-1 and Figure 6.4.6-2.

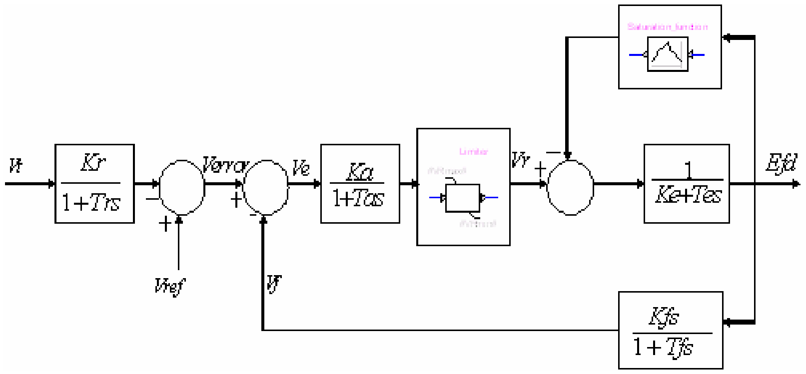

Figure 6.4.6-1: Exciter block diagram

The values of the parameters in the exciter are given in the following table:

Table 6.4.6-2: Input, output, parameters of Exciter and Automatic Regulator [6]

Field voltage Efd	output
Terminal Voltage Vt	input
Reference voltage Vref	input
Regulator voltage Vr	signal
Feedback Vf	signal
Control error Ve	signal
Gain of amplifier Ka	200
Gain of feedback Kf	0.038
Gain of regulator Kr	1

Gain of exciter Ke	-0.17
Time constant of amplifier Ta	0.06 s
Time constant of exciter Te	0.95 s
Time constant of regulator Tr	0 s
Time constant of feedback Tf	1 s
Regulator high limit Vrmax	6
Regulator low limit Vrmin	-6
Exciter high limit	10

The values of the parameters above result from literature [6], they have been adapted to the requirements of this study.

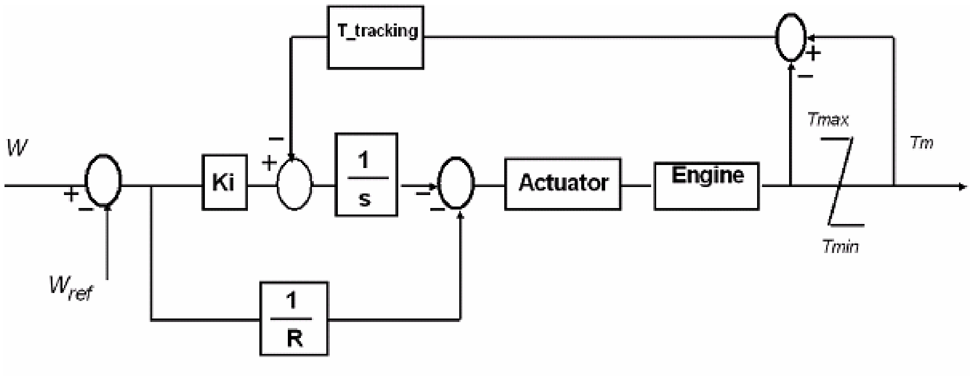

Figure 6.4.6-2: Governor block diagram

The parameters of the Governor block diagram are [6]:

- angular speed reference ω_{ref}= 157 rad/s,
- gain K_i= 41.5,
- gain constant 1/R= 0.0642,
- time constant actuator $T_{actuator}$= 0 s,
- time constant engine T_{engine}= 0.039 s,
- time constant tracking $T_{tracking}$= 10 s.

Symbols:

- T_m: mechanical power,
- T_{max}: mechanical power high limit,
- T_{min}: mechanical power low limit,
- ω: angular speed.

6.4.6.3. Transformer (LV/MV: 400V/21 000 V)

The diesel genset is connected to the MV network (20 kV) through a set-up transformer that has the following characteristics [1] and [2]:

Table 6.4.6-3: Transformers LV/MV parameters

Number of transformers	1	Nominal voltage MV	21 kV
Rated apparent power	2 MVA	Leakage impedance	6% Ucc
Nominal voltage LV	400 V		

6.4.7. Energy storage (Power injector)

As wind power is an intermittent energy source (wind power varies randomly), an energy storage system is required to obtain a high wind penetration and so to ensure supply obligation. In practice, energy is stored in different storage devices (e.g. batteries, flywheel, super capacitors…) and re-injected in the network later. The storage system allows to reduce diesel generator run times and consequently the fuel consumption of the diesel generator when wind power is available. In our study, the energy storage system is modelled as a power injector, because data and models (converters, storage devices…) are not available. So, the power, frequency and voltage on the network are ensured by the power injector. Reference [8] has inspired the data chosen for power injector (for more details on the power injector see 6.8.1). Then it has been adapted to meet the requirements of the power injector.

6.5. Power system and cases studied

The integration of wind turbines and diesel generator to an interconnected or isolated electrical network can generate some technical problems like:

- under-or overvoltages, frequencies, power variations on the network,
- increase of fault levels in the network,
- stability and ability of distribution generation to remain synchronized with the network (for instance asynchronous and synchronous machines),
- lack of operation or improper operation of protection systems,
- ….

Concerning the "Les Saintes" network:

- isolated mode,
- peak load (1384 kW and 519 kVAR),
- minimum capacity of the diesel generator about 480 kW (30% of the nominal power). In fact, the diesel should not be used with power lower than 50% and possibility down to 30% in order to avoid clogging up the machine (engine damage) [2].

Note: protections against over speed, over voltage… of diesel genset, the wind farm and grid have not been modelled in this study.

6.5.1. System operating states

The following configurations or power system and events or disturbances taken in account for this study:

Table 6.5.1-1: system operating states (isolated network)

States	Components (source generation) status			Events (disturbances, faults)
	Diesel Genset (DG)	Wind Farm (WF)	Storage System (ST) (Power Injector: PI)	
Scenario (or case) 1	On	Off	Off	Connection of DG
				Disconnection of DG
				Short-circuit at DG terminals
				Short-circuit on the MV network (substation Crawen)
				Disconnection of loads
				Connection of loads
Scenario (or case) 2	On	On	Off	Connection of WT
				Disconnection of WT
				Wind speed variation (gust, …)
				Shut-off of WT and Wind Farm)
				Shut-off of DG
				Short-circuit at DG terminals
				Short-circuit on the MV network (substation Crawen)
Scenario (or case) 3	On	On to Off	Off to On	Shutdown of WF and connection of Power Injector
	On to Off	On	Off to On	Shutdown of DG and connection of Power Injector

For each case described in table 6, curves have been plotted in graphs:

- electric and mechanical quantities of diesel genset (e.g. active and reactive power, frequency and voltage variations, rotor speed, …),
- electric and mechanic quantities of one wind turbine (or wind farm),
- electric quantities on the network,
- electric quantities of the power injector.

6.5.1.1. Scenario 1: diesel generator power system

The goal of the simulations is to make sure the diesel functions correctly in normal operation concerning active power, reactive power, voltage, frequency and stability.

Power system (or components available):

- diesel generator: On (nominal conditions)/Off

- load: P= 1384 kW, Q= 519 kVAR

6.5.1.1.1. Experimental procedure

The diesel generator is connected to grid, then different events or disturbances are applied at time= ti:

- Case 1.1: connection/disconnection of diesel generator,
- Case 1.2: short-circuit on the LV network (diesel terminals),
- Case 1.3: disconnection of loads "Terre de Haut" (loss load),
- Case 1.4: connection of loads "Terre de Haut".

6.5.1.1.2. Case 1.1: Connection/disconnection of diesel generator

The procedure (or simulation set-up) is:

- at t= 1 s, diesel generator is connected to the network (nominal capacity),
- at t= 5 s, it is disconnected from the network.

The main electrical quantities computed by the EMTP-RV are shown in the following figure:

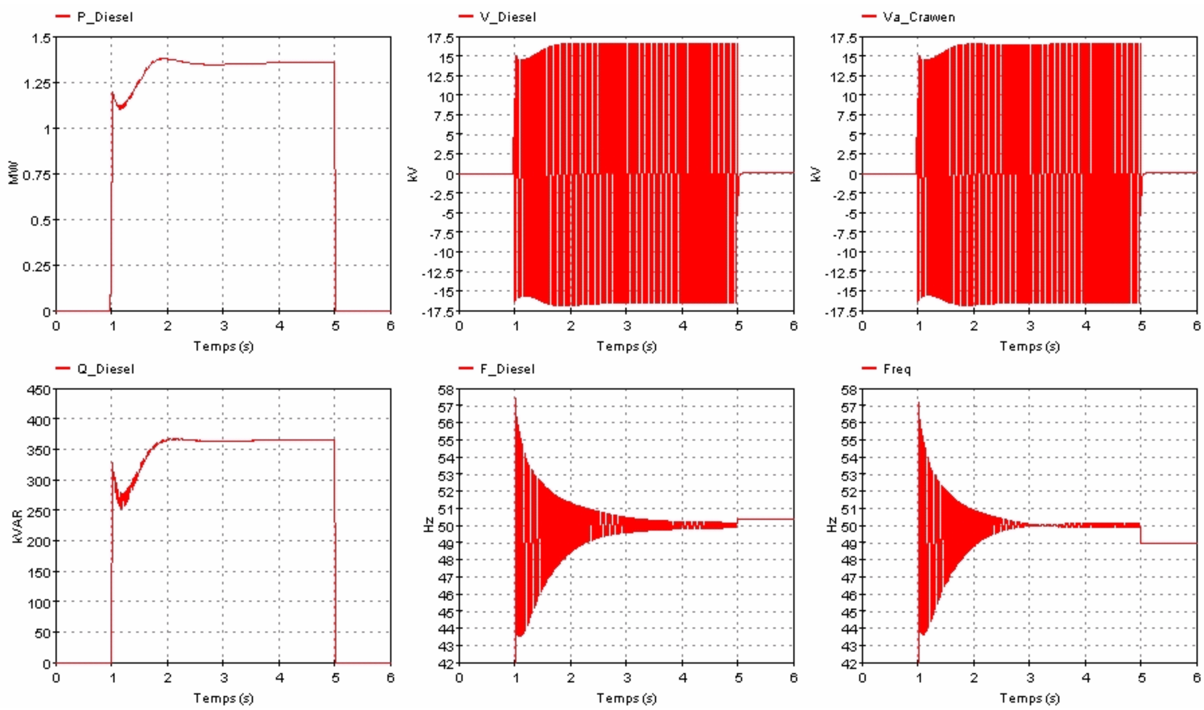

Figure 6.5.1-1: Active, reactive power, frequencies and voltages of diesel generator and on the MV network (substation Crawen)

<u>Results, interpretation and analysis</u>

The diesel operates as a synchronous generator sending active and reactive power into the network, particularly into the loads (1355 kW and 366 kVAR). The synchronous generator controls frequency and voltage on the network. The diesel synchronous generator has to be continuously operating, resulting in high fuel consumption. The results corroborate the manufacturer's data sheet and basic calculations.

6.5.1.1.3. Case 1.2: Short-circuit at diesel generator terminals

The aim of these simulations is to compare the impact of different short-circuits (symmetrical and unsymmetrical) on the dynamic behaviour of the diesel generator, particularly its stability. In fact, different fault types lead to different dips, i.e. a different relation between the remaining voltages in the three phases.

In this case, a single (two or three) phase short-circuit at the diesel terminals is simulated by setting voltage phase a (a and b or a, b and c) to zero (see Figure 6.5.1-2).

The procedure (or simulation set-up) is:

- diesel genset is connected to the grid (nominal operation),
- at t= 5 s, a single (two or three) phase short-circuit is applied at diesel generator terminals (LV network: between the generator and the transformer),
- at t= 5.5 s, it is cleared at t= 5.5 s.

The figures below illustrate the dynamic behaviour of the synchronous machine (SM) during and following the short-circuits at the diesel terminals.

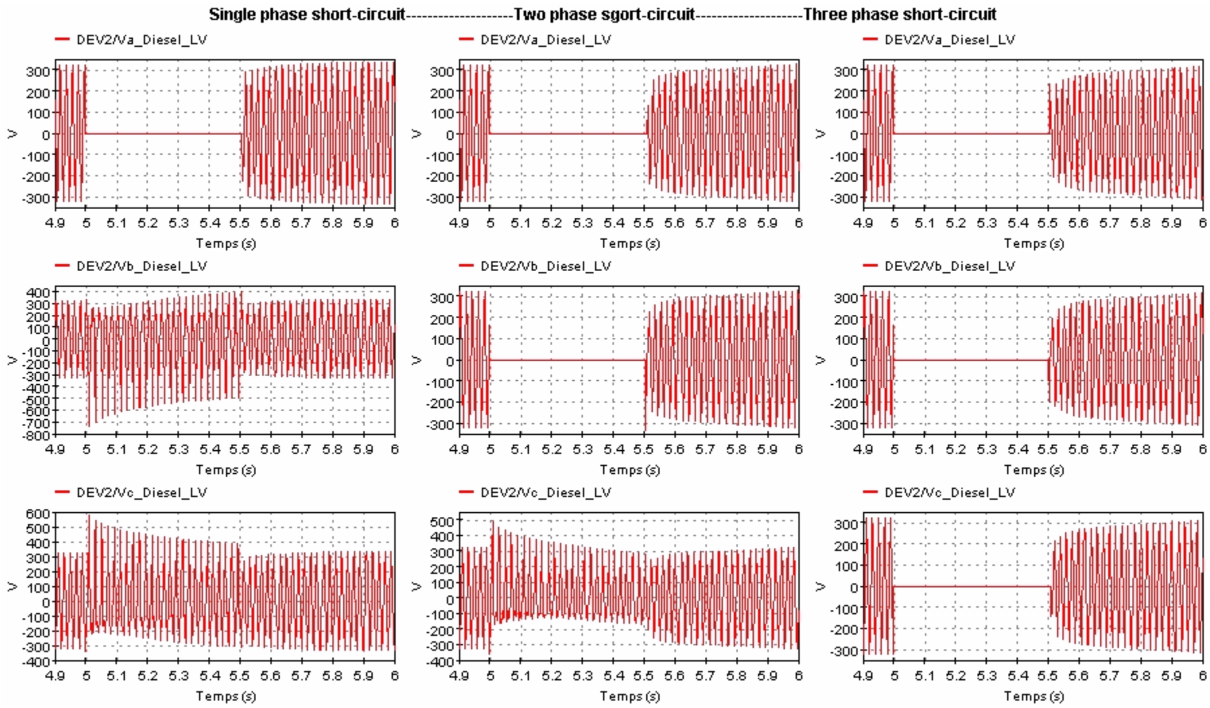

Figure 6.5.1-2: Voltages in all 3 phases of diesel generator during and following a fault at diesel terminals

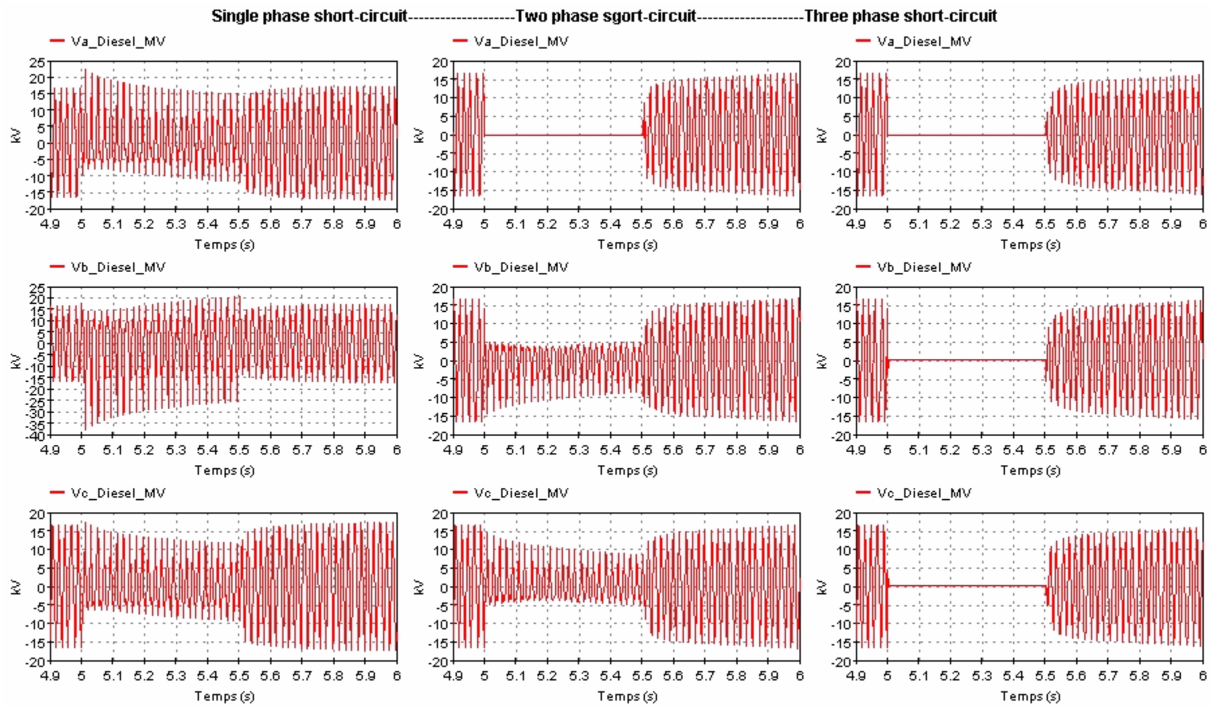

Figure 6.5.1-3: Voltages in all 3 phases on the MV network during and following a fault at diesel terminals

Note: a Dy connected transformer changes the type voltage dip, for instance a voltage dips single phase (LV network) into voltage dips two phase (MV network). A three phase short-circuit is not affected by the transformer (Dy coupled transformer).

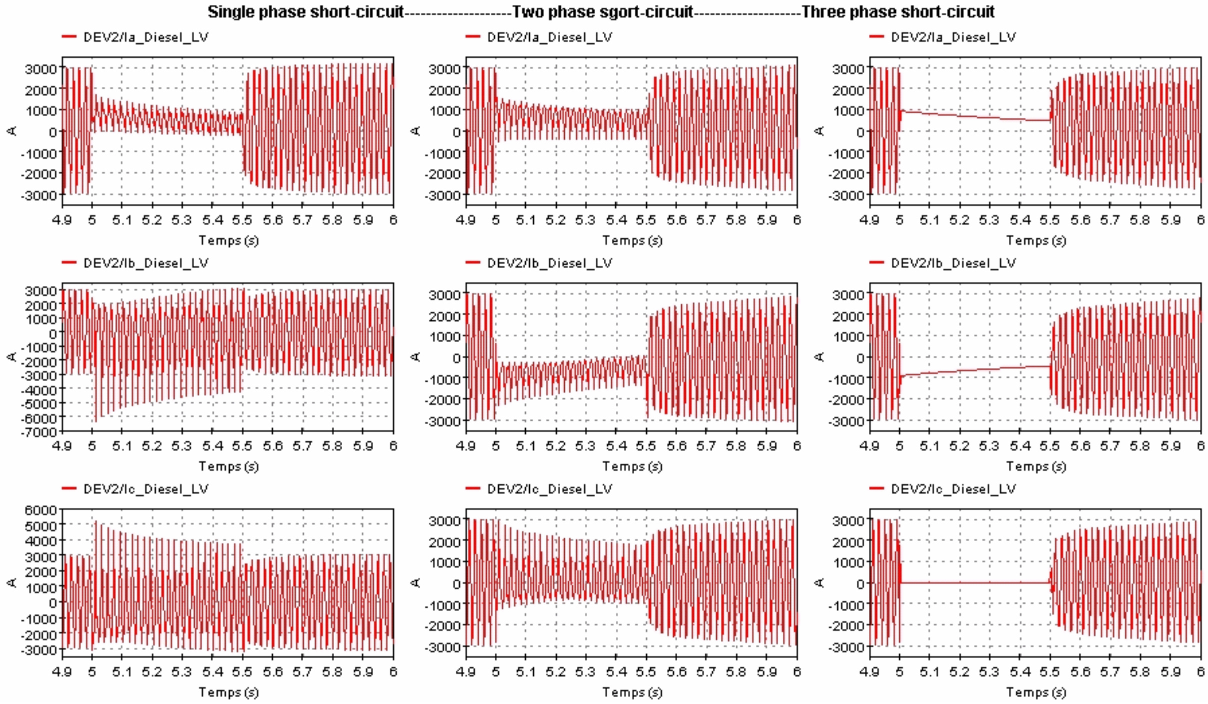

Figure 6.5.1-4: Current in all 3-phases of diesel generator during and following a fault at diesel terminals

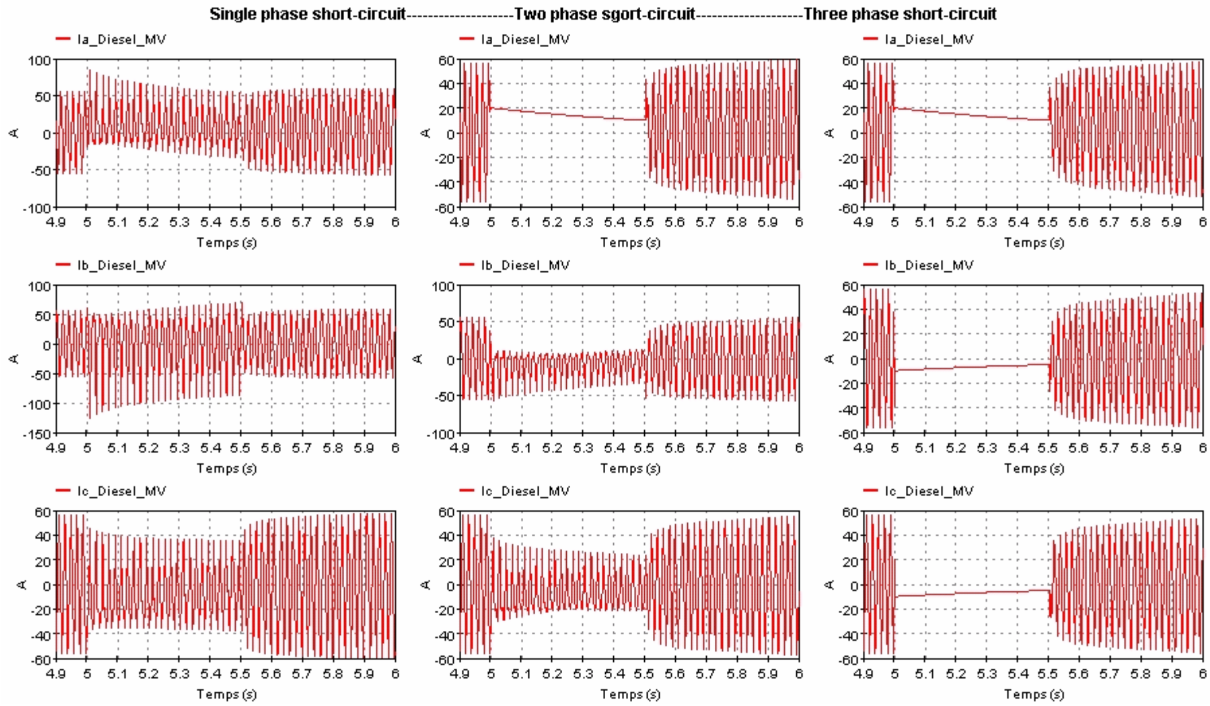

Figure 6.5.1-5: Current in all 3 phases on the MV network during and following a fault at diesel terminals

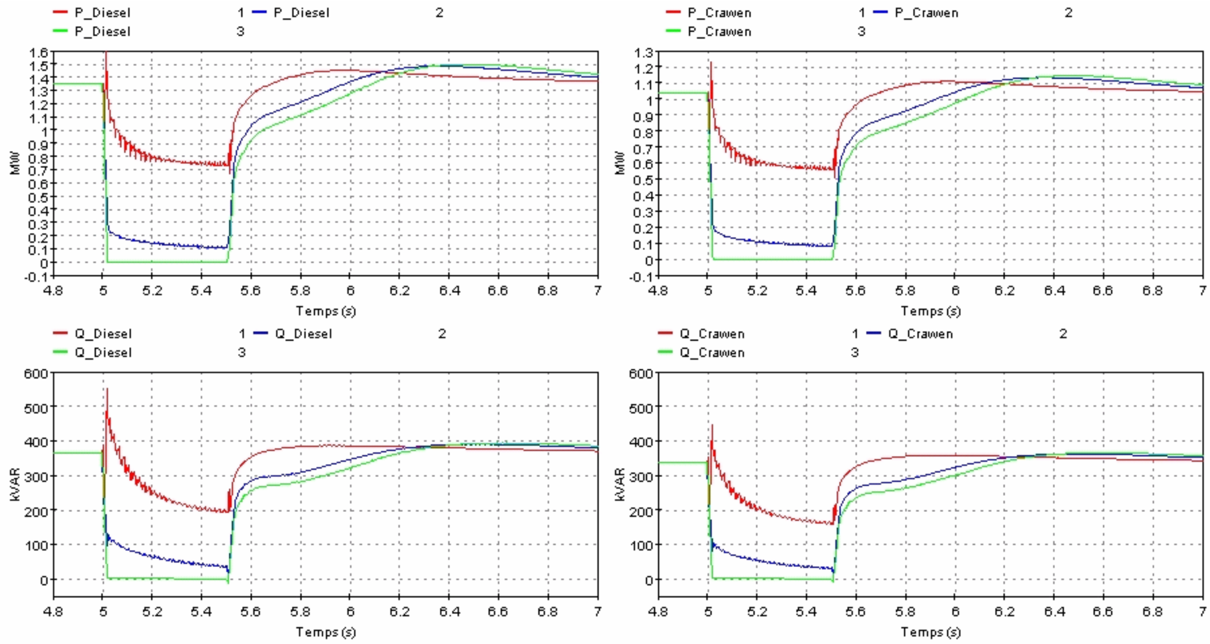

Figure 6.5.1-6: Active and reactive power in all 3 phases of diesel generator (MV network) and at substation Crawen (MV network) during and following a fault at diesel terminals

<u>Remarks:</u>

Red: a single short-circuit, Blue: a two phase short-circuit, Green: a three phase short-circuit.

