CESI

Assessment, in the framework of the ELMED project, of the maximum electricity production capacity from non-programmable renewable energy sources (RES) connectable to the Tunisian grid in accordance with security and quality requirements

Task C : definition of the maximum power generated by non dispatchable renewable sources, acceptable by the Tunisian generation-transmission system considering the network reinforcements identified in the first phase of the study

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GLOSSARY

AC :	Alternate Current
ATR :	Auto-transformer
AVR :	Automatic Voltage Regulator
CCGT :	Combined Cycle Gaz Turbine
CCT :	Critical Clearing Time
CSP :	Concentrating Solar Power
DC :	Direct Current
DFIG :	Double Fed Induction Generator
ENTSO-E/SCR:	European Network of Transmission System Operators of Electricity/Synchronous Continental Region (European interconnected system: former UCTE)
HVDC :	High Voltage Direct Current
NTC :	Net Transfer Capacity
P:	Electric Power
PMGEN:	Mechanical Power
PSS :	Power System Stabiliser
PV :	Photovoltaic
RES :	Renewable Energy Source

1 SCOPE OF THE ANALYSIS

According to the work plan, this analysis aims to assess the maximum acceptable intermittent generation from renewable energy sources for the Tunisian transmission system.
After having assessed the overall value of the maximum intermittent generation penetration, we verified the system performances with static and dynamic analyses, applied both to peak and minimum load conditions, starting from the grid configuration determined in Task B [2] without any additional network reinforcement.

2 SUMMARY OF THE STUDY PROCESS FOR TASK C

The study process follows the methodology illustrated in [1] (see par. 3.2 end) that is here summarised with some additional details.

The study is basically split in three phases:

1. *"single bus-bar" analysis*, where the maximum connectable non-dispatchable RES generation is determined, considering only the constraints of the conventional generating units (i.e. frequency regulation reserve). The analysis will be carried out in both loading conditions (maximum and minimum), choosing the lower value as the generation level that shall remain connected in peak and minimum load conditions.
   At the end of this phase, the sites for the installation of the RES generation plants will be chosen among those proposed by STEG.
2. *Static analysis*, where the previously assessed renewable generation will be connected to the grid, introducing no further reinforcements except those strictly requested for the RES generation plants connection.
   Thereafter, a "redispatching" will be necessary, following the "merit-order" criterion and thus reducing the production of the most expensive generating units. The new ELMED power plant will be considered on the top of the merit order.
   In this analysis active power flows are checked in both scenarios (peak and minimum load), searching eventual overloads or voltage violations, moreover a "N-1" security analysis is carried out as well.
3. *Dynamic analysis*, where two main sets of analysis are carried out, i.e. :
   - sensitivity analysis, in order to determine the effects on the grid of the fluctuations of non-dispatchable RES generation;
   - fault analysis, in order to verify the behaviour of the Tunisian system during main contingences which could cause the disconnection of renewable power plants.

   As reference, the RES generation plants connection's criteria suggested in [3] have been considered, both to evaluate the sensitivity analysis results and to determine the renewable plants' behaviour in case of grid faults.
   At the end of this phase, we determine to what extent the non-dispatchable RES generation connected to the Tunisian system influences its stability, verifying that such an intermittent generation level can be accepted.

3 ASSESSMENT OF THE MAXIMUM NON-DISPATCHABLE RES GENERATION IN COMPLIANCE WITH THE CONTRAINTS OF THE CONVENTIONAL GENERATING UNITS

In this chapter the maximum non-dispatchable RES generation that is possible to inject in the Tunisian power grid has been assessed. Since the study assumptions affect the results, these assumptions have been described and justified according to what already established in Task 1 [1].
Both peak and minimum load scenarios have been analysed in order to determine the most restrictive situation.
Thereafter the sites chosen for the installation of the new RES power plants have been reported, emphasising the criteria followed for these choices.
The grid representation considered in this "first level" analysis has been the "Single Bus Bar" configuration (Fig. 3-1), already described in Task 1 [1], which represents a considerable simplification, but not an approximation, to define the total non-dispatchable renewable generation for Tunisian electric system taking into account the reserve criterion. It depicts the grid as a single bus bar with all the traditional generators, RES generators, loads and the HVDC system connected to the same bus in order to investigate, as first step, the global constraints concerning the connection of non-dispatchable power generation (i.e. presence of sufficient reserve). These constraints refer to the capability of the conventional generators to cope with the fluctuations of the renewable generation.