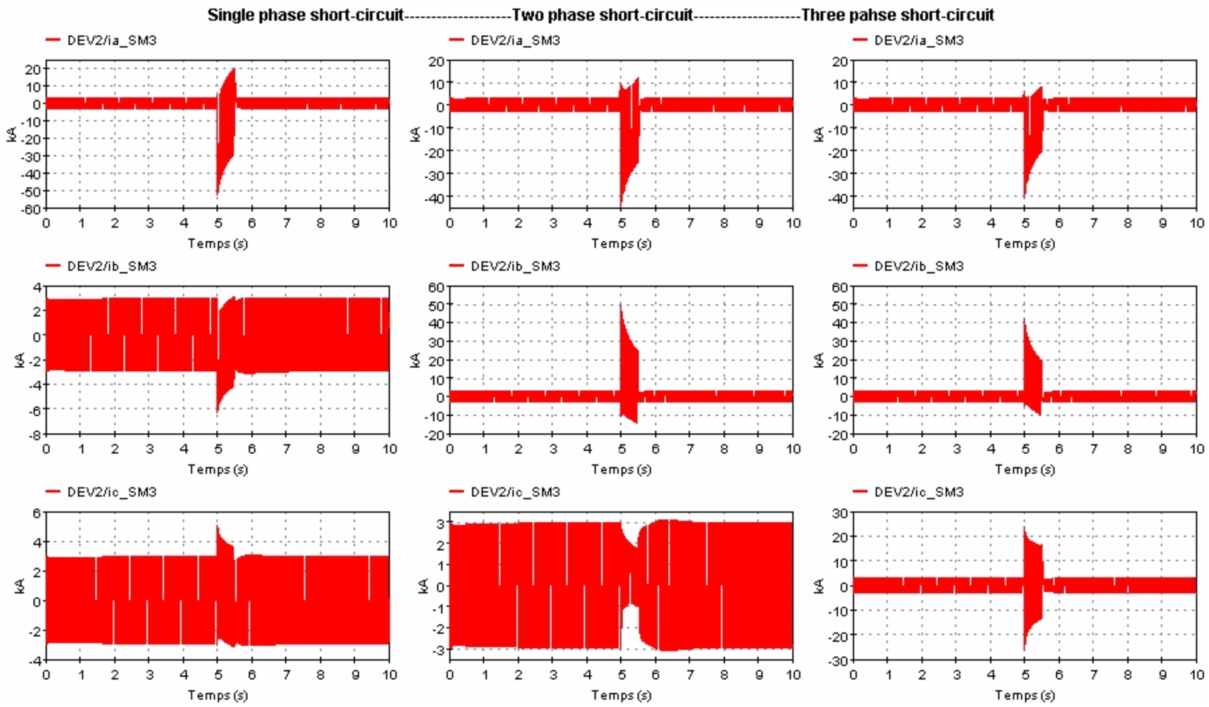

Figure 6.5.1-7: Current in all 3 phases (armature winding current) of diesel generator (SM3) during and following a fault at diesel terminals

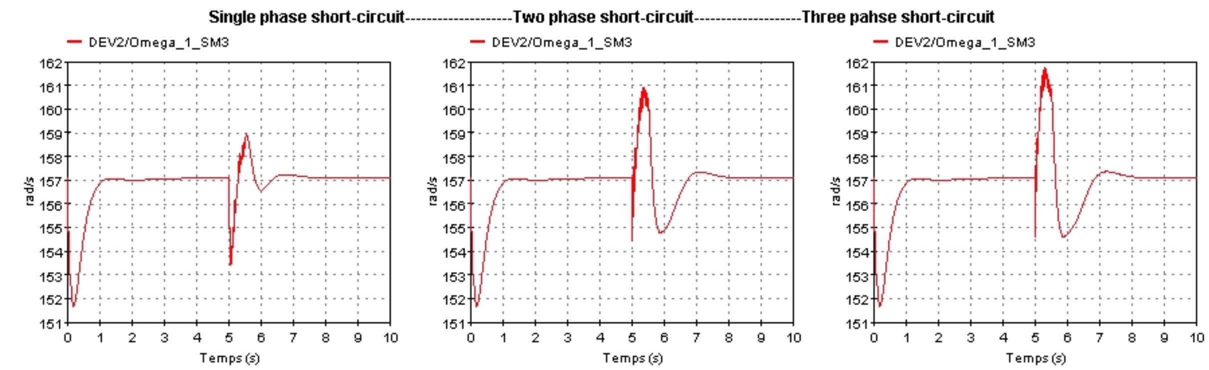

Figure 6.5.1-8: Rotor speed of diesel generator (SM3) during and following a fault at diesel terminals

<u>Results, interpretation and analysis</u>

The curves above show the impact of different types of short-circuits (single/two/three phase) on the network, particularly on the active, reactive power, voltages, frequencies…. After the clearing of fault, transient recovering voltages, currents … may be observed.

NB: in case of a symmetrical fault, the minimum RMS-voltage is the same in all phases (a, b, and c: the three terminals of the synchronous machine). But, in case of an unsymmetrical fault, phase's voltages and currents have non-equal magnitudes during the fault (voltage and current imbalances).

Simulations show that:

- Voltage drops to zero in the faulted phases (in all phase in case of 3-phase fault or unfaulted phases in case of 1 or 2-phase fault).
- Voltage increases in the unfaulted phases, e.g. a single phase short-circuit (voltage imbalance).
- Overvoltages caused by a 1-phase short-circuit are much higher than the ones originating from the 2 or 3-phase short-circuit. The maximum value of overvoltage factor in the unfaulted phases is of 2.25 times (relative to the neutral point $Vn = \frac{Un * \sqrt{2}}{\sqrt{3}}$: 326.6 V for LV or 16.3 kV for MV, 736.4 kV on the LV network and 38.1 kV on the MV network).
- Short circuit current from diesel generator is several times the nominal current (inrush current) and then it decreases. The maximal peak current is approximately the same for the 2 and 3-phase to ground fault. The maximal peak current is approximately of - 6344 A at diesel generator terminals (or - 125.6 A for MV network) during a 1-phase to ground fault.
- During the faults, the active and reactive power drop and at the same time the rotor speed of diesel generator increases. The power flow is reduced for a 1 or 2-phase short-circuits.
- After clearing of fault, the voltage goes up and at the same time the rotor speed of the diesel generator decreases and returns to synchronism speed.

The importance of voltage dips (or power dips) depends on the types of faults (1, 2 or 3-phases short-circuit).

Although it occurs less often, the 3-phase short-circuit has a more severe effect (voltages dips, active and reactive power flow, rotor speed) than the 1 or 2 short-circuit or any other disturbance. However, the synchronous machine, i.e. diesel generator is stable during and after clearing of short-circuit (1, 2 or 3-phase) of duration 500 ms. In fact, after some temporary fluctuations, the rotor speed returns to synchronism and the rotor angle to a constant value. In addition, one obtains a good agreement between simulations and theory of synchronous machines [9], [10], [11] and [12]

6.5.1.1.4. Case 1.3 &1.4: Disconnection/connection of loads "Terre de Haut"

Normally, this case is the consequence of a fault on the network, resulting in a sudden connection/disconnection of loads (islanding). The procedure (or simulation set-up) is:

- at t= 0 s, the diesel generator (synchronous machine SM3) is connected to the part load (P= 321 KW: Terre de Bas),
- at t= 1 s, the load Terre de Haut is connected to the full load (P= 1384 kW),
- at t= 5 s, the load Terre de Haut is disconnect from the network (P= 321 kW: part load).

The figures below present the dynamic behaviour of power system network during the connection and disconnection of loads.

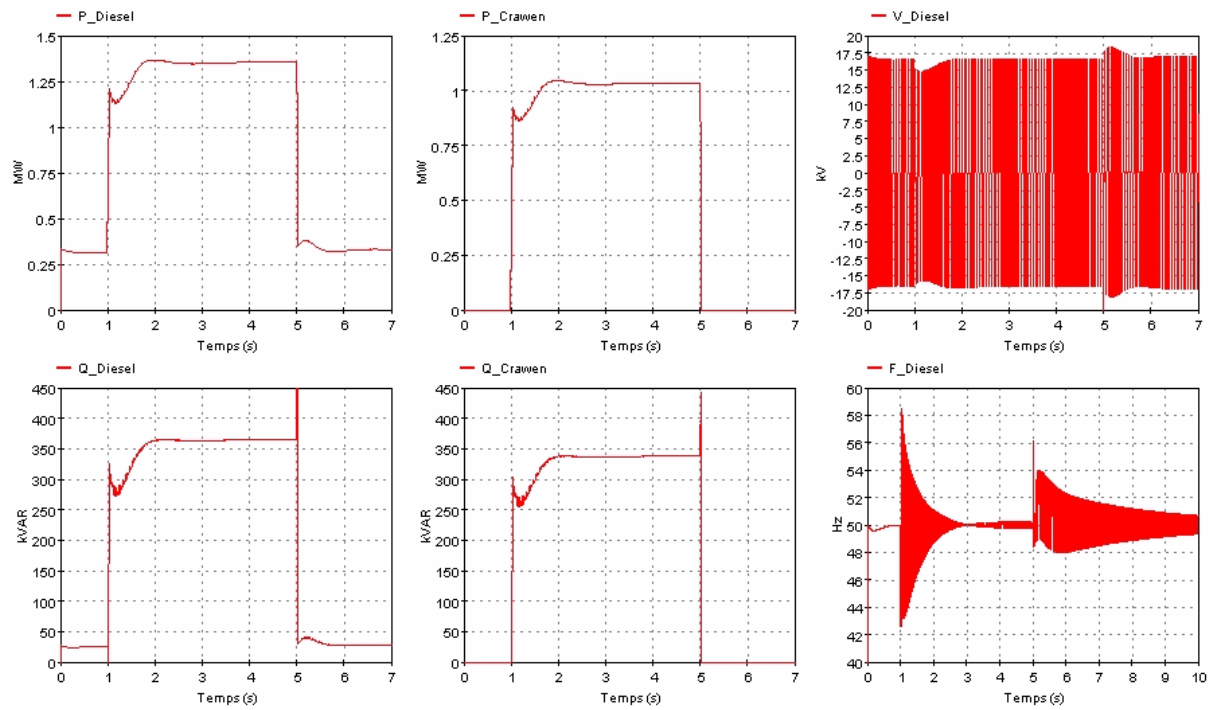

Figure 6.5.1-9: Active, reactive power, frequency and voltage of diesel generator and at substation during a sudden connection and disconnection of loads

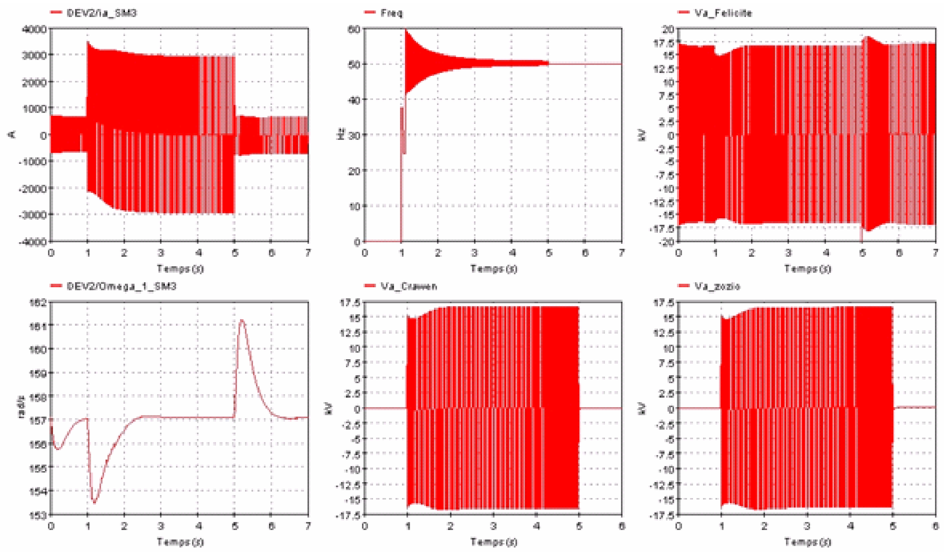

Figure 6.5.1-10: Winding current,, rotor speed and frequency of diesel generator (SM3) - Voltages at substations during a sudden connection and disconnection of loads

<u>Results, interpretation and analysis</u>

Simulations show that there is:

- an undervoltage during connection of load Terre de Haut (at t= 1 s, voltage about 14.7 kV),
- an overvoltage during the disconnection of loads (at t= 5 s, voltage about 18,25 kV).

These under/overvoltages (factor ± 1.1) are compensated in less than 1 s by regulations of diesel. One observes oscillations damped on the frequencies of diesel and on the network (± 10 Hz around 50 Hz). The rotor speed of the synchronous machine (diesel) follows the grid frequency. The system remains stable during and following the connection or disconnection of loads (see voltages, currents, active and reactive power, rotor speed, torque…).

6.5.1.1.5. Description of the results and conclusions

The main conclusions of the simulated cases are:

- diesel generator imposes the voltage and frequency on the network (for the operation of the wind farm in isolated mode),
- behaviour of the synchronous generator during and after a short-circuit, connection/disconnection of diesel or loads is satisfactory and in conformity with the theory of the synchronous machines [9] and [10].
- time response of the governor to load change shows its efficiency. The shorter the better.

These results show that the power system is dynamically stable and reliable, especially diesel generator control (response time of the AVR and excitation system). In conclusion, the dynamic behaviour of diesel model is satisfactory (frequency, voltage, balance of active and reactive power on the network).

6.5.1.2. Scenario 2: diesel generator and wind turbines

The wind turbines generators operate in parallel with a diesel generator on an isolated network. The goal of the five following simulations is to study the interaction between wind turbines and diesel generator and the loads in response to different types of events or disturbances on the grid.

Power system (or components available):

- diesel generator: On (nominal or normal conditions)/Off
- wind turbines: On (nominal or normal conditions)/Off
- load: P= 1384 kW, Q= 519 kVAR (peak load)

6.5.1.2.1. Experimental procedure

The diesel generator is connected to the grid, then different events or disturbances are applied at time= ti:

- Case 2.1: connection/disconnection of wind turbines (in gusts)
- Case 2.2: wind speed variations (wind gusts…),
- Case 2.3: short-circuit on the LV network,
- Case 2.4: short-circuit on the MV network,
- Case 2.5: disconnection of loads "Terre de Haut" (part load or islanding).

<u>Rate of penetration of wind power</u>

There is a limitation of the penetration of wind power into the power system due to loads and to minimum power output of diesel generator (minimum stable operation diesel genset). Thus, the penetration of wind power depends on the number of wind turbines and the wind speed considered (wind power output).

This rate of penetration is given in Table 6.5.1-2 and Table 6.5.1-3.

Table 6.5.1-2: Level of penetration for wind speed 20 m/s (with a capacitor bank C= 4.8 mF)

Number of wind turbines connected		3	2	1
Wind Farm	P(kW)	877	584	292.4
(v= 20 m/s)	Q(kVAR)	196	133.5	67.5
Diesel Genset	P(kW)	517	797	1070
	Q(kVAR)	179	239	301.5
Substation Crawen	P(MW)	1.06	1.05	1.04
	Q(kVAR)	347	344.8	341.6
Load Network	P(MW)	1.38	1.37	1.36
Rate of penetration Diesel Genset	T_{DG} (%)	32.3	49.8	6.7
Rate penetration Wind Farm	T_{WT} (%)	63	42	21

Table 6.5.1-3: Level of penetration for wind speed 10 m/s (with a capacitor bank C= 2.6 mF)

Number of wind turbines connected		5	4	3	2	1
Wind Farm	P(kW)	770	616	462	261.4	130.7
(v= 10 m/s)	Q(kVAR)	13	9.6	6.6	16.3	7.2
Diesel Genset	P(kW)	603	755	905	1102	1228
	Q(kVAR)	357	360	360	351	360
Substation Crawen	P(MW)	1.05	1.05	1.05	1.04	1.04
	Q(kVAR)	343	344	342.6	341	339.7
Substation Fond de Cure	P(kW)	720	719	719	716	714
	Q(kVAR)	244	243	243	243	242
Load Network	P(MW)	1.35	1.35	1.35	1.35	1.35
Rate of penetration Diesel Genset	T_{DG} (%)	43.5	54.5	65.4	79.6	88.7
Rate of penetration Wind Farm	T_{WT} (%)	56.6	44.5	33.3	18.8	9.4

NB: $T_{DG} = \frac{P_{DG}}{P_{load}}$ (0 < TDG < 1), $T_{WT} = \frac{P_{WF}}{P_{load}}$, $P_{load} = P_{WF} + P_{DG} - P_l$

where:

- P_{DG}: diesel genset power (power delivered from the diesel generator),
- P_{WT}: wind turbines power (power delivered from the wind turbines),

- P_l: electrical losses in the network (power dissipation),
- P_{load}: load or demand 1384 kW full load (power required by loads).

In the simulations it was considered that:

- wind park is composed of five WTGs: P_{wind}= 5*150 kW= 750 kW. The rated capacity of each wind generator is 150 kW with a constant wind speed of 10 m/s for all wind generators. A capacitor bank of 48 kVAR is installed at wind turbine generator terminals in order to keep an admissible power factor (2.6 mF with a power factor > 0.9),
- diesel generator used has a rated capacity of 1600 kW (minimum stable operation diesel is 480 kW= 30% of the nominal power in order not to create a clogging of the diesel),
- simulations don't take into account the action of diesel and wind turbine protections….

6.5.1.2.2. Case 2.1: Connection/disconnection of wind turbines

<u>Connection of wind turbines</u>

The diesel generator is connected to loads (1384 kW/519 kVAR), operating at its nominal power, voltage, speed and frequency, when the wind turbines are connected to the network. The following figures show the active and reactive power of one wind turbine.

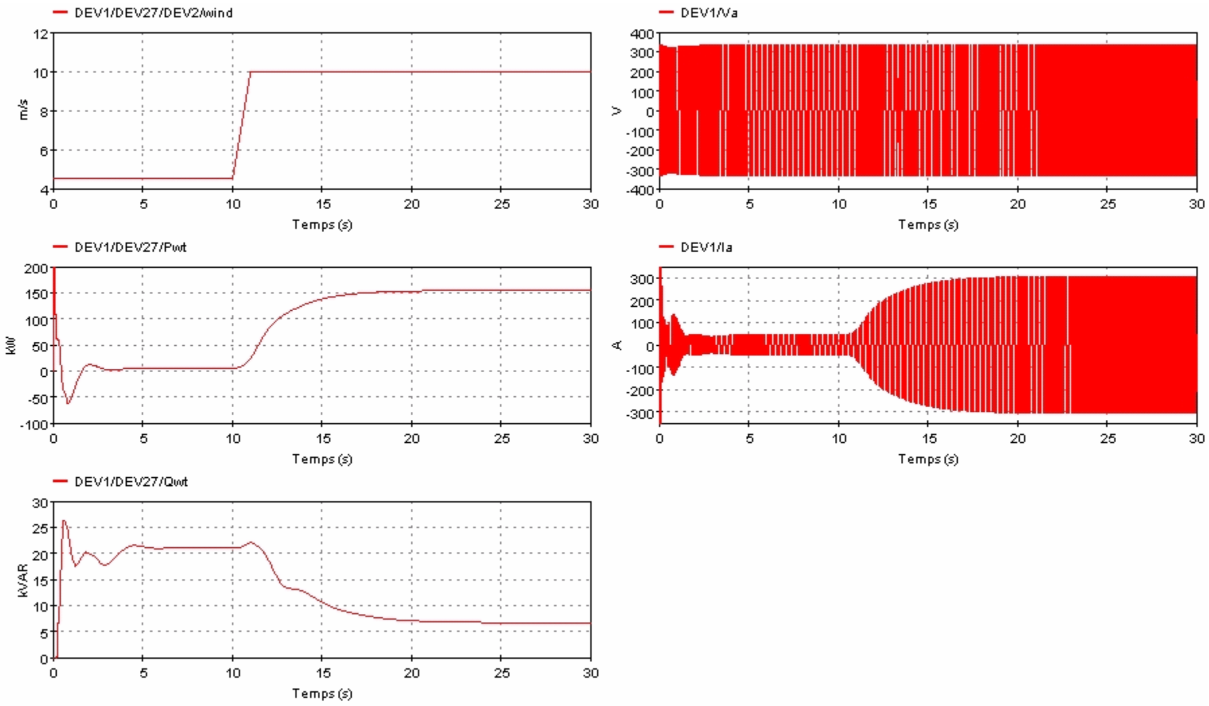

Figure 6.5.1-11: Wind speed, active, reactive power, voltage and current of a wind turbine (Asynchronous Machine: ASM)

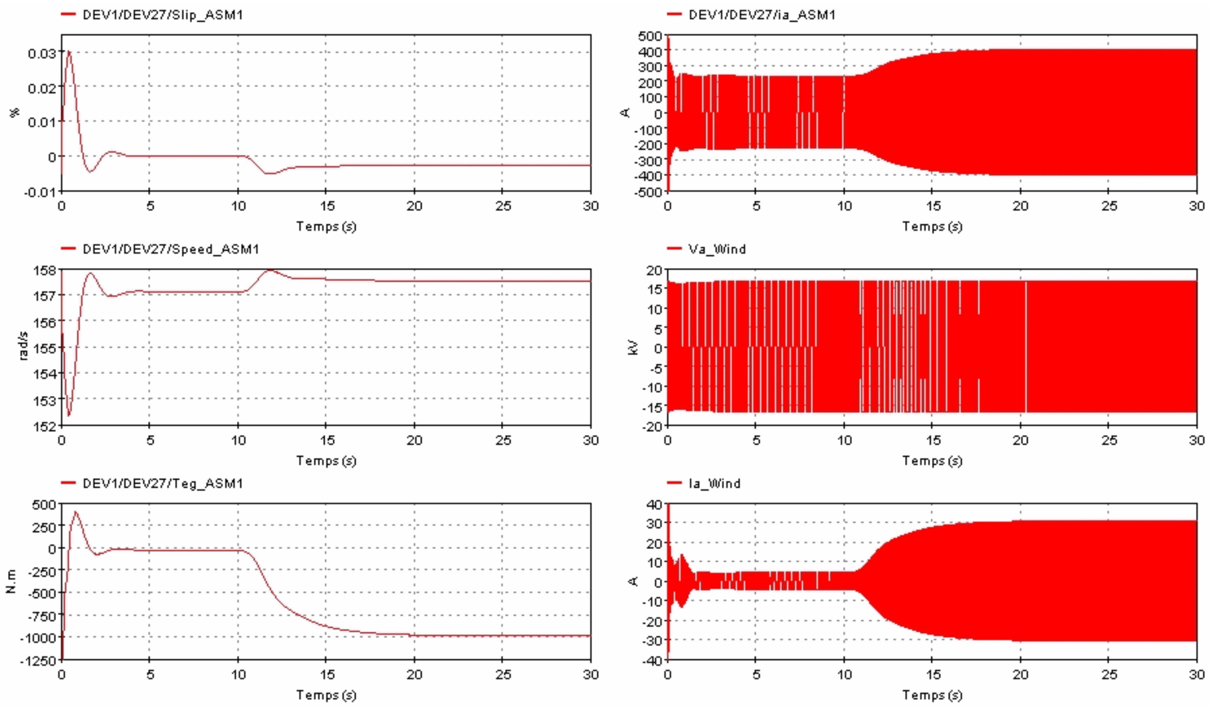

Figure 6.5.1-12: Slip, rotor speed, electromagnetic torque, current of a wind turbine (Asynchronous Machine: ASM1) - Voltage and current on the MV network

Results, interpretation and analysis

Initially the diesel generator supplies the active and reactive power to the loads (and the reactive power absorbed by the wind turbines). At cut-in wind speed (4.5 m/s), the asynchronous machine consumes an important reactive current during a few seconds. There is also an inrush current in the generator because of magnetization of induction machine and a sudden rms voltage drop at the wind turbine terminals. At t= 10 s, wind speed increases linearly from 4.5 ms to 10 m/s, resulting in an increase from 28 kW to 770 kW power output of wind farm. At the same time, the diesel power generation drops from 1384 kW to 603 kW, because the wind farm is supplied with the difference: 770 kW. Each asynchronous machine (wind turbine) operates as a generator (154 kW/6.7 kVAR, slip < 0, electromagnetic torque < 0).

These results corroborate the manufacturer's data sheet and basic calculations (power, voltage, current…) [3].

Disconnection of wind turbines in gusts

Procedure (or simulation set-up) is:

- at t= 0 s the diesel and five wind turbines are connected to the grid (in normal operation),
- at t= 30 s, five wind turbine are disconnected in gusts (every 5 seconds).

The wind speed, the active and reactive power output of diesel and wind farm are presented in the following curves:

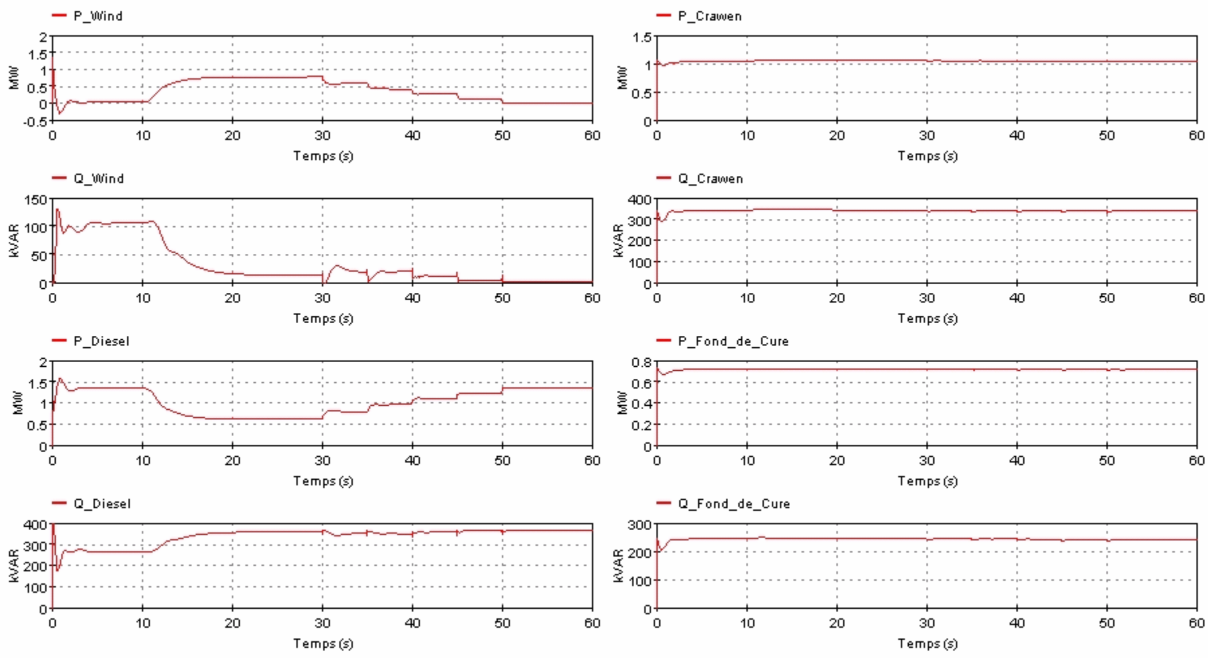

Figure 6.5.1-13: Active, reactive power of diesel generator, the wind farm and at substations (Crawen & Fond de Cure) in case of disconnection in gusts

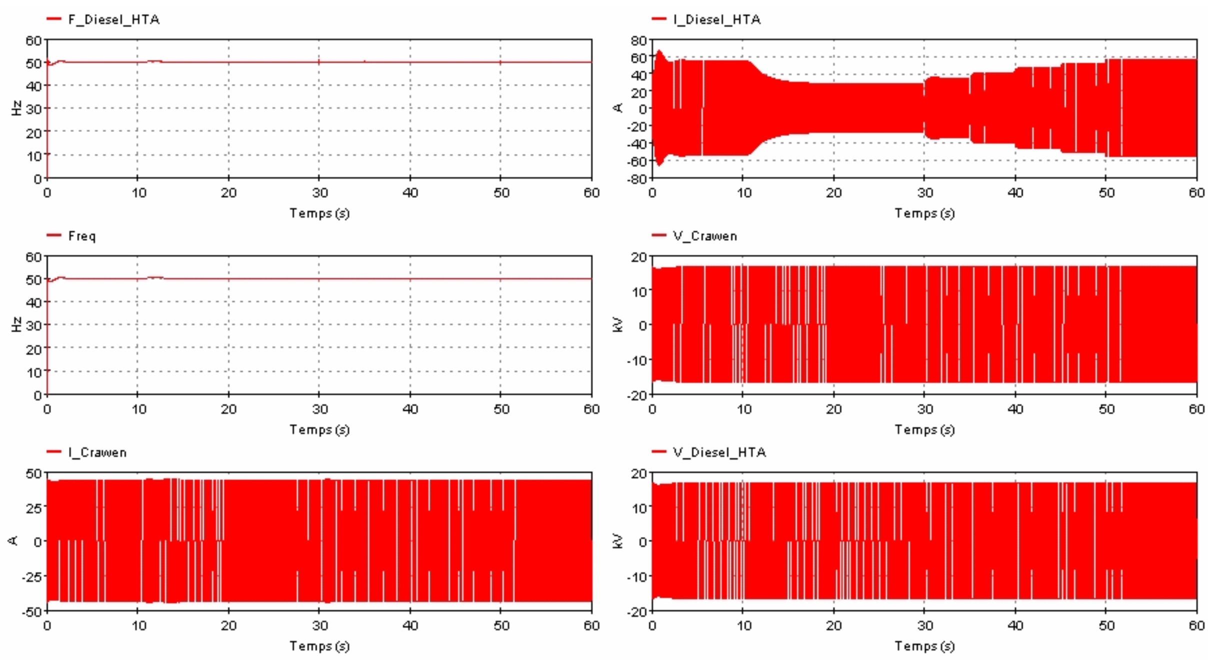

Figure 6.5.1-14: Frequencies, voltages, currents of diesel generator and at substation Crawen in case of disconnection in gusts

<u>Results, interpretation and analysis</u>

Figure 6.5.1-13 shows the simulation results in case of disconnections in gusts, particularly the active and reactive output power of diesel generator. The latter maintains the power

balance in the system power (at all times $P_{load} \approx P_{\_Diesel} + P_{\_Wind}$). The system is very stable, because the diesel-regulator thoroughly controls the frequency and voltage output on the network (via its governor and its exciter).

6.5.1.2.3. Case 2.2: Wind speed variation: gusts, extreme speed and turbulence

The main goal is to observe the dynamic behaviour of hybrid system (wind/diesel and loads) according to variations in wind speed such as: gusts and cut-out wind speed.

<u>Wind Gusts</u>

The impact of a gust, i.e. a fast fluctuation of wind on the power system is simulated. In normal operation, wind speed is set at 10 m/s, then at t=20 s, wind speed increases suddenly at 15 m/s for 10 s (see Figure 6.5.1-15). Figure 6.5.1-15, Figure 6.5.1-16 and Figure 6.5.1-17 show the dynamic response of the power system to wind gusts.

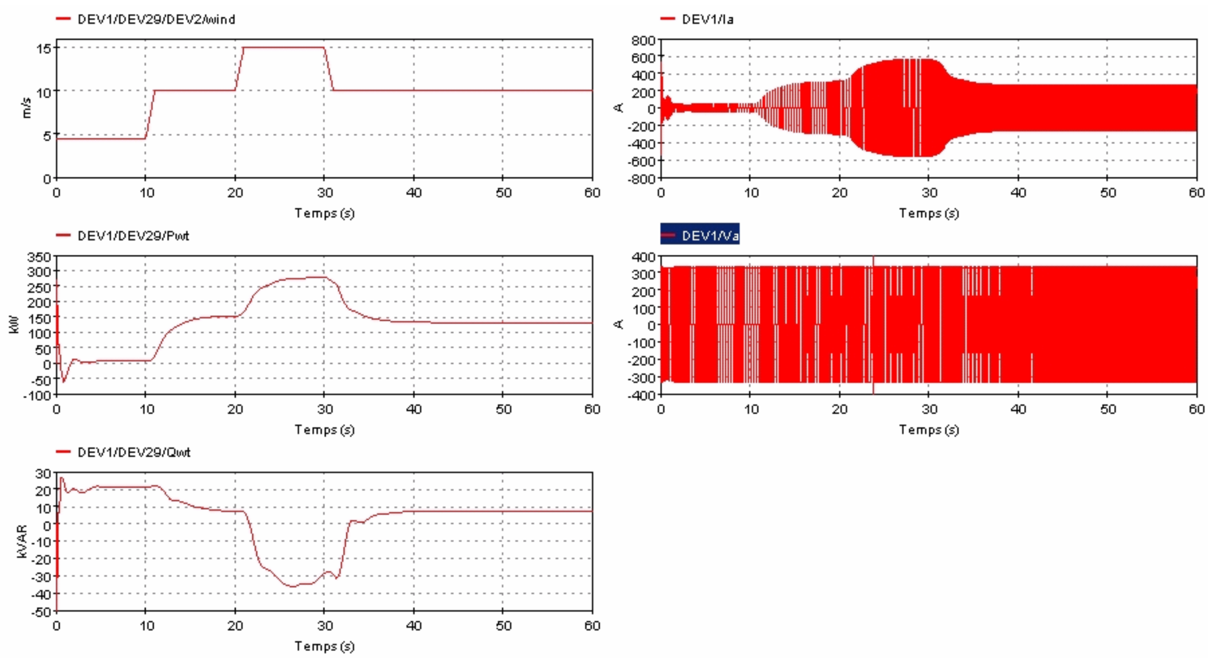

Figure 6.5.1-15: Wind speed, current, voltage, active and reactive output power of a wind turbine in case of wind gust

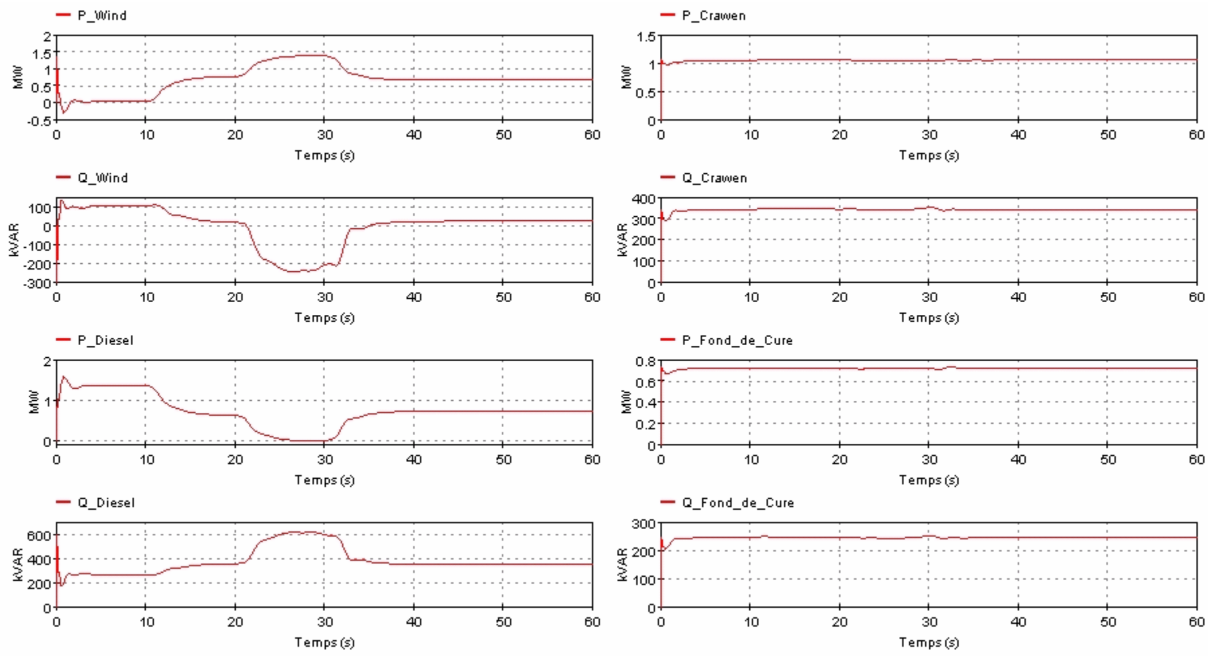

Figure 6.5.1-16: Active, reactive power output of the wind farm - Active, reactive power output of diesel generator - Active, reactive power at substations (Crawen & Fond de Cure) in case of wind gust

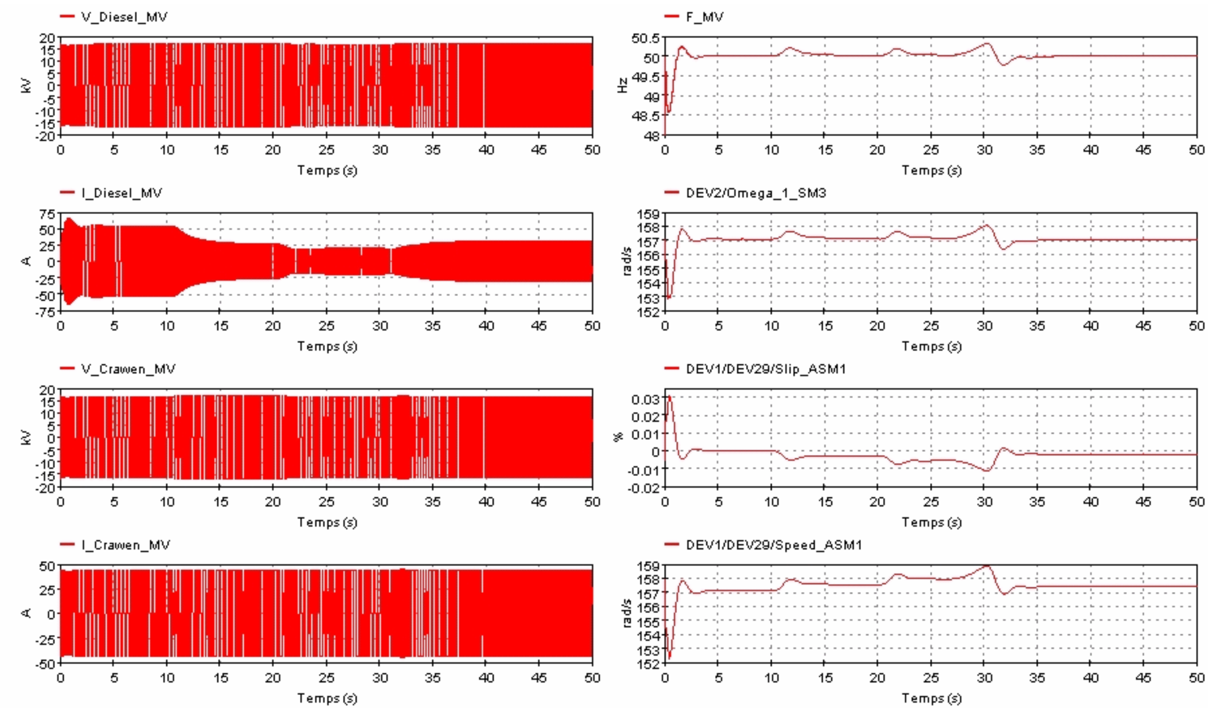

Figure 6.5.1-17: Voltage, current, rotor speed of diesel generator (SM3) - Voltage, current and frequency at substation Crawen (MV network) - Slip and speed rotor of a wind turbine (ASM1) in case of wind gust

Results, interpretation and analysis

Simulation results show that:

- wind power is function of wind speed, i.e. of the mechanical torque. In fact, there is an obvious relationship between wind speed and power generation. So, if wind speed varies rapidly, so does the output power. The slip also depends on the mechanical power,
- grid frequency follows approximately the rotor speed (to within slip),
- wind speed reaches its peak at t= 30 s with 5*275 kW active power output of the wind farm (275 kW for each wind turbine). Consequently, the diesel power decreases approximately down to zero. In this case, 100% wind power penetration is reached, i.e. the maximum wind power percentage allowed. But, it exceeds the technical limits of diesel,
- reactive power wind farm decreases to reach - 210.4 kVAR during a gust of wind, because capacitor bank is not adequate for this operating point (no unity power factor). In fact, the size of the capacitor bank has been determined for 150 kW output power of wind farm and not for 275 kW.

The power system is stable during and following wind gusts (10 m/s to 15 m/s wind speed), the diesel drops down to zero and ensures the voltage and frequency regulations. However, such an operation mode must be avoided, because the rotor of diesel accelerates a lot and the network can become unstable. The diesel low limits require consideration and can be used further to restrict the total wind generation.

Cut-out wind speed

The purpose of this case is to simulate the impact of cut-out wind speed on the power system (wind farm/diesel generator). The Figures below illustrate the waveforms associated with this simulation.

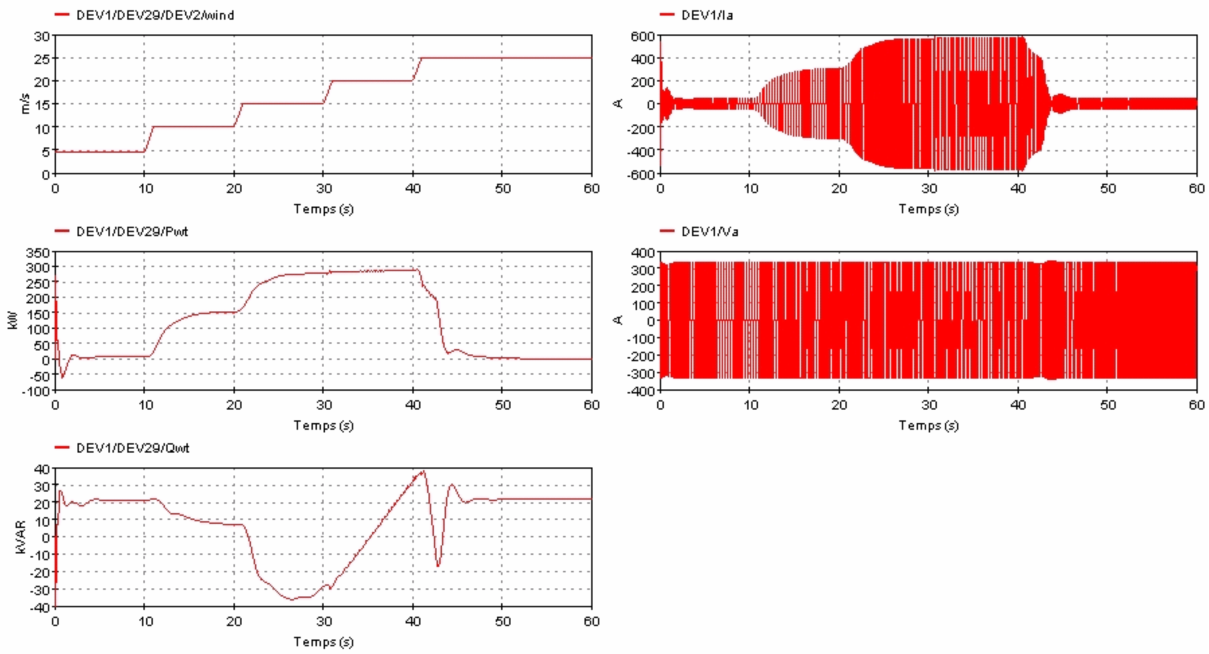

Figure 6.5.1-18: Wind speed, current, voltage, active and reactive power output of a wind turbine during and following a cut-out wind speed

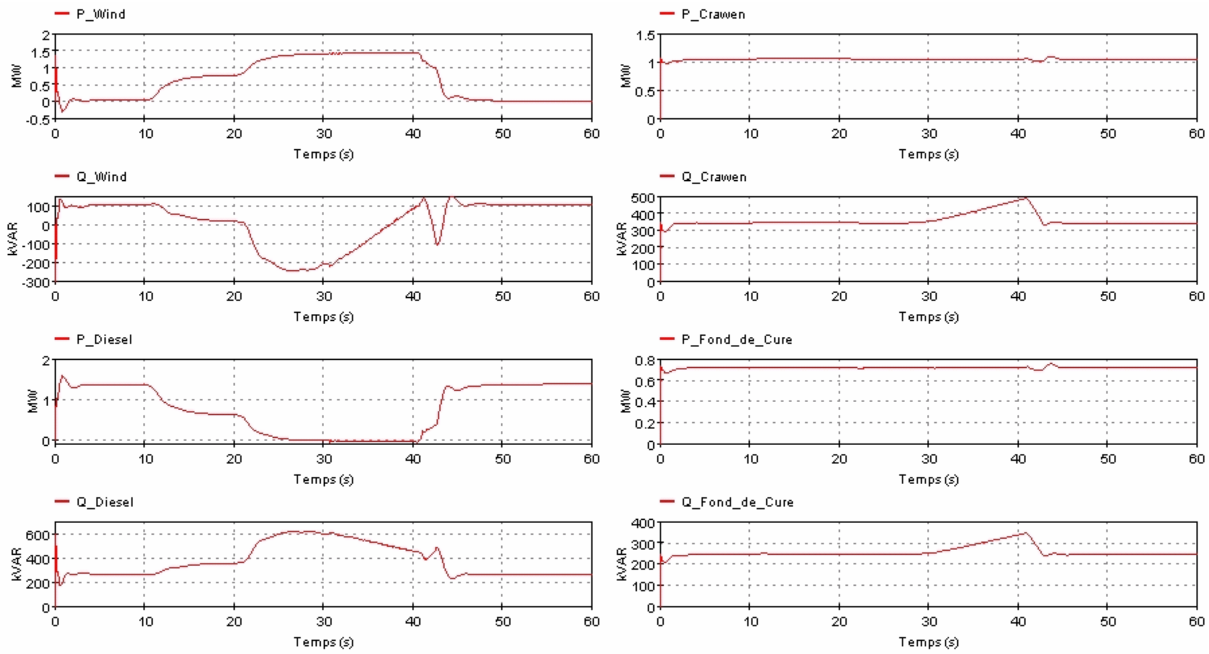

Figure 6.5.1-19: Active and reactive power output of the wind farm - Active and reactive power output of diesel generator - Active and reactive power at substations (Crawen & Fond de Cure) during and following a cut-out wind speed

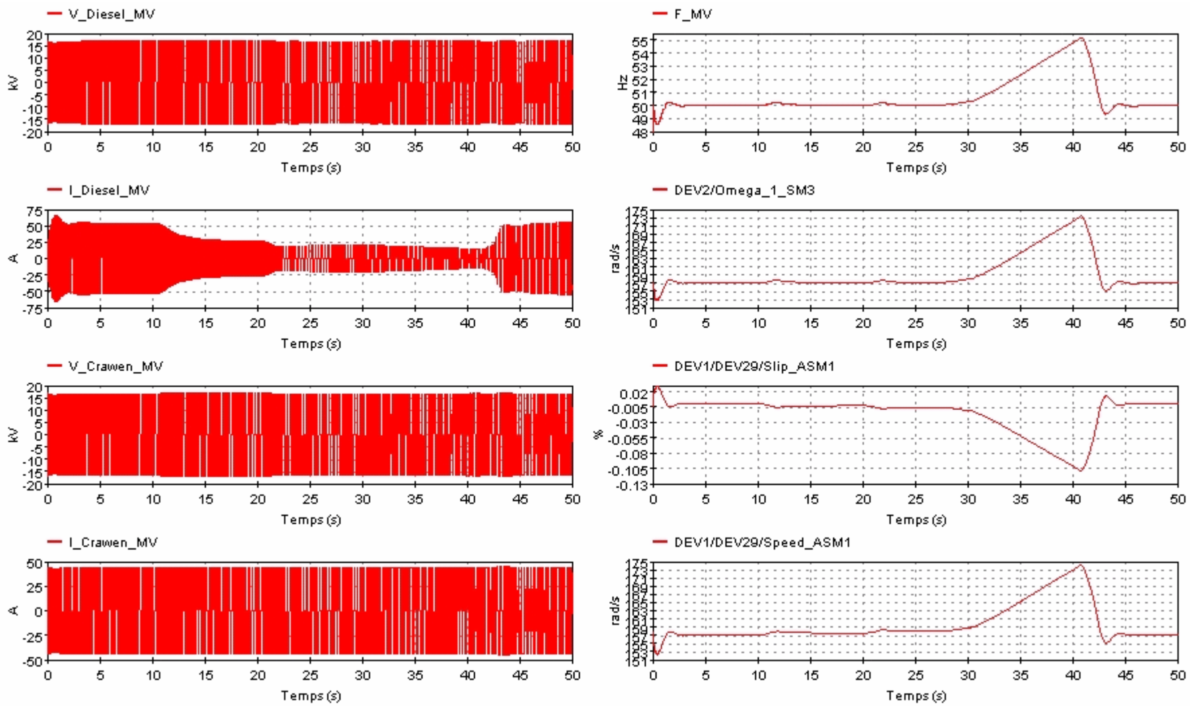

Figure 6.5.1-20: Voltage, current, rotor speed of diesel generator (SM3) - Voltage, current and frequency at substation Crawen (MV network) - Slip and speed rotor of a wind turbine (ASM1) during and following a cut-out wind speed

<u>Results, interpretation and analysis</u>

One can note that:

- as of a wind speed= 15 m/s, let 1375 kW wind power be, the diesel turns into a motor, i.e. negative output power of diesel,
- after cut-out wind speed= 25 m/s (t= 41 s), there is an increase in frequency on the network and rotor speed of diesel (56.2 Hz and 176 rad/s in peak respectively),
- after cutting-out the wind speed, making the wind farm unavailable, the diesel provides the power required by the loads (about 1384 kW)

The diesel is able to follow the variations in wind power within short delay (response time). Moreover, a hybrid power system is able to minimize diesel fuel consumption and diesel engine run time.

6.5.1.2.4. Case 2.3: Short-circuit at diesel generator terminals

The target is to study the dynamic behaviour of the wind and diesel power system, when a fault occurs at diesel generator terminals.

Procedure (or simulation set-up) is:

- diesel generator and wind turbines are connected to the grid (normal operation),

- at t= 20 s, a fault (1, 2 or 3-phase short-circuit) is made to occur at diesel generator terminals. Then, the fault is cleared in 500 ms (eliminated at t= 20.5 s).

Figure 6.5.1-21 to Figure 6.5.1-26 illustrate the dynamic behaviour of the synchronous and asynchronous generators during and following a short-circuit at diesel terminals.

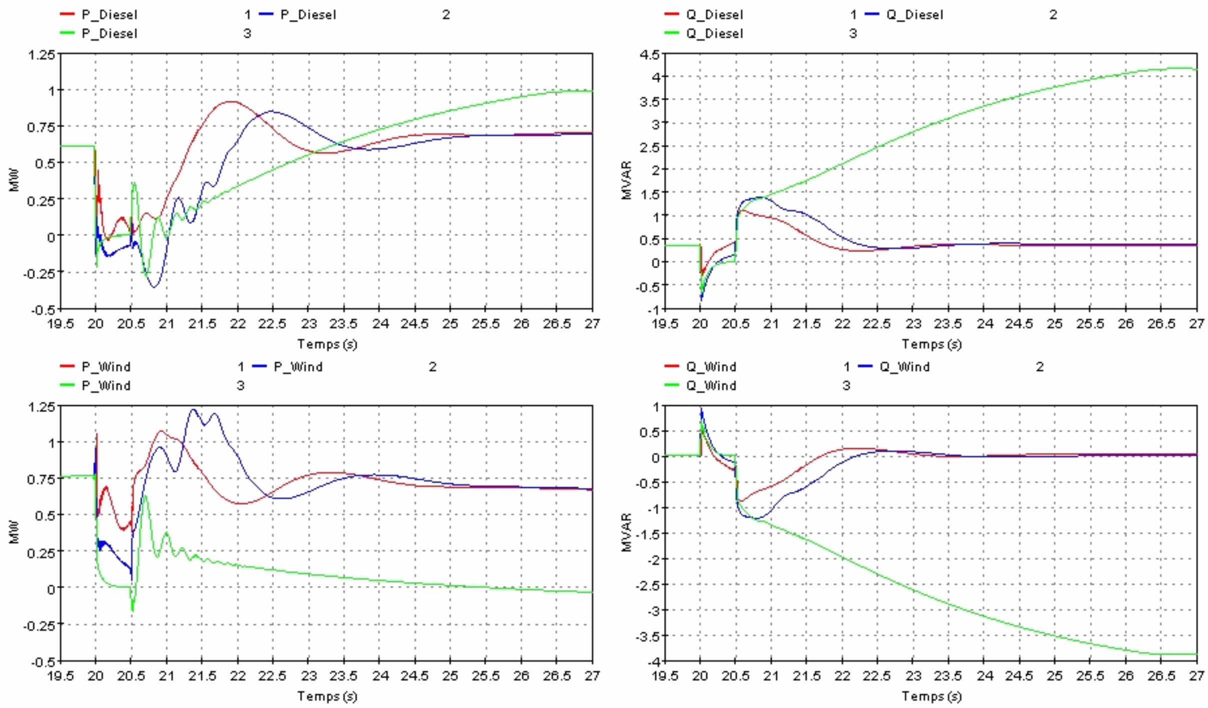

Figure 6.5.1-21: Active and active power of diesel generator during and following a fault at diesel generator terminals

Remarks: Red: a single short-circuit, Blue: a two phase short-circuit, Green: a three phase short-circuit.

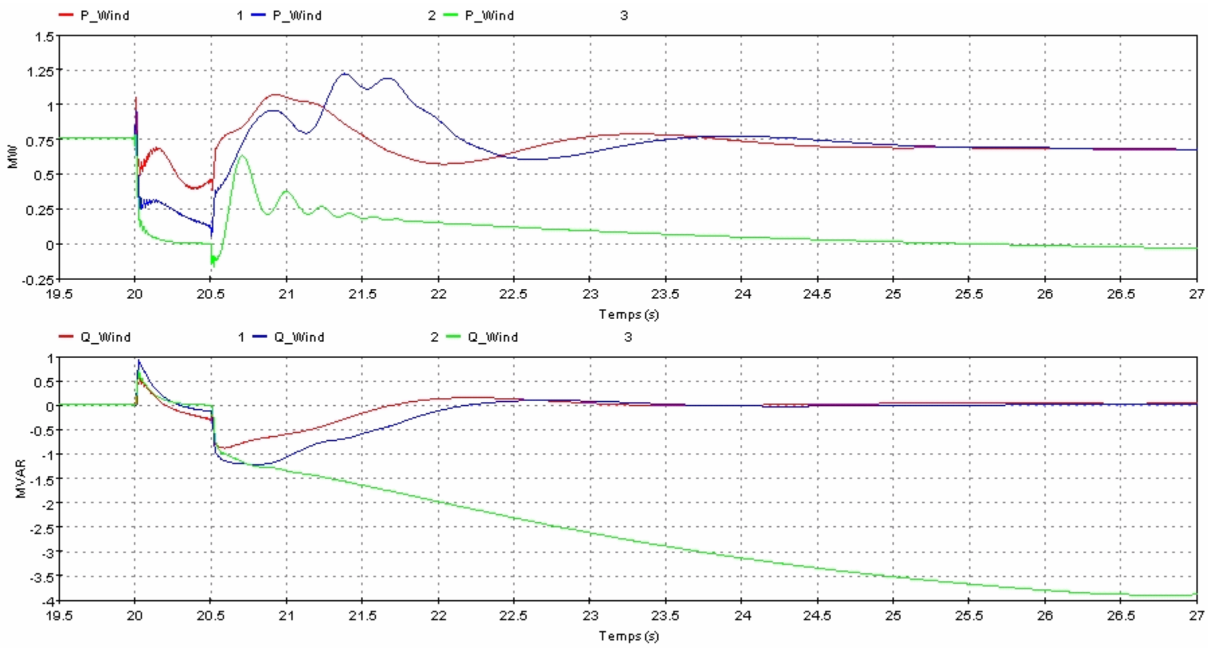

Figure 6.5.1-22: Active and reactive power of the wind farm during and following a fault at diesel generator terminals

Remarks: Red: a single short-circuit, Blue: a two phase short-circuit, Green: a three phase short-circuit.

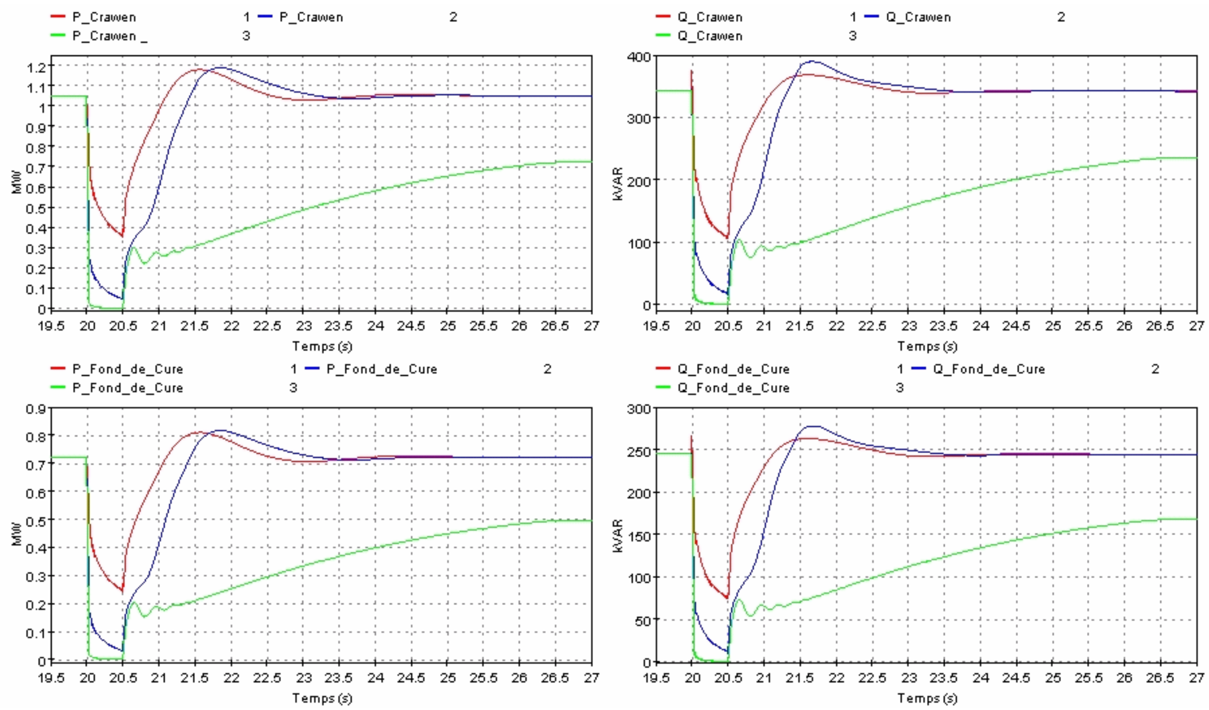

Figure 6.5.1-23: Active and reactive power at substation Crawen during and following a fault at diesel generator terminals

Remarks: Red: a single short-circuit, Blue: a two phase short-circuit, Green: a three phase short-circuit.

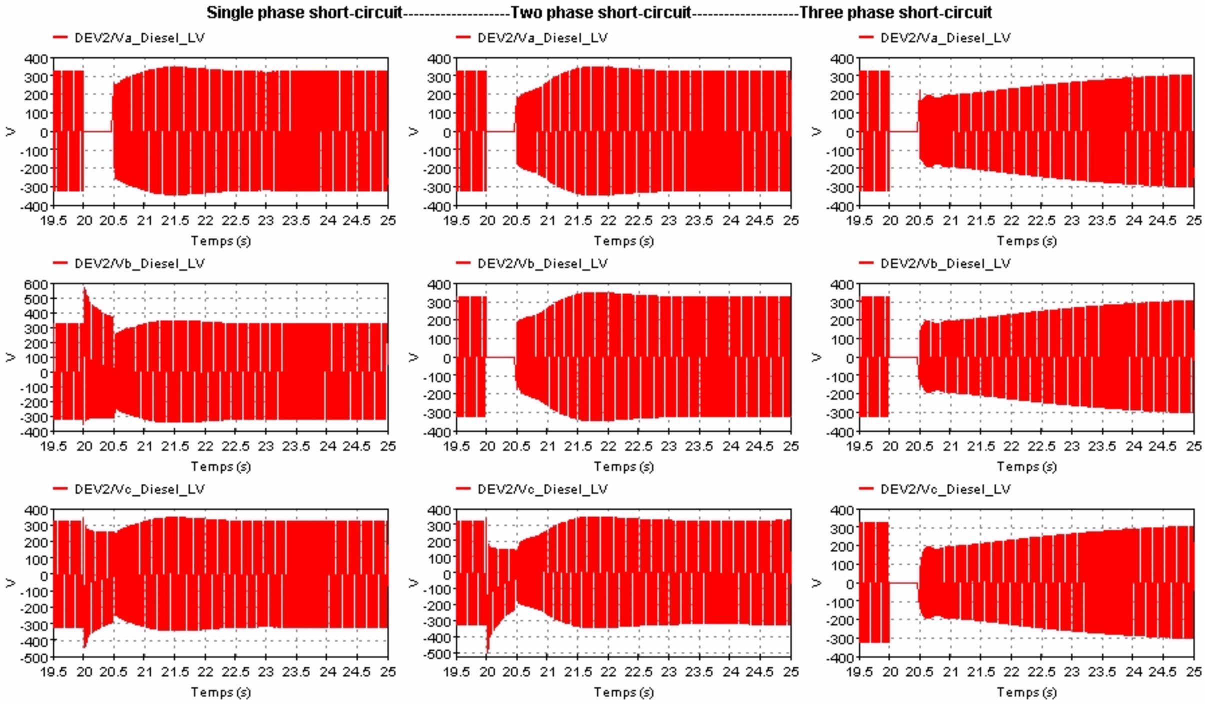

Figure 6.5.1-24: Voltages in all 3 phases of diesel generator during and following a fault at diesel generator terminals

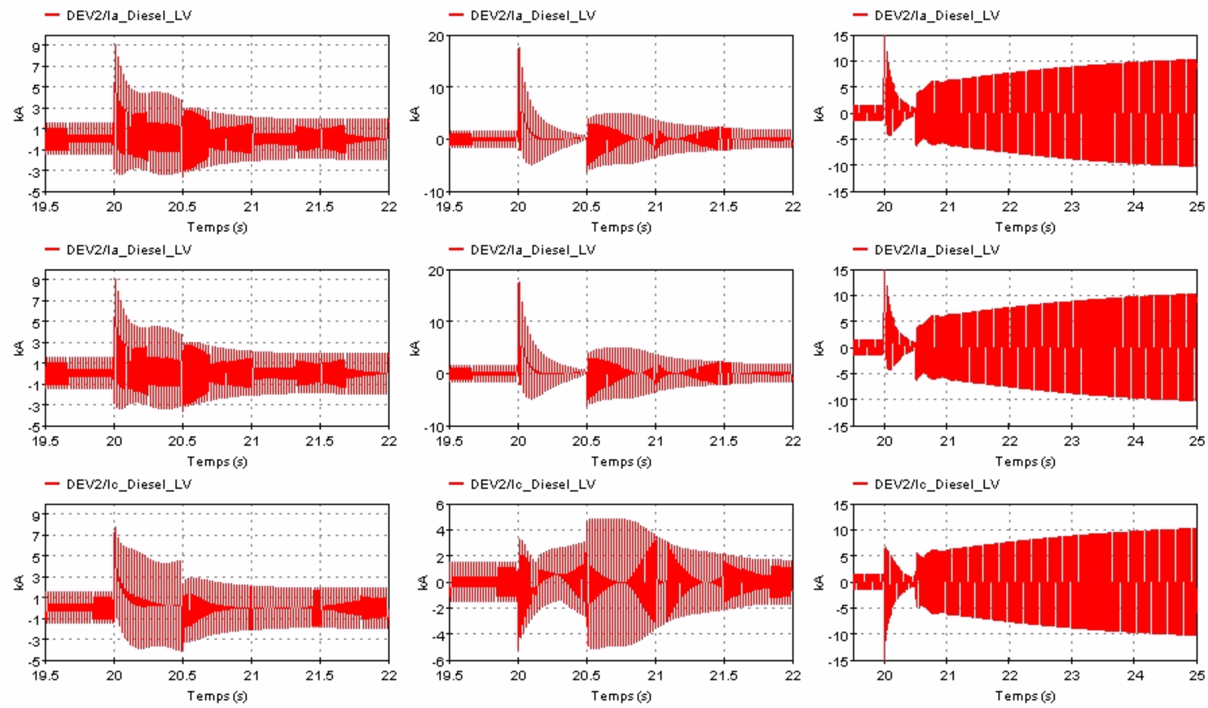

Figure 6.5.1-25: Currents in all 3 phases of diesel generator during and following a fault at diesel generator terminals

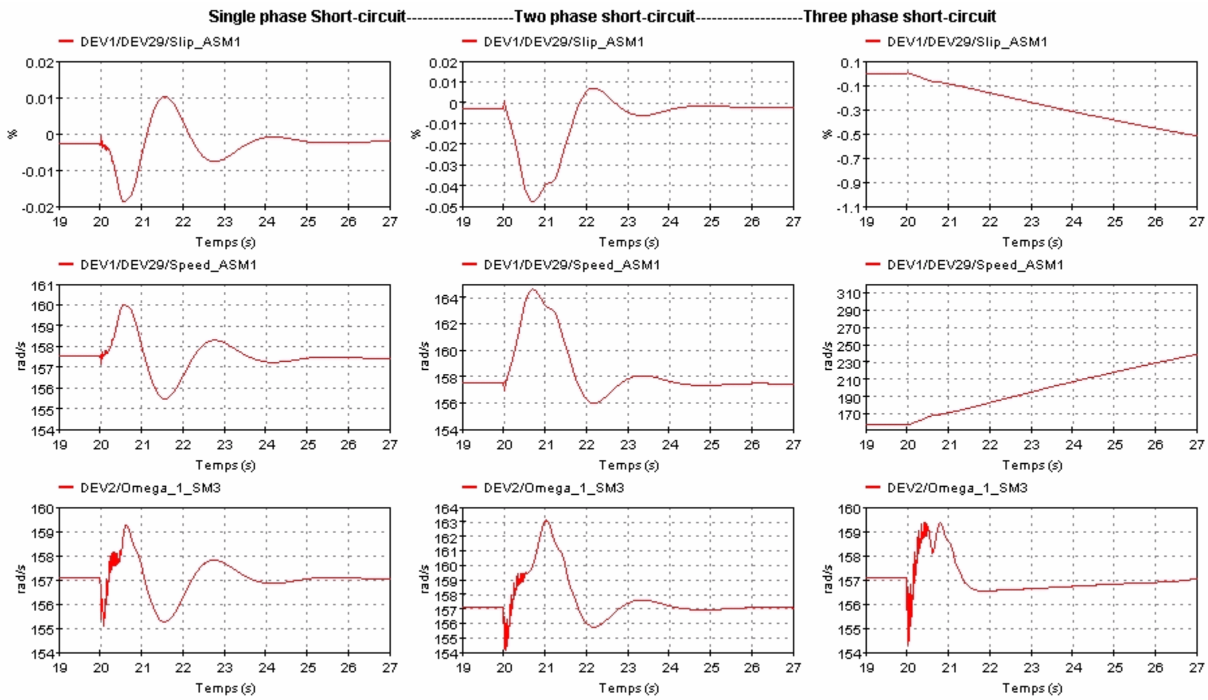

Figure 6.5.1-26: Slip, rotor speed of diesel generator (SM3) and a wind turbine (ASM1) during and following a fault at diesel generator terminals

<u>Results, interpretation and analysis</u>

When a short-circuit occurs at the diesel generator terminals, the voltage drops, the armature current rises rapidly to a high peak and the rotor of the machine accelerates. After the clearing of short-circuit (protection, self-clearing), the voltage recovers its normal value, the rotor speed and current as well.

One can see on Figure 6.5.1-21 to Figure 6.5.1-26:

- voltage dips in the faulted phases and returns to its pre-fault value,
- overvoltages (or undervoltages) in the unfaulted phases during the short-circuit,
- active and reactive power dips on the network during the fault. The active power to send into the network is reduced in case of a 1, 2-phase short-circuit and reaches zero in case of a 3-phase short-circuit,
- rotor speed increases during the fault and it decreases after clearing of fault,
- short-circuit current on the LV network can reach the nominal current several times (6 to 11 times at the nominal current) and decreases during the fault,
- grid frequency follows the rotor speed for the synchronous machine,
- grid frequency approximately follows the rotor speed concerning the asynchronous machine (difference corresponding to the slip). So, if the frequency changes, the rotor speed changes too.

NB: overvoltages in the unfaulted phases depend on types of short-circuits in faulted phases (1, or 2-phase) and capacitance of transformer.

The results show that the wind turbines (asynchronous ASM generator) lose its stability in case of a three phase short-circuit of 500 ms duration and the network becomes unstable. In fact, the rotor speed of the asynchronous machine and the power on the network do not return to normal operation (initial value). On the other hand, in case of a single or two phases short-circuit, the power system is stable, i.e. the rotor speed, power… comes back to synchronism speed, nominal value…. So, a three phase fault is the most severe regarding overspeed and voltage dips. The rotor speed might set off the protections: overspeed, overcurrent ….

NB: protections have not been taken into account in this study.

6.5.1.2.5. Case 2.4: Short-circuit at wind turbine terminals

A three phase short-circuit at wind turbine terminals is simulated. The procedure here is the same as in case 2.3 above. The simulation results are illustrated in the following figures:

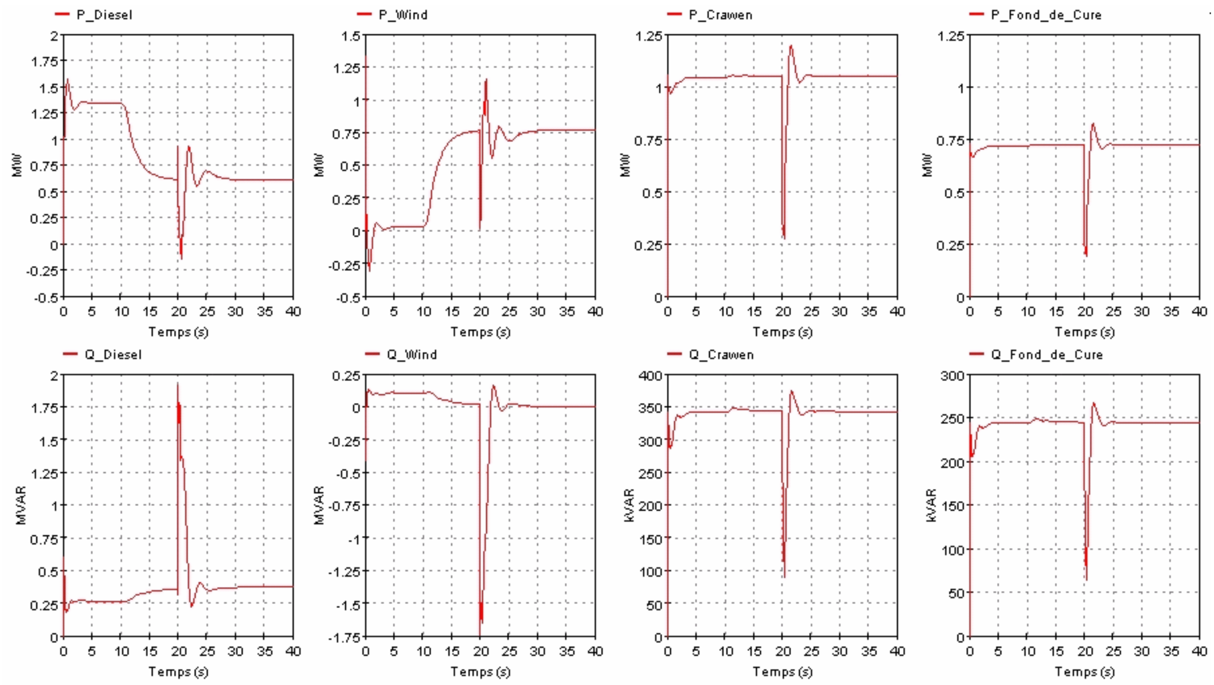

Figure 6.5.1-27: Active and reactive power of diesel generator and the wind farm - Active and reactive at substations (Crawen & Fond de Cure) during and following a fault at wind turbine terminals

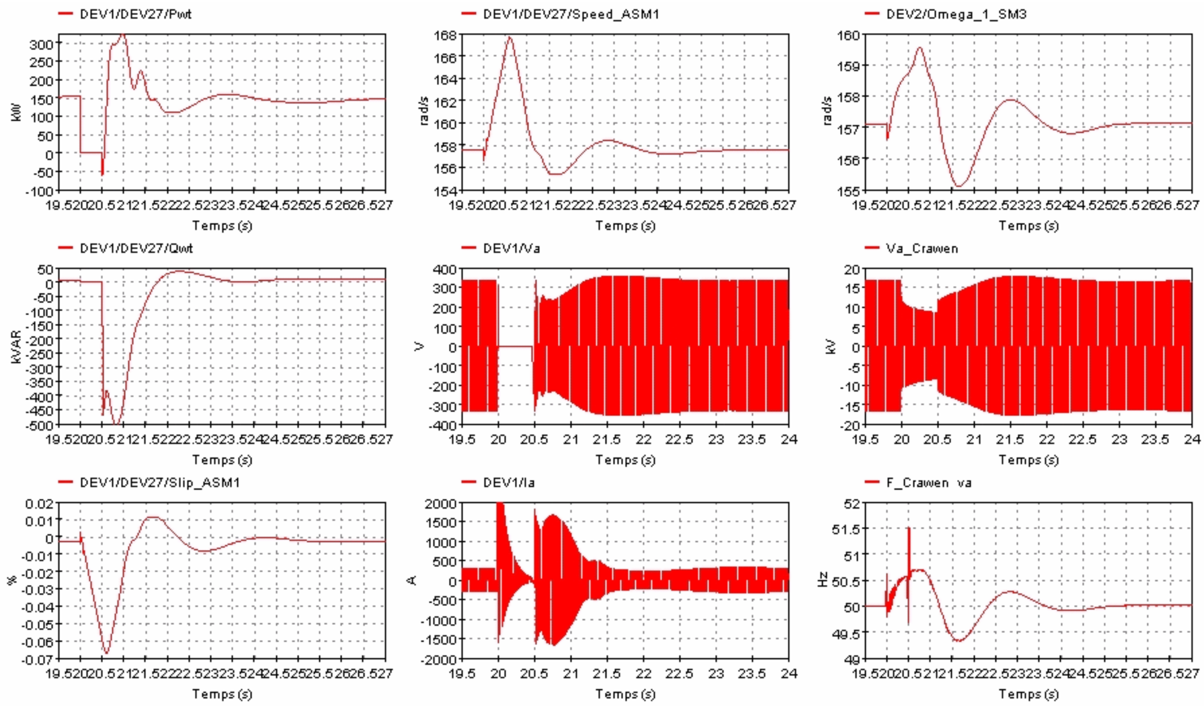

Figure 6.5.1-28: Active, reactive power, slip, rotor speed, voltage and current of a wind turbine (ASM1) - Rotor speed of diesel generator (SM3) - Voltage and frequency at substation Crawen during and following a fault at wind turbine terminals

<u>Results, interpretation and analysis</u>

As expected, the simulation results show that during a three phase short-circuit at wind turbine terminals, the output power and the voltage drop to zero and the rotor accelerates. After the clearing of the fault, the voltage system recovers its initial value. The power system remains stable during and following a three short-circuit at wind turbine terminals (see voltage, power and rotor speed on Figure 6.5.1-27 and Figure 6.5.1-28).

6.5.1.2.6. Case 2.5: Short-circuit at substation Crawen

A single/two phase and three phase short-circuit on the 20 kV network (Medium Voltage - substation Crawen) are simulated.

The procedure (or simulation set-up) is:

- diesel generator and wind turbines are connected to the grid (normal operation),
- at t= 20 s, a fault (1, 2 or 3-phase short-circuit) is made to occur at substation Crawen. Then, the fault is cleared in 500 ms (eliminated at t= 20.5 s).

The curves below show the transient state and the dynamic behaviour of the asynchronous (wind turbines) and synchronous (diesel) generators.

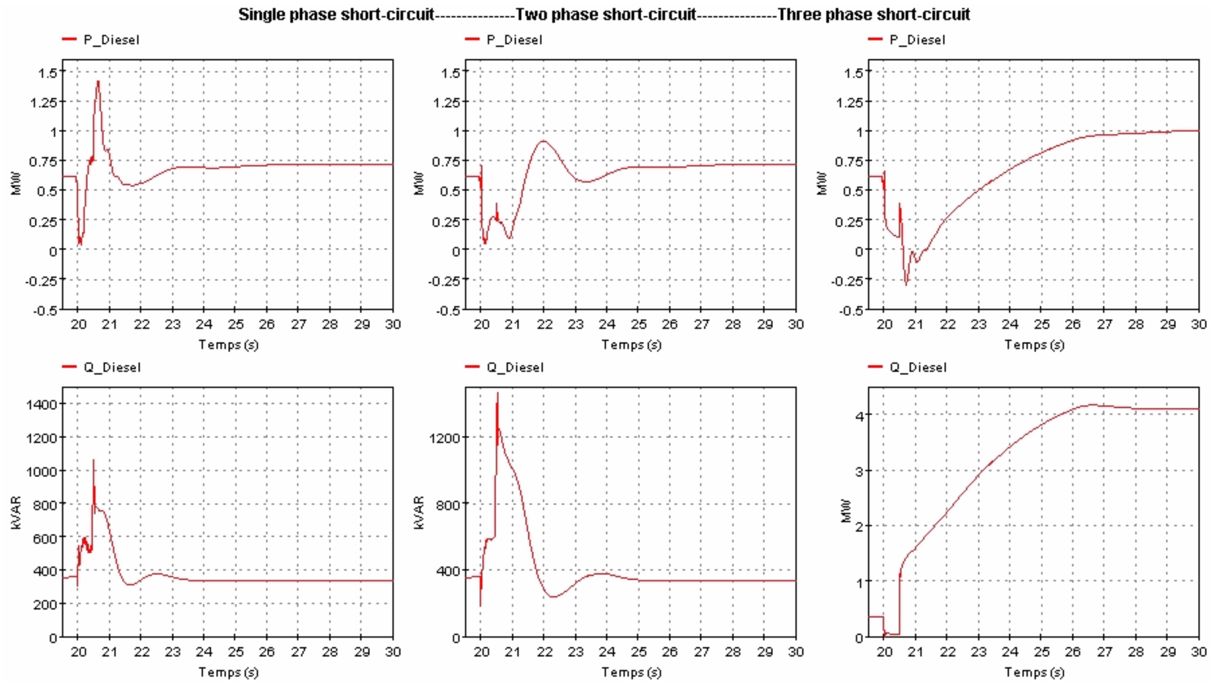

Figure 6.5.1-29: Active, reactive power of diesel generator during and following a 1, 2 or 3-phase short-circuit at substation Crawen (MV network)

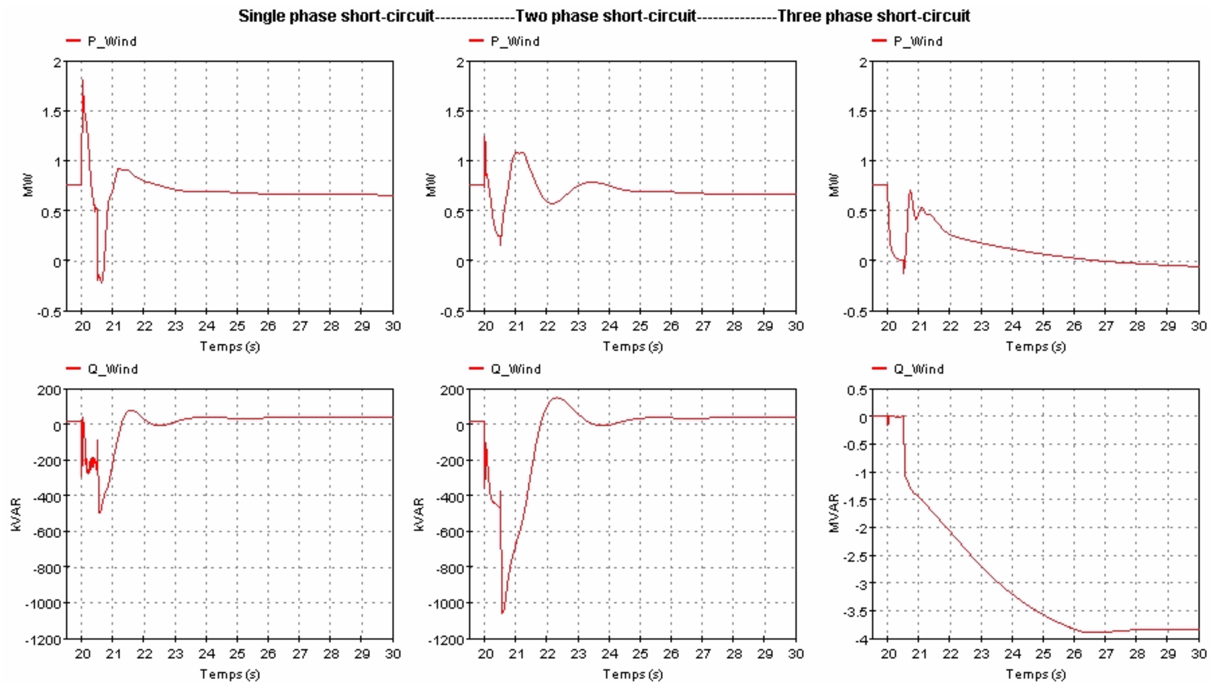

Figure 6.5.1-30: Active, reactive power of the wind farm during and following a 1, 2 or 3-phase short-circuit at substation Crawen (MV network)

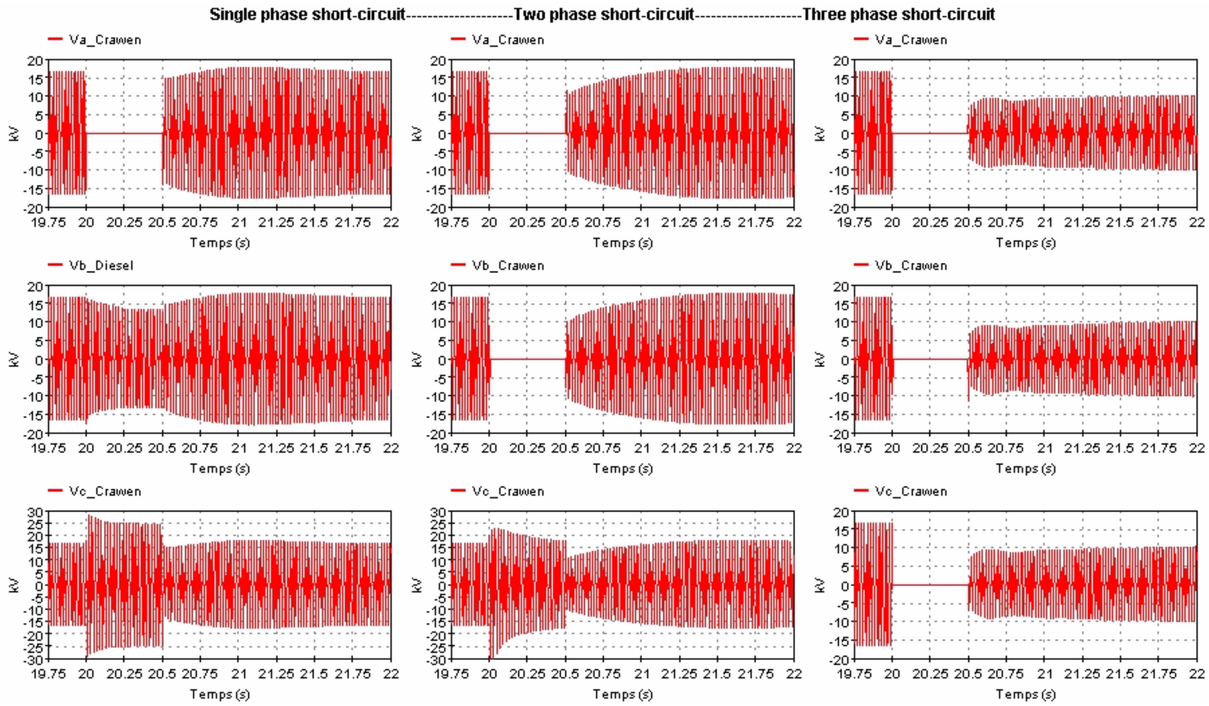

Figure 6.5.1-31: Voltages in all three phases (a, b and c) at substation Crawen during and following a 1, 2 or 3-phase short-circuit at substation Crawen (MV network)

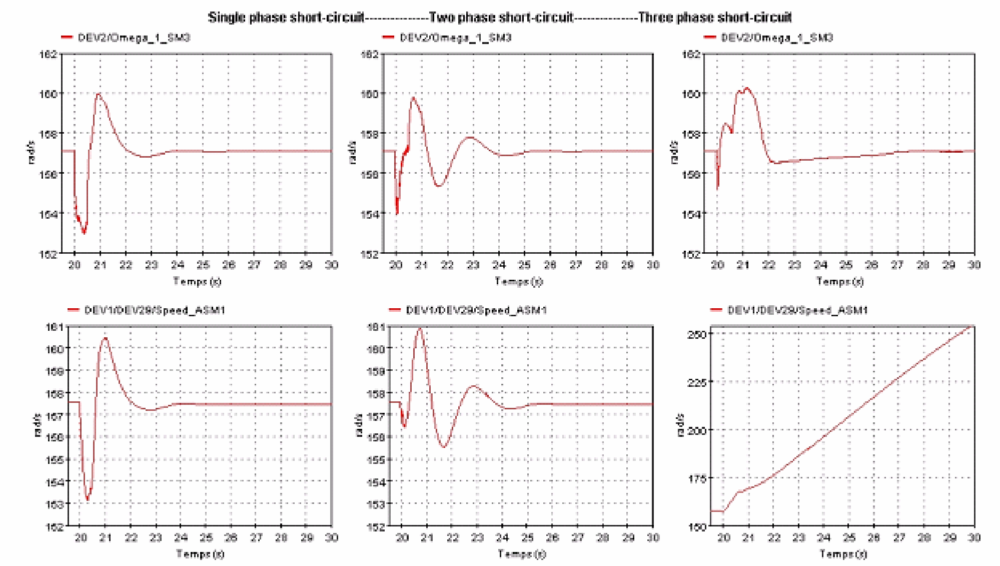

Figure 6.5.1-32: Rotor speed of diesel generator (SM3) and a wind turbine (ASM1) during and following a 1, 2 or 3-phase short-circuit at substation Crawen (MV network)

Results, interpretation and analysis

For an unsymmetrical fault (1 and 2-phase short-circuit) of duration 500 ms, the wind turbines generators remain connected to the network. On the other hand, for a three short-circuit at substation Crawen, the wind turbine loses stability, resulting instability of network.

The figures above show that the three phase short-circuit is the most constraining in terms of stability, voltage dips, power dips, rotor speed….

6.5.1.2.7. Case 2.5 bis: Three phase short-circuit at substation Crawen - fault clearance time)

In order to analyze the impact of fault clearance time, particularly on the stability of power system, several durations have been simulated. The power system operating in normal conditions (nominal power, voltage…), a 3-phase short-circuit at Crawen substation (MV network) is applied. Then, the short-circuit is cleared in 100 ms, 250 ms and 500 ms.

The following figures show the simulation results for 100 ms, 250 ms and 500 ms fault time (see Figure 6.5.1-33 to Figure 6.5.1-36).

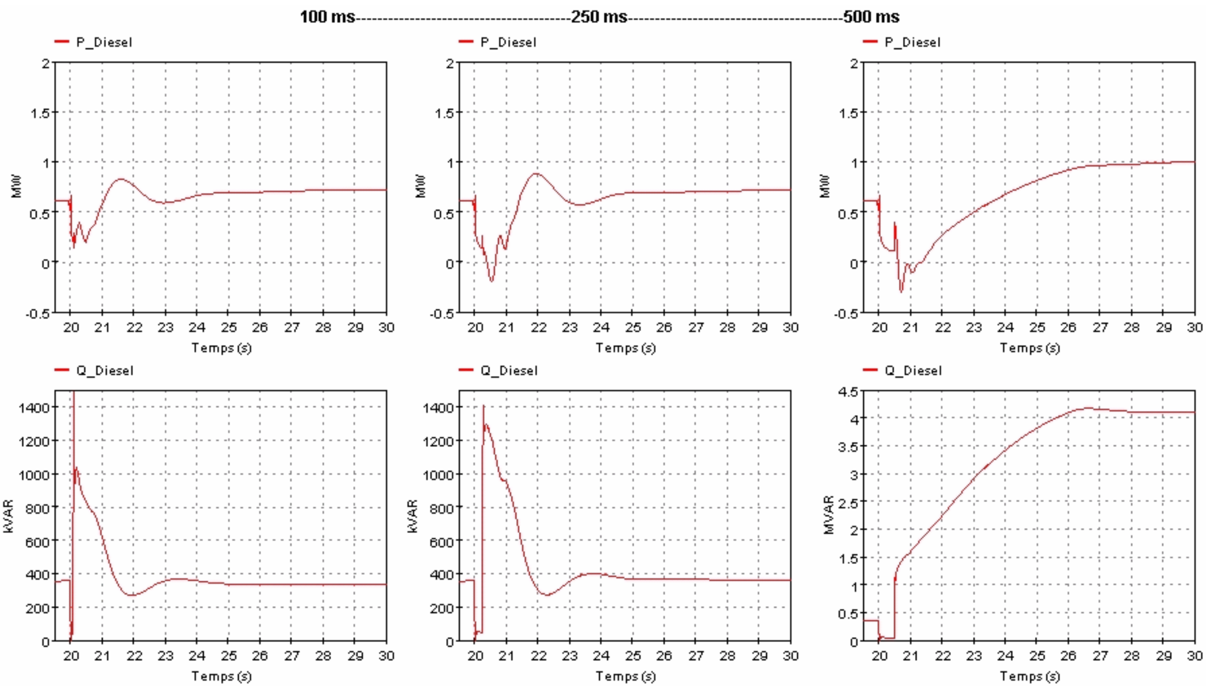

Figure 6.5.1-33: Active, reactive power of diesel generator during and following a 3-phase short-circuit at substation (MV network) cleared in 100 ms, 250 ms and 500 ms

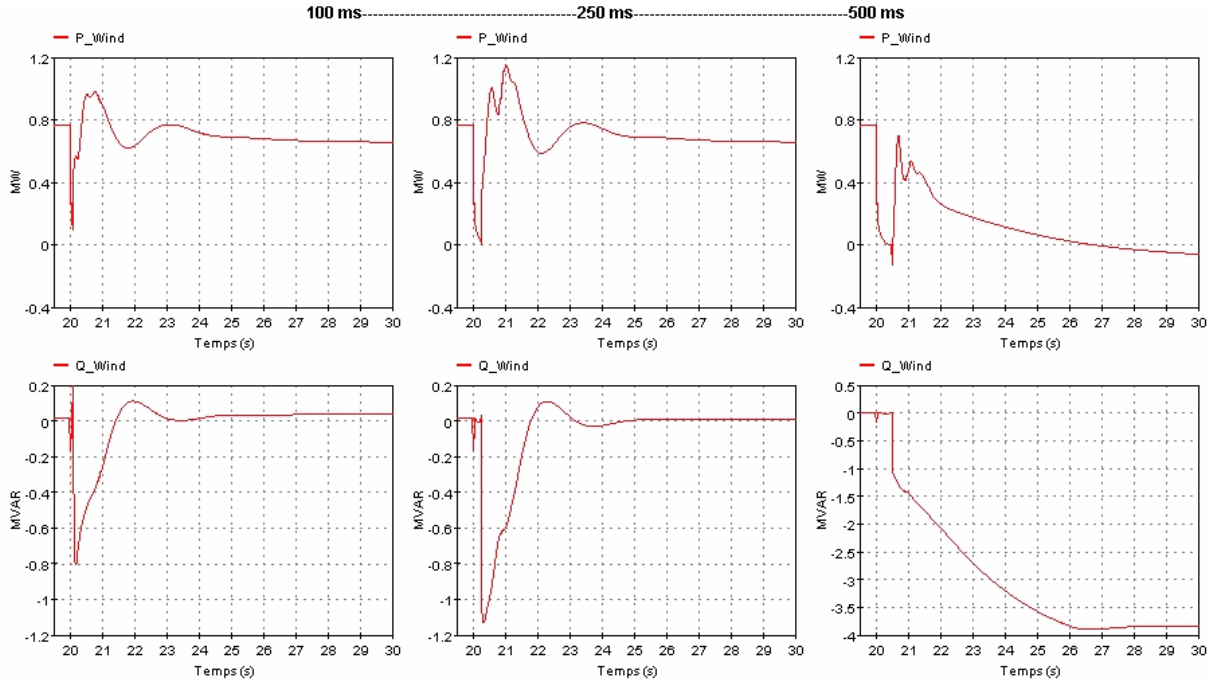

Figure 6.5.1-34: Active, reactive power of the wind farm during and following a 3-phase short-circuit at substation Crawen (MV network) cleared in 100 ms, 250 ms and 500 ms

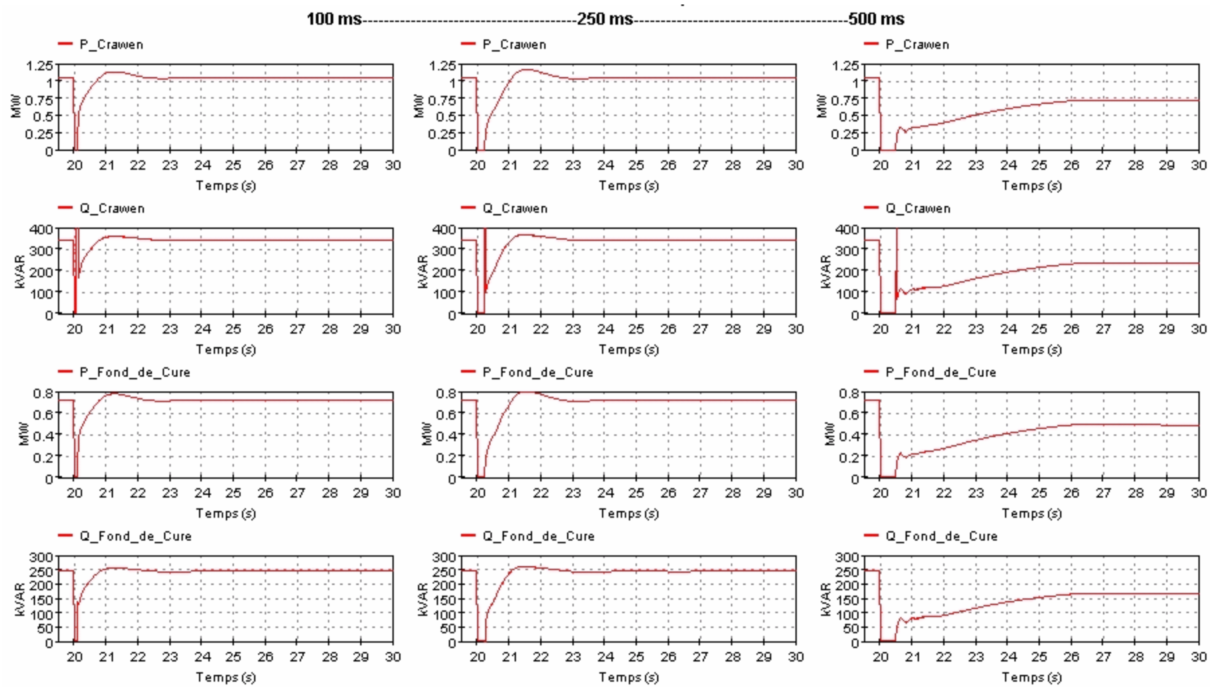

Figure 6.5.1-35: Active and reactive power at substations Crawen & Fond de Cure (MV network) during and following a 3-phase short-circuit at substation Crawen cleared in 100 ms, 250 ms and 500 ms

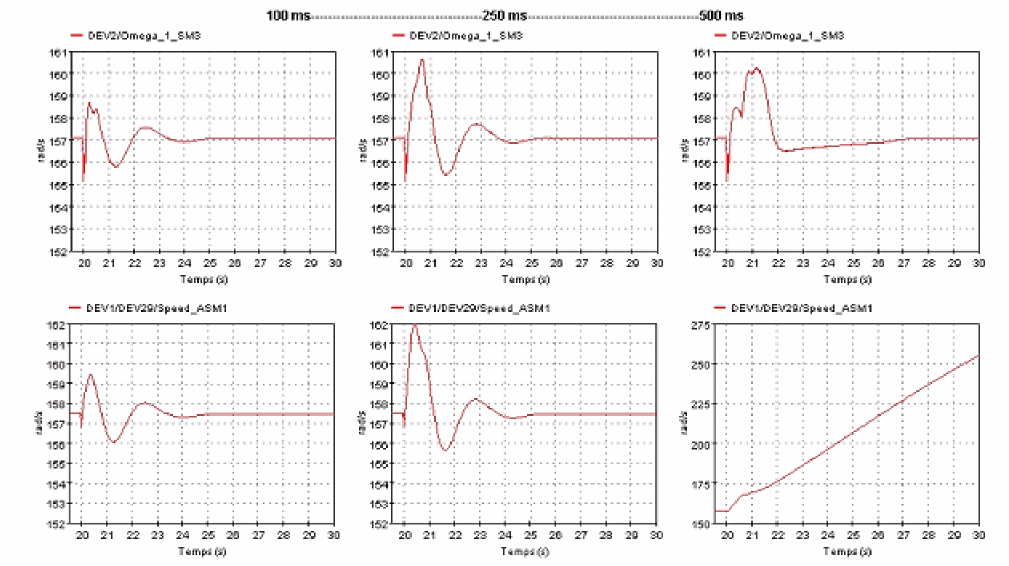

Figure 6.5.1-36: Rotor speed of diesel generator (SM3) and a wind turbine (ASM1) during and following a 3-phase short-circuit at substation Crawen (MV network) cleared in 100 ms, 250 ms and 500 ms

Results, interpretation and analysis

As can been seen on the figures above, the time limits for the clearing of fault (short-circuit) before loss of stability of the power system is about 300 ms (transient stability limit). As expected, fault-clearing times affect only dip duration.

6.5.1.2.8. Case 2.6: Disconnection of loads Terre de Haut

The aim is to simulate a sudden disconnection of loads (islanding or part load). The procedure (or simulation set-up) is:

- diesel generator and wind farm are connected to the grid (normal operation:
- P_{wind}= 770 kW and P_{Diesel}= 603 kW) and the load is set to 1384 kW (full load),
- at t=30 s, the load is set to 321 kW, i.e. the load Terre de Haut is disconnected from network, while the wind power stays the same (770 kW).

The simulation results are illustrated on figures Figure 6.5.1-37 to Figure 6.5.1-40.

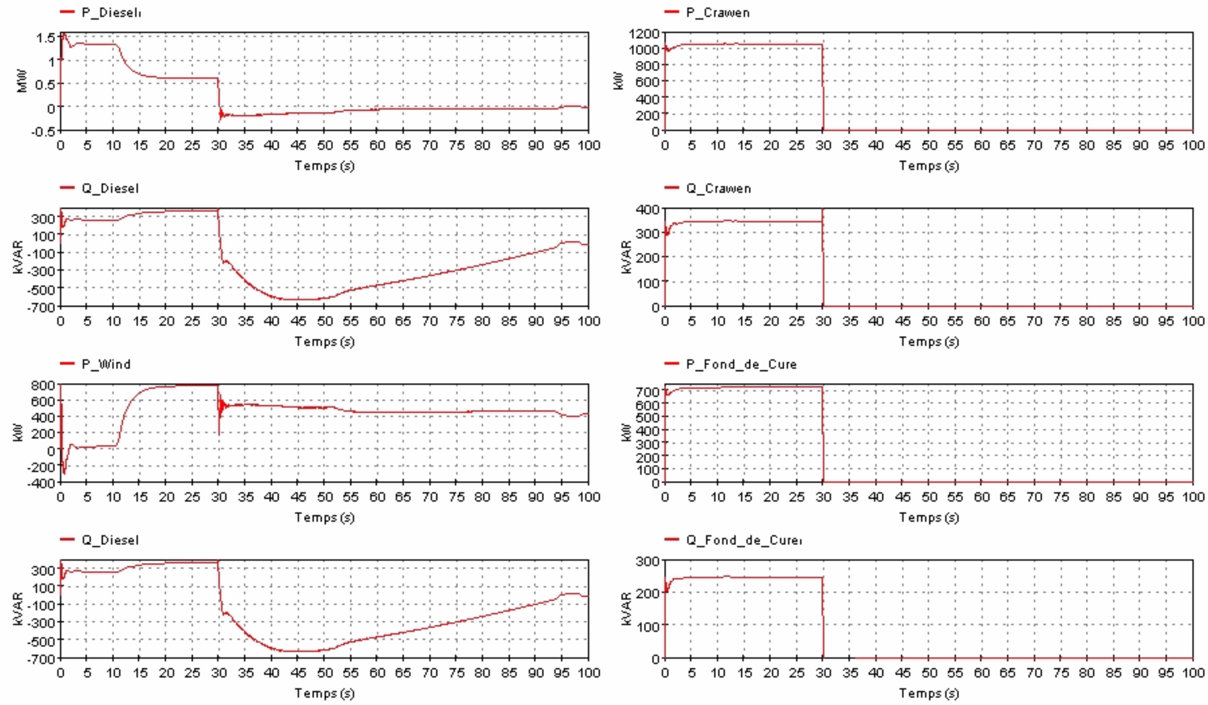

Figure 6.5.1-37: Active, reactive power of diesel generator and the wind farm during and following a disconnection of loads

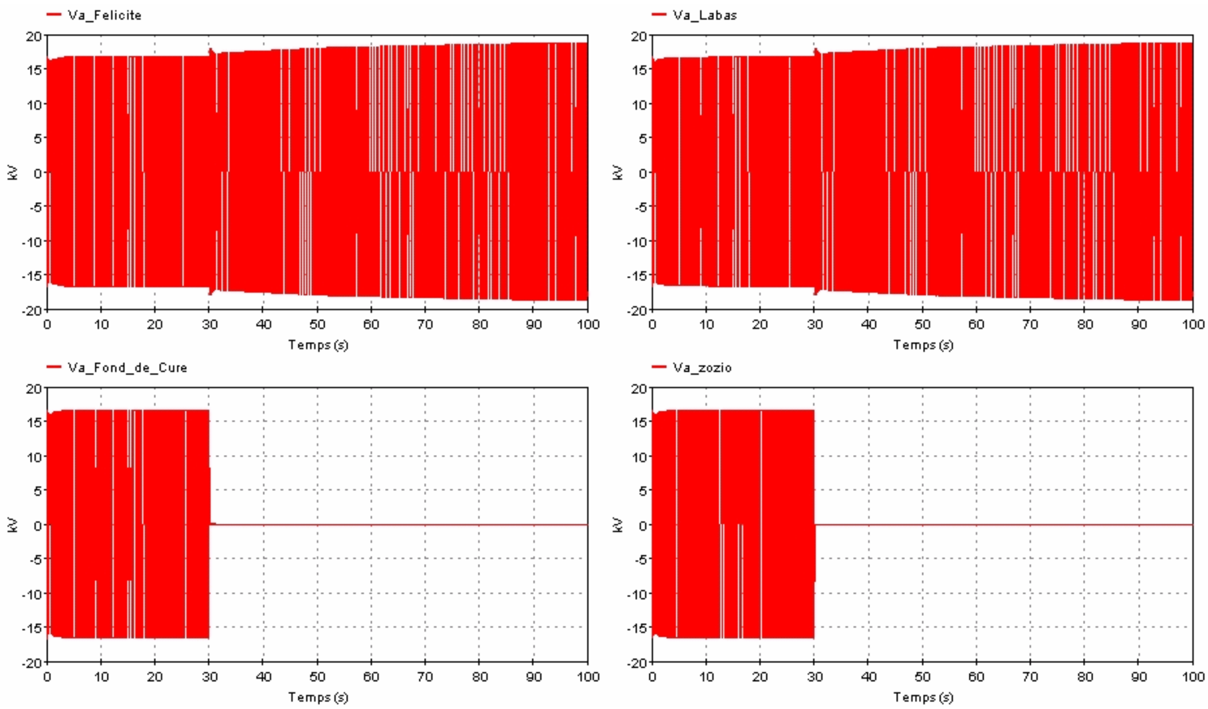

Figure 6.5.1-38: Voltages on the MV network (substations: Felicite, La Bas, Fond de Cure and Zozio) during and following a disconnection of loads

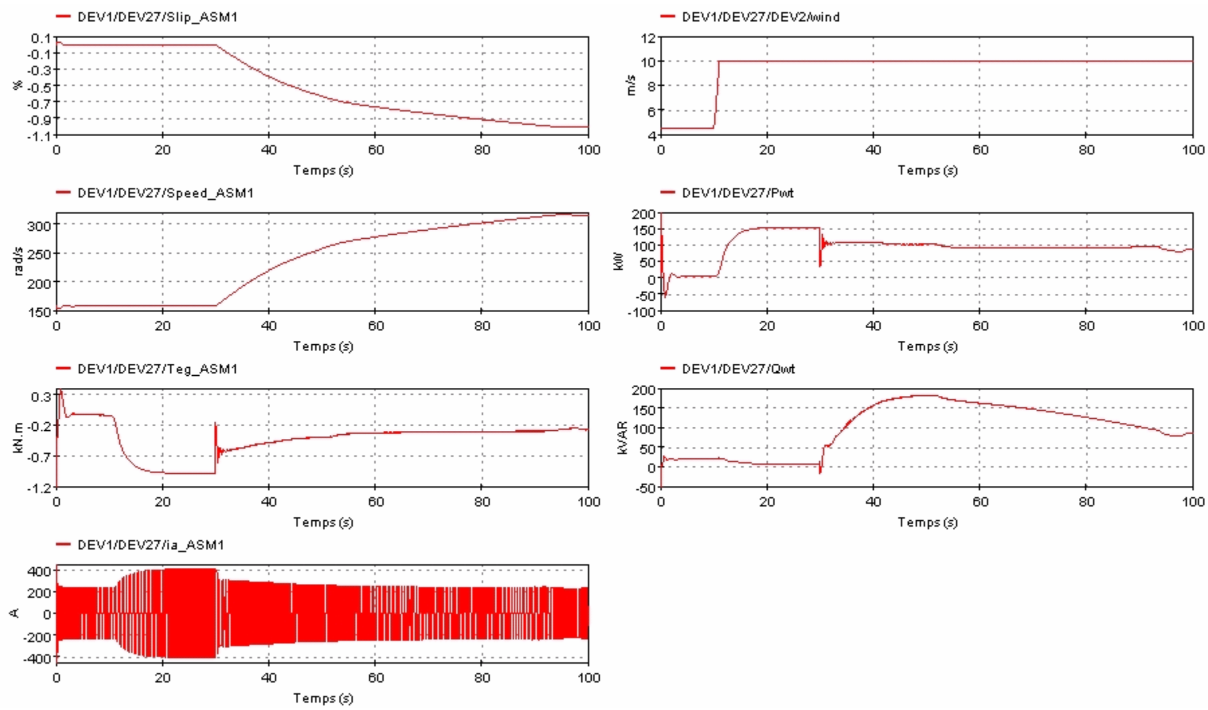

Figure 6.5.1-39: Slip, rotor speed, electromagnetic torque and current of a wind turbine (ASM1) during and following a disconnection of loads

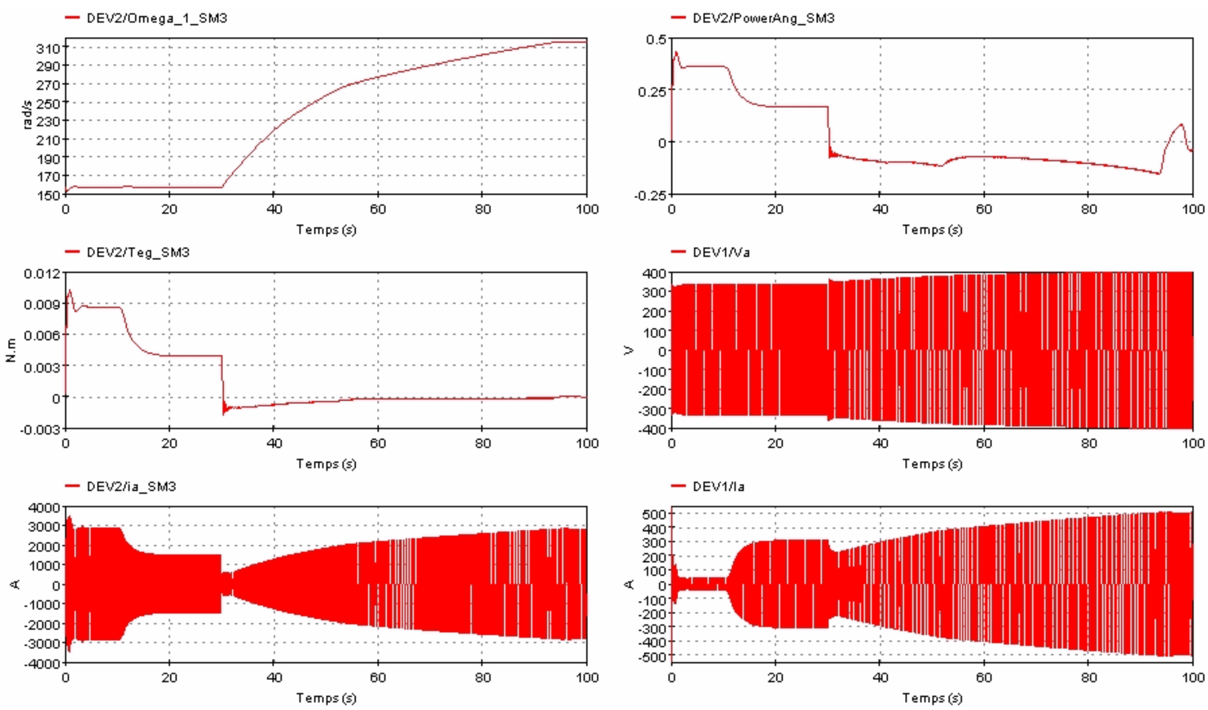

Figure 6.5.1-40: rotor speed, electromagnetic torque, rotor angle, voltage and current of diesel generator (SM3) during and following a disconnection of loads

<u>Results, interpretation and analysis</u>

In this case, the wind output power (5*150 kW) exceeds the power required by the load (321 kW). Exceeding active power is consumed by the diesel (-197 kW) and wind farm (537 kW). As a result, the synchronous generator (diesel genset) becomes a synchronous motor, which tends to accelerate the rotor speed of diesel. This operation mode, i.e. oversized wind turbine in comparison to the loads results in gradual increase in frequency and voltage diesel, as well as voltage on the whole network (404.2 V LV, 18.8 kV MV and f>> 50 Hz). In such an operation, i.e. diesel generator operating as a synchronous motor, the rotor speed increases a lot (Nn >> 1500 tr/min), the diesel governor loses its speed control and the frequency rises. As a result, the power system becomes unstable: the power and rotor speed of diesel (synchronous machine) and wind turbines (asynchronous machine) do not return to their nominal value. In this simulation, the low operation limit of the diesel (synchronous motor) is observed and will be used to restrict wind generation/diesel generation (see Figure 6.5.1-41, omega_1_SM3 on Figure 6.5.1-40).

On the other hand, the power system becomes stable again when 2 wind turbines operate on the network, they produce about 2*150 kW (see Figure 6.5.1-41)

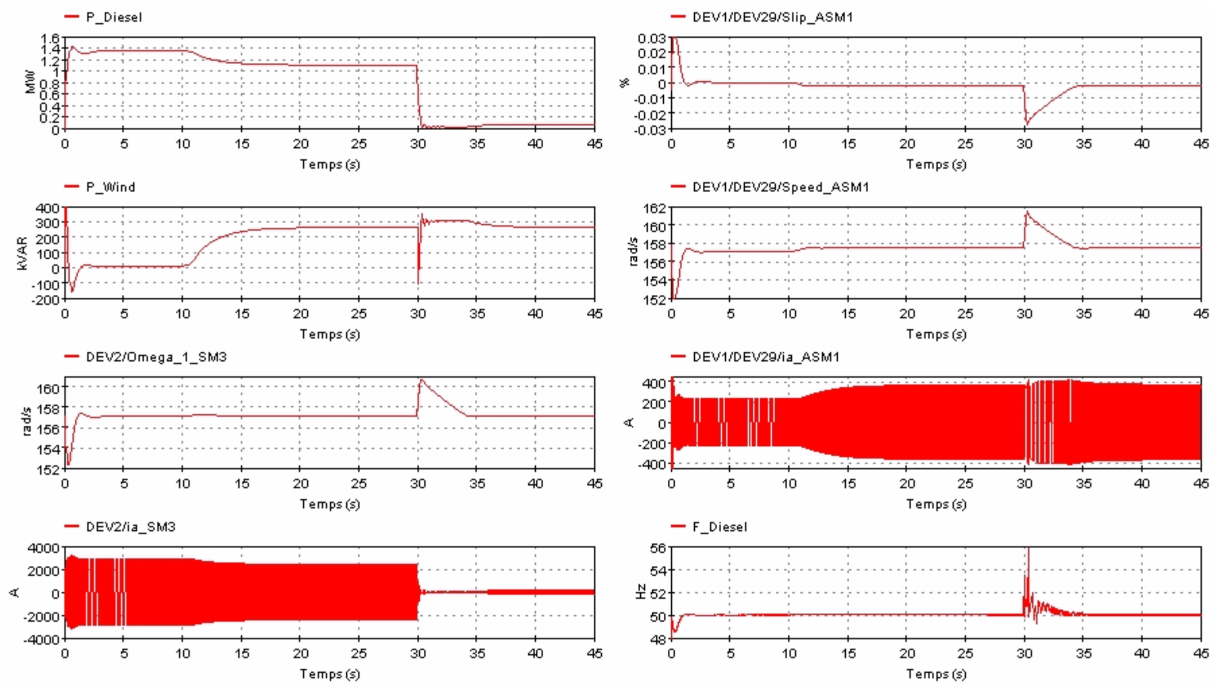

Figure 6.5.1-41: Active power, rotor speed, current, slip, frequency of diesel generator (SM3) and a wind turbine (ASM1) during and following a disconnection of loads

6.5.1.3. Scenario 3: DG on/off, WT on/off and Power Injector on/off

The purpose is to study the dynamic behaviour of a wind farm, diesel generator and power injector operating in parallel with the idea of a power injector replacing the energy storage systems, e.g. discharge of batteries. The power injector can either be connected in parallel to the wind farm (5*wind turbines) terminals or only to one wind turbine terminals through a step-up LV/MV transformer.

6.5.1.3.1. Case 3.1: Disconnection of the wind farm and connection of a power injector

In case of disconnection of the wind farm on the network (caused, for instance, by wind changes or by a constraining fault), the power injector supplies the active and reactive power delivered by the wind farm. So, it functions as if the power injector replaced the wind farm (e.g. shutdown wind turbines).

The procedure (or simulation set-up) is:

- diesel genset and wind farm are connected to the grid (normal operation),
- at t= 30 s, the wind turbines are disconnected from the network and at the same time the power injector is connected to the grid (LV network).

The main electrical quantities computed by software can be seen in the following figures.

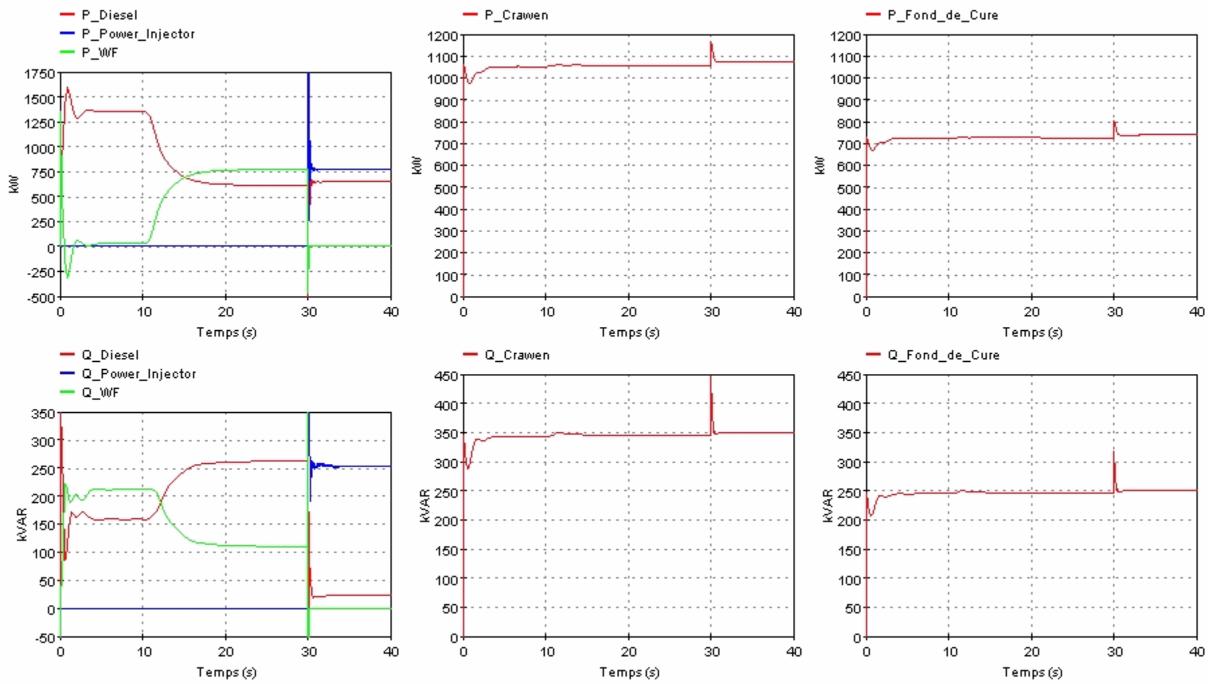

Figure 6.5.1-42: Active and reactive power of diesel generator, the wind farm, the power injector and at substations in case of disconnection of wind farm

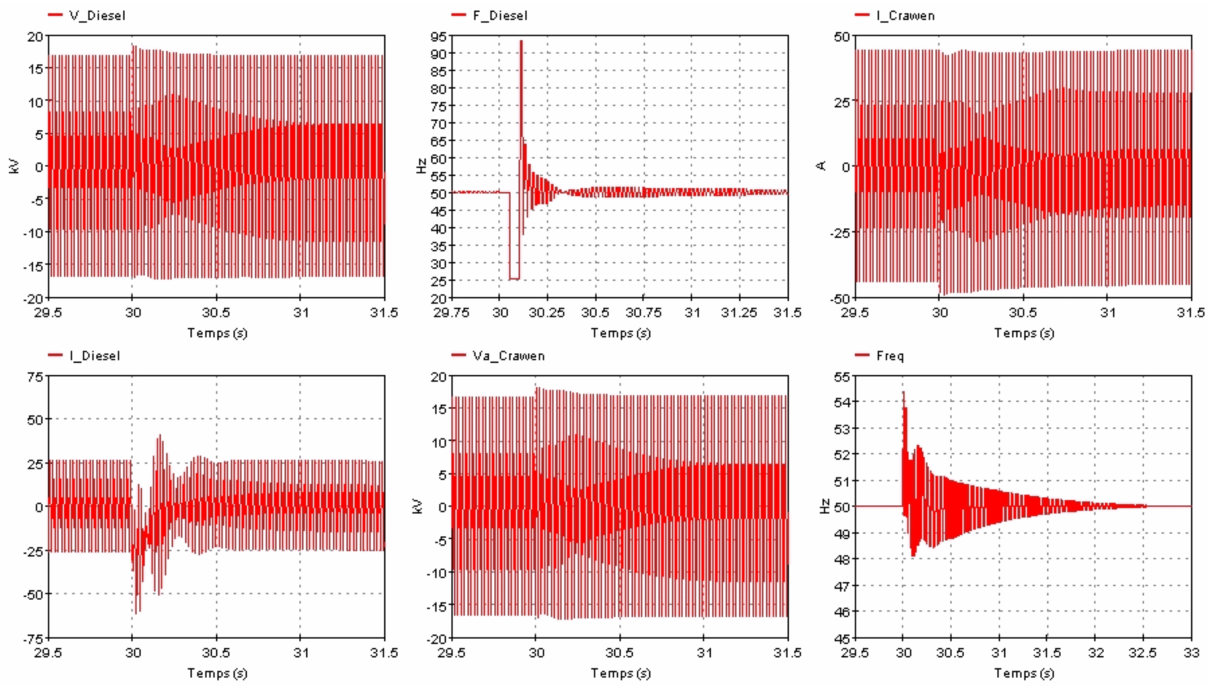

Figure 6.5.1-43: Voltages and frequencies of diesel generator and at substation Crawen in case of disconnection wind farm

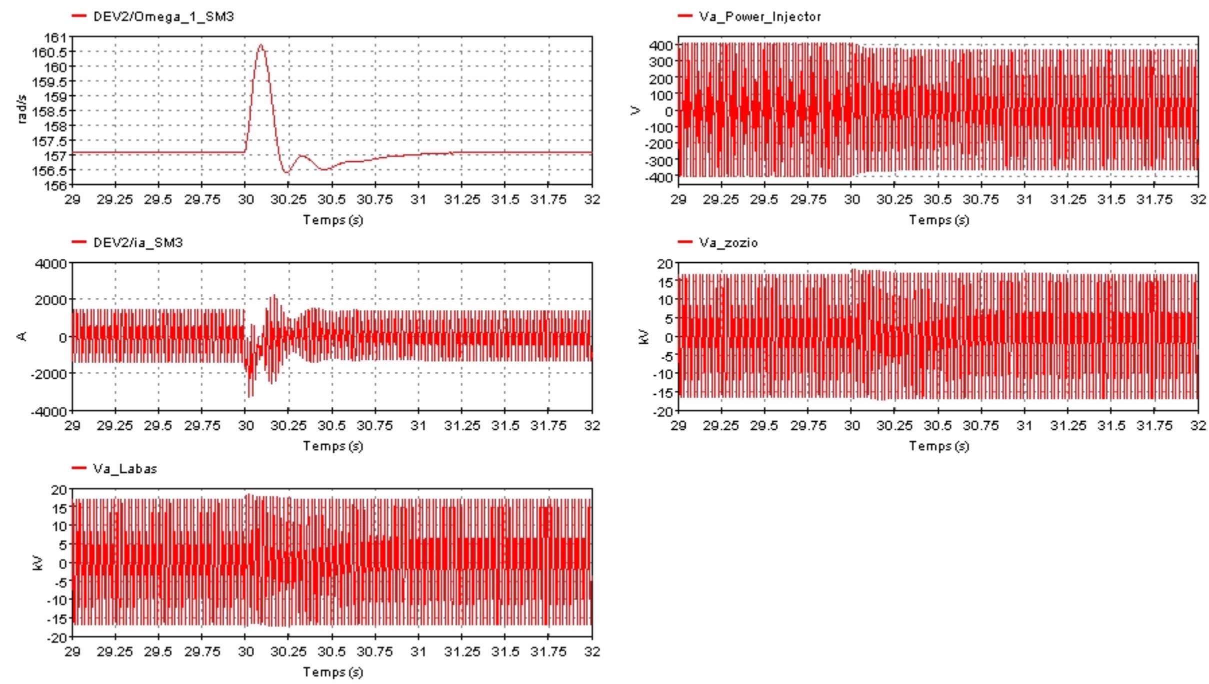

Figure 6.5.1-44: Speed rotor, current of diesel generator - Voltages of the power injector and at substation Zozio in case of disconnection wind farm

Figure 6.5.1-45 shows the power injector's dynamic response in case of disconnection of the wind farm.

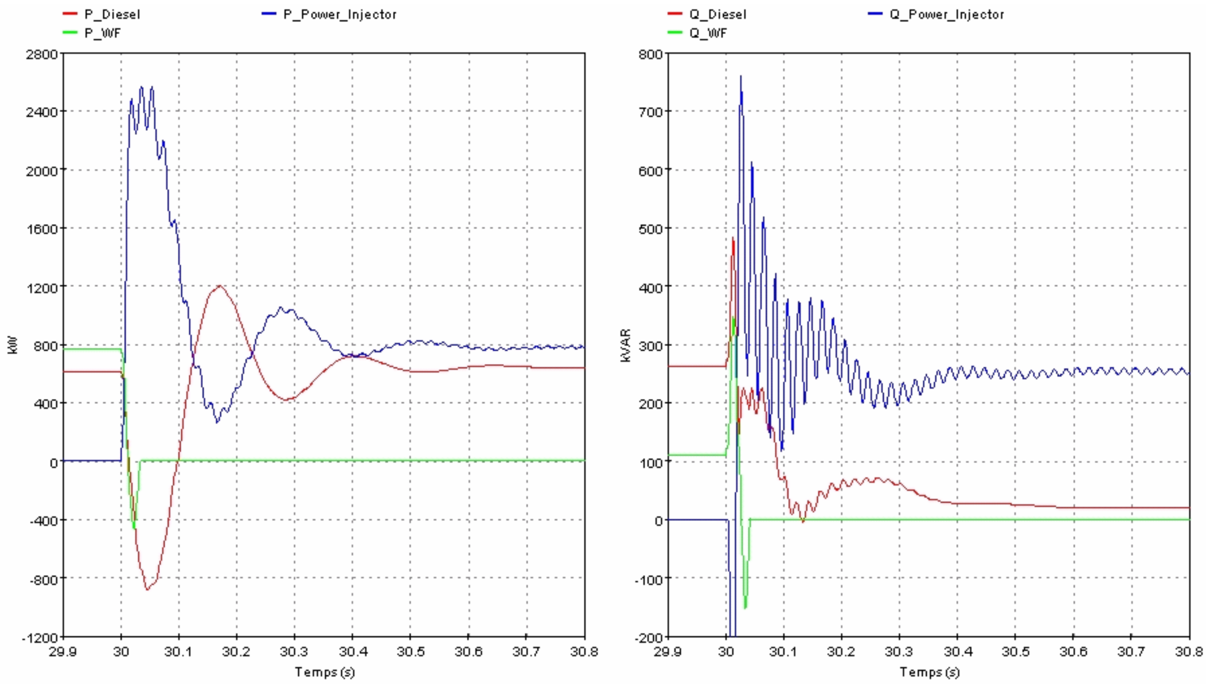

Figure 6.5.1-45: Active and reactive power of diesel generator, the wind farm and the power injector following the wind farm disconnection

<u>Results, interpretation and analysis</u>

Concerning the final state, as expected, the active power output of the power injector is similar to the initial output of the wind farm. Nevertheless, it should be noted that the reactive power final situation is very different from the initial one: the global amount of reactive power generated is reduced by a third, and it is mainly produced by the power injector, instead of the diesel generator.

Concerning the transient (see Figure 6.5.1-42 to Figure 6.5.1-45), it appears that the injector response is very fast, so that the power output is temporarily higher than the wind farm previous output. As a consequence, the frequency reaches 51 Hz, and damped oscillations can be observed on the diesel and the injector active outputs. This situation could be improved by adjusting the controls of the injector.

As the simulation results show, the power system (diesel and power injector) is stable and efficient from a dynamic point of view during and following its connection to the network, the electric and mechanical quantities reach their normal operation and magnitude a few milliseconds (see Figure 6.5.1-45, specifically dynamic responses).

6.5.1.3.2. Case 3.2: Disconnection of diesel and connection of a power injector (energy storage)

In this simulation, the power injector replaces the diesel generator when the diesel generator is shutdown in case of an incident or an outage.

The procedure (or simulation set-up) is:

- diesel genset and wind farm are connected to the grid (normal operation),
- at t= 30 s, the diesel generator is disconnected from the network and at the same time the power injector is connected to the grid (LV network).

The simulation results can be seen in the following figures.

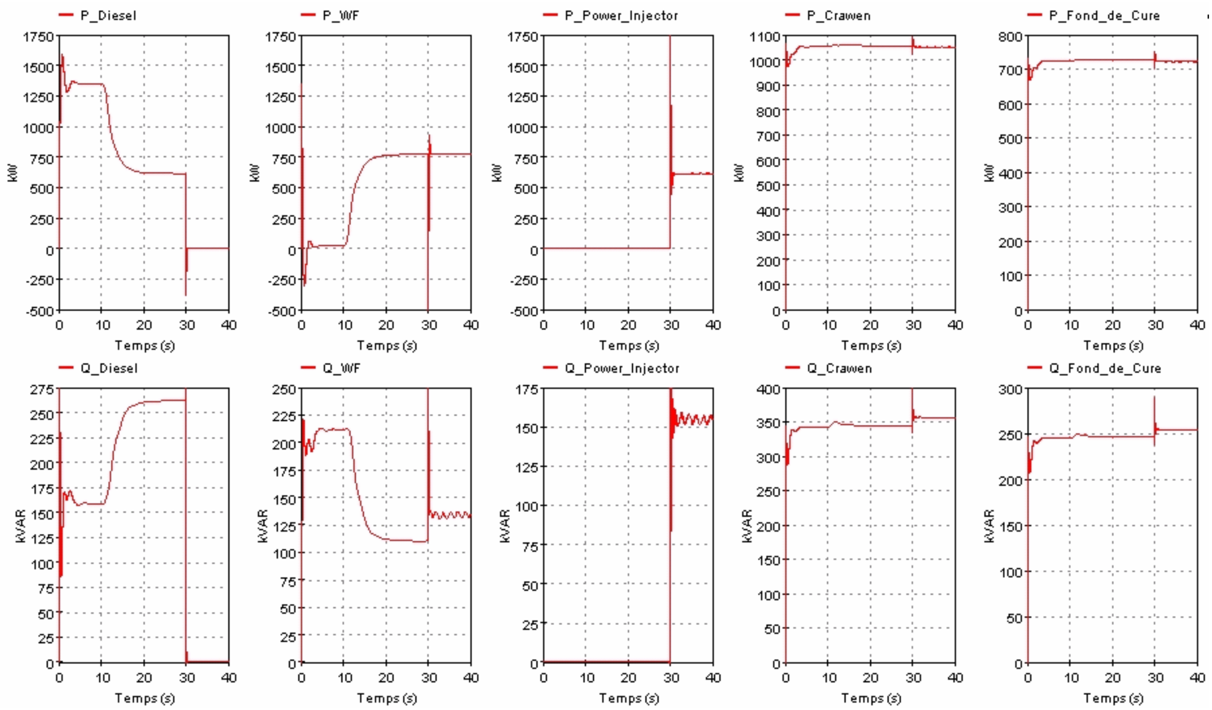

Figure 6.5.1-46: Active and reactive power of diesel generator and the wind farm - Active and reactive power of the power injector - Active and reactive power at substations (Crawen and Fond de Cure) following the diesel unit disconnection

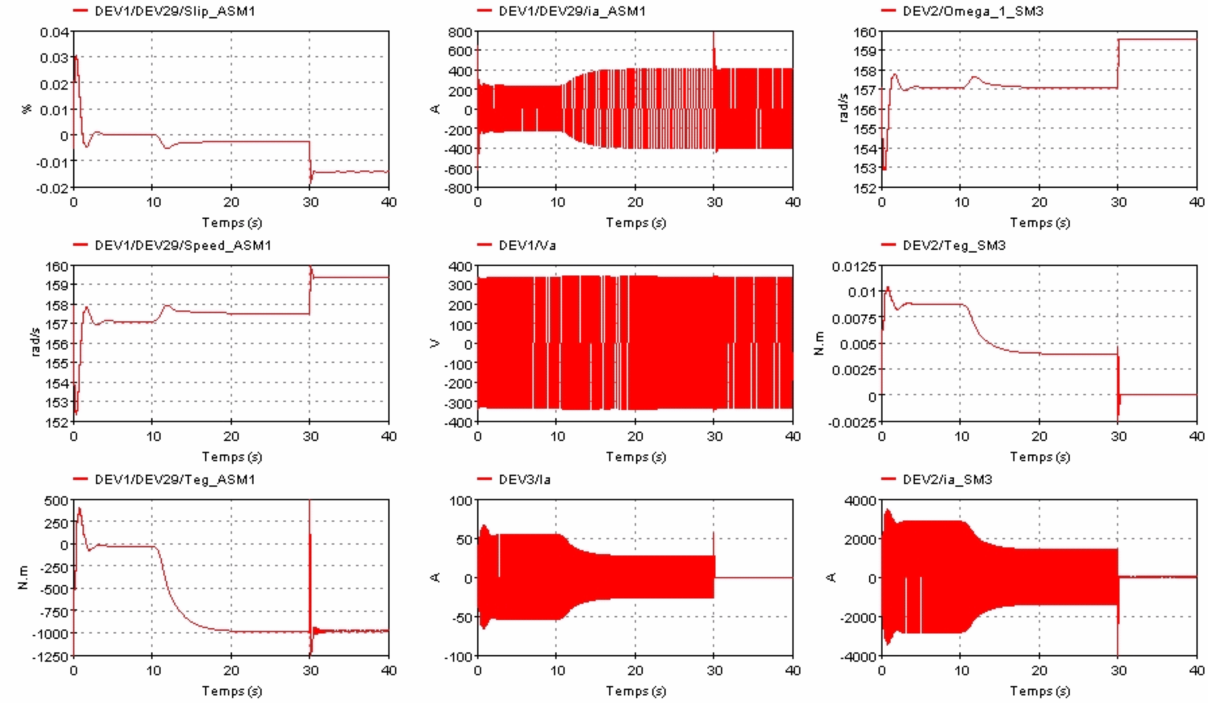

Figure 6.5.1-47: Slip, rotor speed, electromagnetic torque, current, voltage and current of the wind turbine (ASM1) - Rotor speed, electromagnetic torque and current of diesel generator (SM3) following the diesel unit disconnection

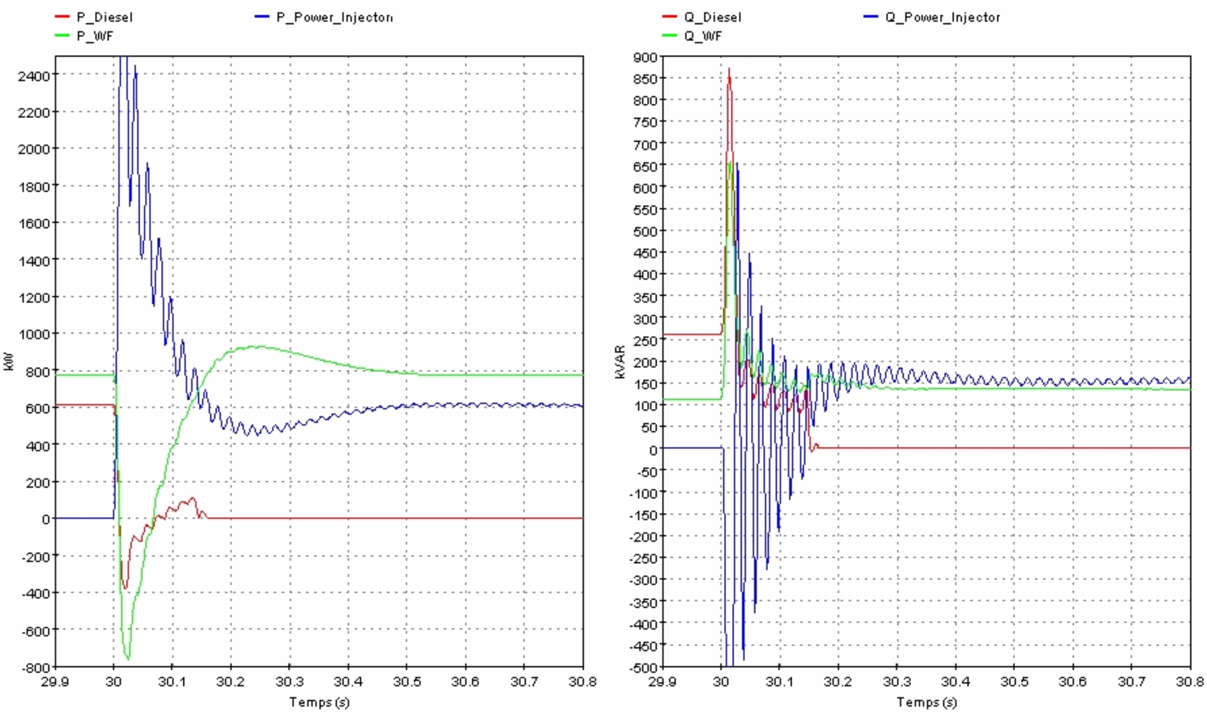

Figure 6.5.1-48: Active and reactive power of diesel generator, the wind farm and the power injector following the diesel unit disconnection

Results, interpretation and analysis

As in case 3.1, the storage device, represented by the injector, generate an active power output equal to the initial output of the shutdown unit (the diesel unit in this case), and the final reactive power situation is significantly different from the initial one. The transient is mostly determined by the governor and voltage control settings.

It should be noted that in the final configuration, the power injector controls the frequency and voltage on the network. It means that the power injector will have to adjust active and reactive power in response to any change occurring on the system, in particular load variations or wind changes.

Remark on the power injector

The storage system has been represented here as a power injector. It supposes that it has an active and reactive power control capability.

In the cases studied, the issue was to examine the behaviour during the transient and the stability of the system. So the storage charge issues were not taken into account. Some guidelines about possible further studies on this aspect are proposed as recommendations in the next section.

6.6. Results, conclusions and recommendations

We shall summarize and analyse the whole of simulation results presented in this report, performed with ElectroMagnetic Transients Program-Revised Version (EMT-RV) software, in order to draw the main conclusions and make some recommendations. The power system components are: a wind farm and diesel generator with energy storage system (power injector) on Les Saintes islands network operated in islanded mode.

6.6.1. Synthesis of simulations carried out

We did describe the overall system and each decentralized generation plant as well as the interaction between the generation sources and the loads. The various systems studied are as follows.

6.6.1.1. Diesel power system and loads

The dynamic behaviour of diesel generator has been studied for various events like:

- connection/disconnection of diesel generator,
- short-circuits at diesel generator terminals (LV network),
- disconnection/reconnection of loads (islanding or sudden load changes).

The diesel generator used was a synchronous machine, equipped with high performance speed and voltage regulators.

6.6.1.2. Wind farm and diesel power system and loads

The dynamic behaviour of hybrid system has been studied for various events like:

- connection/disconnection of wind turbines,
- wind changes (low wind speed, gusts, high wind speed)
- wind extreme speed (cut-out wind speed),
- short-circuits at diesel generator terminals (LV network),
- short-circuits at wind turbine generators terminals (LV network),
- short-circuits at substation Crawen (MV network),
- disconnection/reconnection of loads (islanding or sudden load changes).

In this power system, the wind turbine generators and diesel generator are operated in parallel on an isolated network. The diesel generator drives the wind turbines (asynchronous generators). We have chosen a wind farm with five wind turbines connected directly to the grid. Each asynchronous generator is equipped with capacitor bank (48 kVAR - 2.6 mF - power factor of 0.95 - Wye connection for the reactive power compensation).

6.6.1.3. Wind farm and diesel system with storage device (power injector) and loads

The interaction between different generation sources and the loads, the dynamic behaviour of hybrid system have been studied for various events like:

- disconnection (shutdown, shut off…) of wind farm,
- disconnection (shutdown, shut off…) of diesel generator.

In fact, if the power generated by the diesel or the wind park is unavailable (intern faults, malfunction of a protection), the storage device (modelled as a power injector) is able to compensate the missing power generation (power, frequency and voltage on the network).

6.6.2. Conclusions

6.6.2.1. Diesel power system

The simulation results have shown a good dynamic behaviour of this power system during and following the disturbances: connection/disconnection of diesel generator, 1, 2 or 3-phase short-circuit of duration 500 ms at diesel terminals and disconnection/reconnection of loads. In fact, thanks to the governor and voltage regulator, the diesel maintains the balance of active and reactive power on the power system: so keeping the network frequency and voltage very close to their nominal value.

As expected, during the short circuit, the voltage drops in the faulted phases, the rotor speed increases. After the disturbance clearance, the voltage and the rotor speed of the diesel generator recover their normal values. The magnitude of: voltage dips, power dips, inrush current, rotor speed… depends on the types of short-circuits (1, 2 or 3-phase) and their location on the network. Their durations depend on the clearing time of the fault. The amplitude and the duration of transient phenomena shown in the simulations prove that the power system remains stable in spite of any faults or events studied.

6.6.2.2. Diesel and wind farm power system

The wind/diesel power system is stable in response to different types of disturbances: connection/disconnection of diesel, connection/disconnection of wind turbines, gusts, 1, 2 or 3-phase short-circuits. It recovers its normal operation after clearing of disturbances. The diesel generator remains synchronized with the network.

- Concerning load/generation balance, the transient imbalances between load and generation are correctly compensated by the diesel genset. Nevertheless, there are limits that are highlighted in the simulation cases: the level of wind penetration should be compatible with the minimum acceptable power output of the diesel, even during wind or load variations. Difficulties may occur when wind power increases due to wind speed variations, or when the load decreases. It should be highlighted that the simulation results do to not take protection devices into account, and focuses on the stability of the generation means. With this approach, it appears that the wind turbine power can reach and even exceed by a few kW the power required by the loads. In this case, the diesel generator becomes a synchronous motor and ensures the voltage and frequency regulation (wind power tries to drive the diesel generator). It should be checked whether it could be temporarily acceptable, and which actions should be taken to bring the system back to a normal situation. The case of a sudden load disconnection (loss of the sub-sea cable between Terre-de-Bas and Terre-de-Haut) is the most constraining one concerning this issue. In this case, as the wind output power exceeds the power absorbed by the suddenly reduced loads, the diesel loses control of its rotor speed. In fact, the excess energy from the wind power tries to drive diesel engine which tends to accelerate the rotor speed too much.
- Concerning the behaviour for a short circuit, the system remain stable if the diesel unit can cover the reactive power required by the asynchronous wind turbines after the short circuit. With the configuration studied, the wind turbines lose stability in case of a 500 ms

3-phase short circuit at the Diesel unit or on a MV node. It should be noted that they remain stable in case of such a fault at the wind farm level, as this case is more favourable to the ability of the Diesel unit to generate reactive power.

To conclude, the wind/diesel power system is dynamically stable, even in extreme operation conditions of operation (for instance wind gusts, high wind power penetration…), except in 2 cases: three phase short-circuit of duration 500 ms or oversized wind turbines in comparison to the loads, making the diesel operate as a motor (negative power output of diesel). In all the other situations or cases studied, the diesel is able to follow the variations of local load and wind generation. It should be reminded that protections are not taken into account in these case studies.

6.6.2.3. Diesel and wind farm power system with a storage device (power injector)

The power injector compensates the lack of power generated by the wind turbines or diesel (e.g. shutdown wind turbines generators or shutdown diesel generator). So, the power injector generates additional power to supply loads.

- Concerning the final state, as expected, the active power output of the power injector is similar to the initial output of the shutdown unit. Nevertheless, it should be noted that the reactive power final situation is different from the initial one : the global amount of reactive power generated may be reduced, and it is not necessarily generated at the same place.
- Concerning the transients, it appears that the injector response is very fast, so that the power output is temporarily higher than the shutdown unit previous output. As a consequence, an over-frequency may occur, and damped oscillations may be observed on the active outputs. This situation could be improved by adjusting the controls of the injector.

6.6.3. Comments on the results

Globally, the behaviour of this microgrid based on Les Saintes is satisfactory. The governor and voltage control of the diesel unit play a mayor role concerning this issue. It is even strengthened by the fact that the diesel unit is much bigger than the load, so that its control capabilities are rather large in comparison with the constraints. The difficulty associated with this size is the diesel unit minimal acceptable active power output, that limits wind power penetration. When the diesel unit is disconnected, the storage device (represented by a power injector) plays this role.

Nevertheless, it should be reminded that several aspects have not been taken into account in this study. First, the protection devices are not represented. In particular, in some cases, the diesel unit behaves temporarily as a synchronous motor. It should be checked whether such behaviour is acceptable or if there are protection devices, which disconnect automatically the generation unit in this case. Secondly, power quality aspects are not considered in this study.

We would also like to remind that the case studies are based on Les Saintes network, but do not correspond exactly to the present power system, in particular concerning the generation means.

6.6.4. Recommendations for further studies

Some limitations highlighted by the present study could be examined with the following guidelines:

- The diesel unit minimal acceptable active power output: this technical constraint is reached in several cases and limits the wind power penetration. Another scenario should be considered with several smaller diesel units, that would also require a central controller to manage the different units.
- The storage system representation: the simplified model as a power injector does not allow to undertake a study of transient responses to short-circuits. A more thorough study would require to model the energy storage system in detail (e.g. device storage, inverter and control).

Moreover, complementary points should be studied concerning the storage issues. In the context of Les Saintes, when the weather is windy, the storage system would give the frequency reference for the asynchronous wind turbines, and perform the voltage and frequency control, so that all the thermal units could be off. Its size in power (MVA) and energy (MWh) should be adapted to the following specifications:

- its control capability should be adapted to the normal load and wind variations ;
- when the wind farm output decreases suddenly due to the wind conditions, it should be able to feed the loads until a thermal unit could be connected ;
- when the wind turbines disconnect because of a fault, it should be able to feed the loads until the wind turbine are back to normal operation after the fault clearance ;
- it could solve partly the difficulties linked with the diesel unit minimal acceptable active power output, as it could store active power to support the diesel generation.

Lastly, it would be interesting to investigate power quality aspects and economic aspects, in particular concerning the storage system.

6.7. References

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6.8. Annex

6.8.1. Wind farm, diesel genset and power injector models

This appendix describes the models used: wind farm (wind turbine generator), diesel genset and power system.

6.8.1.1. Wind farm (wind turbine generator)

The power generated by the wind turbine is defined as follows: $P = \frac{1}{2} * A * \rho * C_p * v^3$ where:

- ρ: air density (kg/s),
- A: swept area of the blade (cross sectional area m^2),
- C_p: performance coefficient function of TSR (TipSpeedRation) and θ,
- v: wind speed (fluid velocity m/s),
- θ: blade pitch angle,
- P: mechanical output power of the turbine (W).

A typical machine power curve P(v) characteristics defines Cp as function of the Tip-Speed Ratio (TSR) given by the equation: $TSR = \frac{\omega_s * R}{v}$ where R is the radius of the wind turbine rotor.

The torque generated by the turbine is represented as: $T = \frac{P}{\omega_s}$, so $T = \frac{1}{2 * \omega_s} * A * v^3 * \rho * C_p$

where:

- T: mechanical torque at the turbine side,
- P: output power of the turbine,
- ω_s: rotor speed of the wind turbine.

This equation show us $TSR = \frac{\omega_s * R}{v}$ and more important $Ct = \frac{C_p}{TSR}$, we find the relation of the controller torque of asynchronous machine: $Tae = \frac{1}{2} * \pi * \rho * R^3 * v^2 * C_t$ where: Ct is the aerodynamic torque coefficient. Moreover, the inertia torque of the hub noted T_{Iss} is given by the following relation: $\frac{dT_{Iss}}{dt} = \frac{(T_{Iss} - T_{ae})}{T_1}$, with T_1 = 2 kg.m^2.

Note: the aerodynamic model uses: wind speed, rotor speed of the wind turbine and blade pitch angle θ (θ is the pitch angle). The “pitch” system allows the adjustment of the lift the blade to wind speed; however the pitch angle θ is a function of wind speed.

The block diagram of the wind turbine model is shown in the following figure:

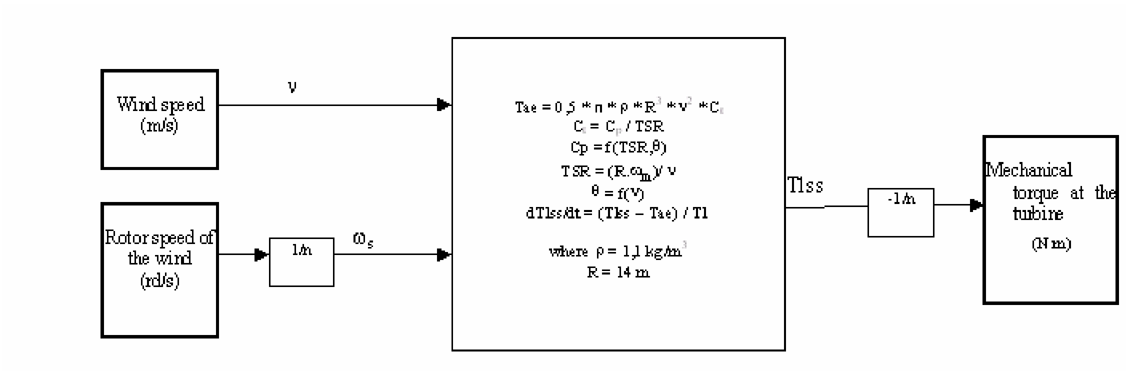

Figure 6.8.1-1: Wind turbine model

The block diagram of wind power regulator is described in the following figure:

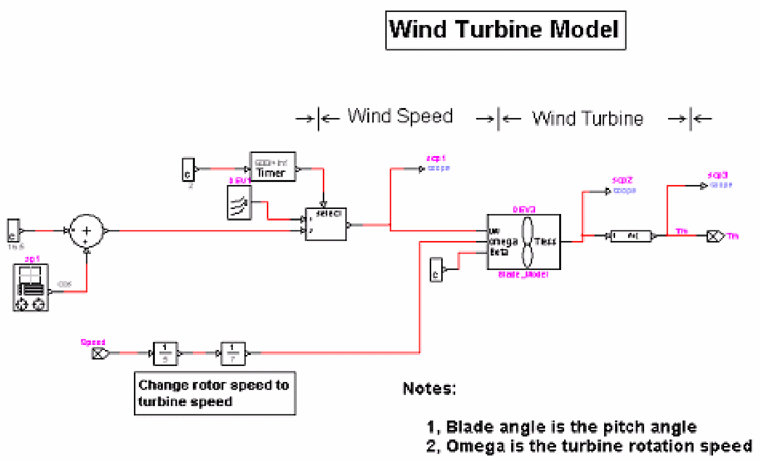

Figure 6.8.1-2: Wind power regulator model

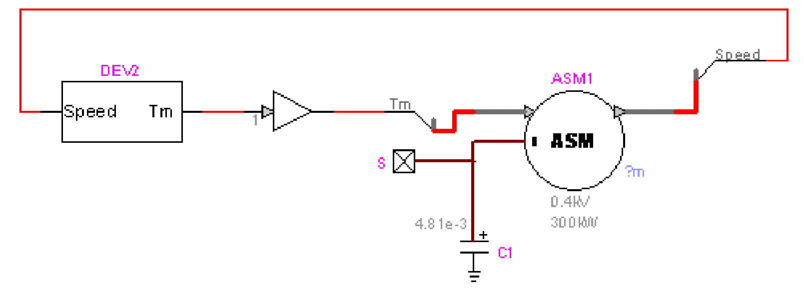

Figure 6.8.1-3: Asynchronous machine model with a capacitor bank

6.8.1.2. Diesel genset (synchronous generator)

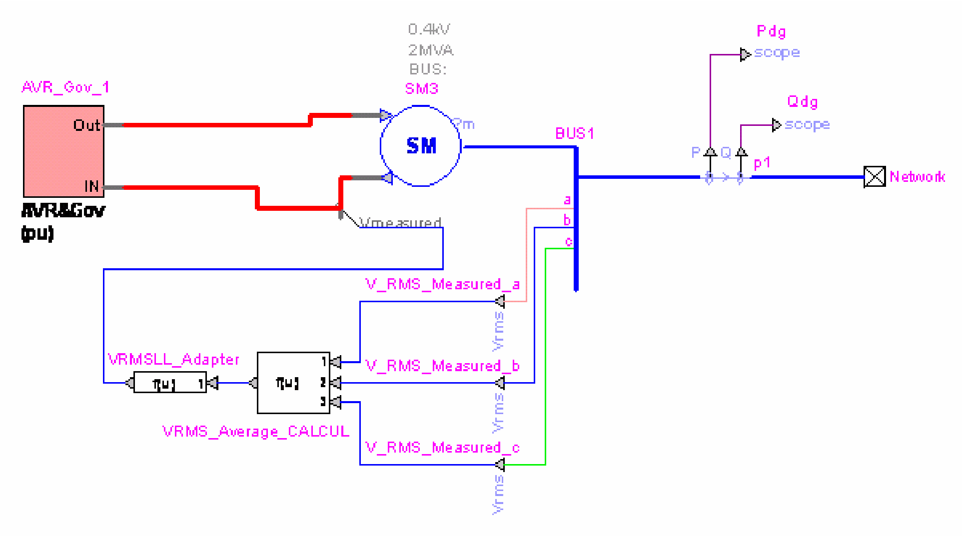

Figure 6.8.1-4: Synchronous machine and AVR & Governor (diesel genset)

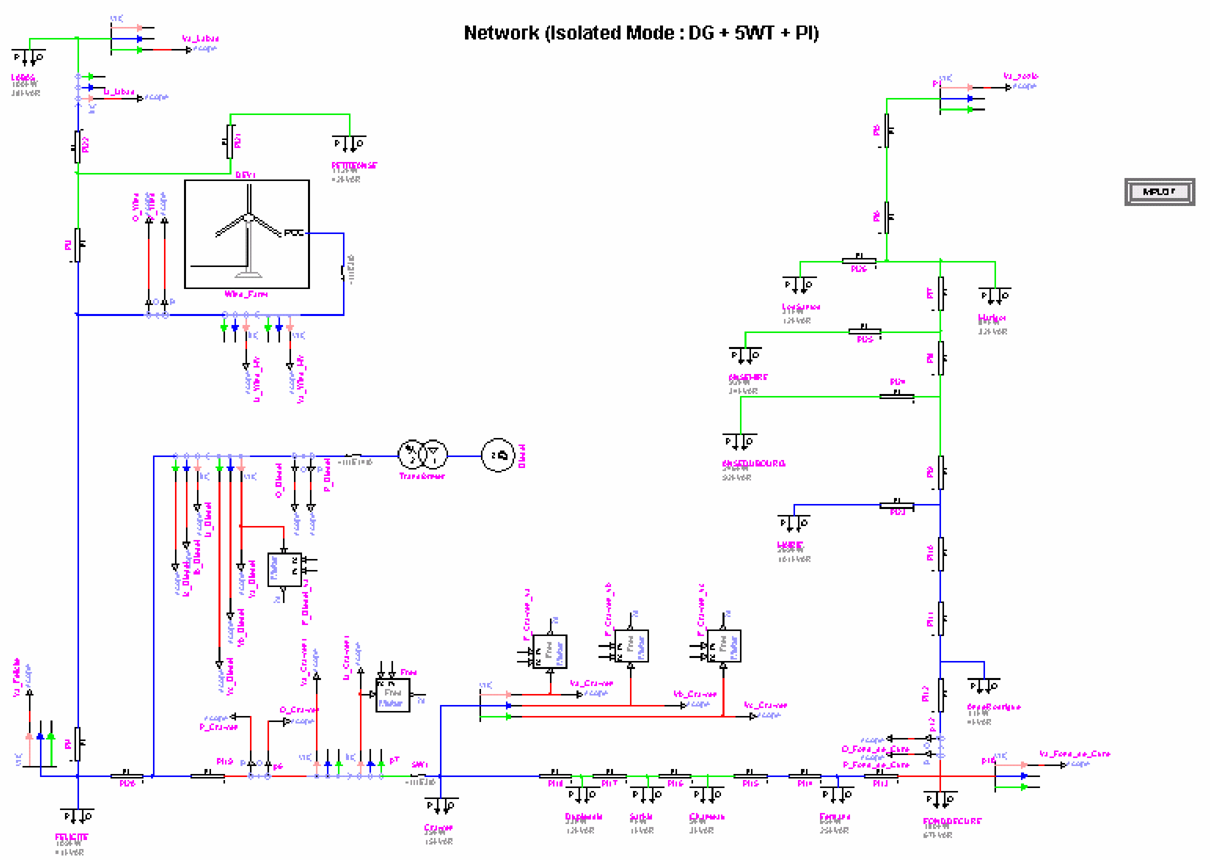

Figure 6.8.1-5: Diagram generated by EMTP-RV for network

6.8.1.3. Power Injector

The power injector used to supply given active and reactive power is given below. It needs voltage and frequency references.

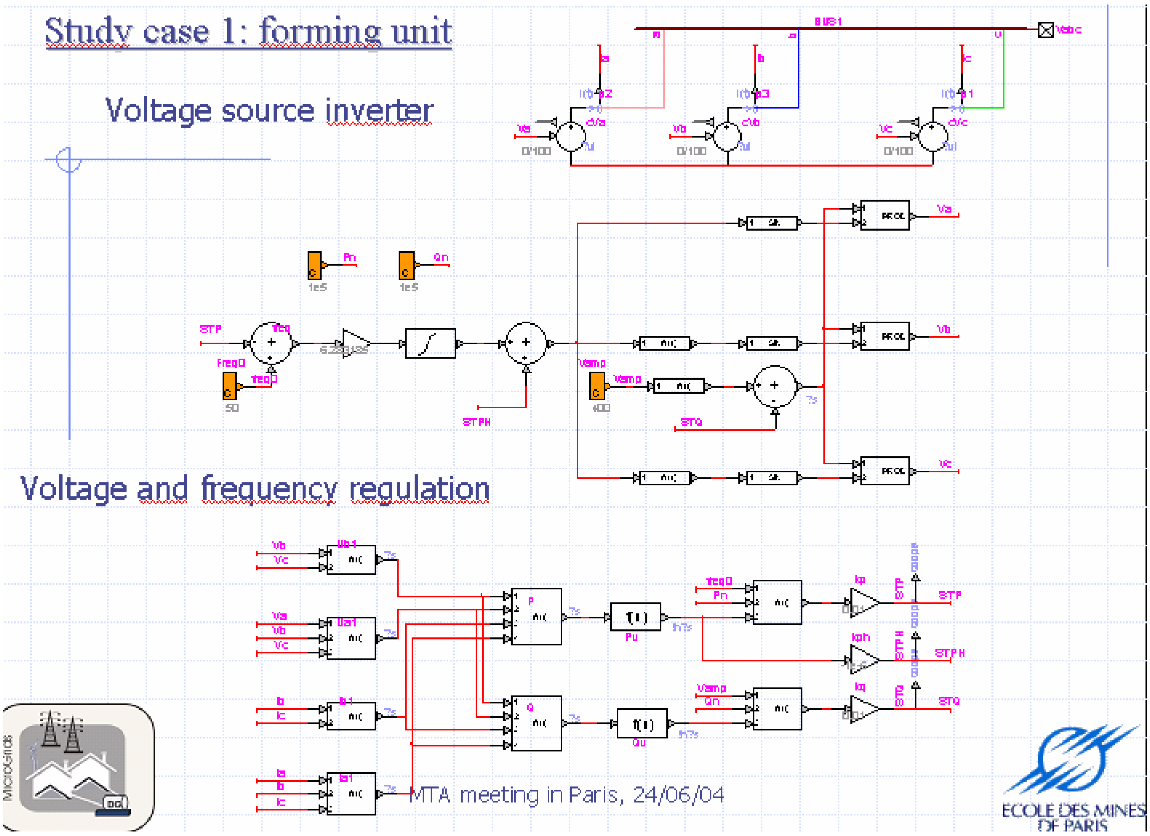

Figure 6.8.1-6: Modelling Power Injector

The power injector (PQ inverter) is described in details in [8].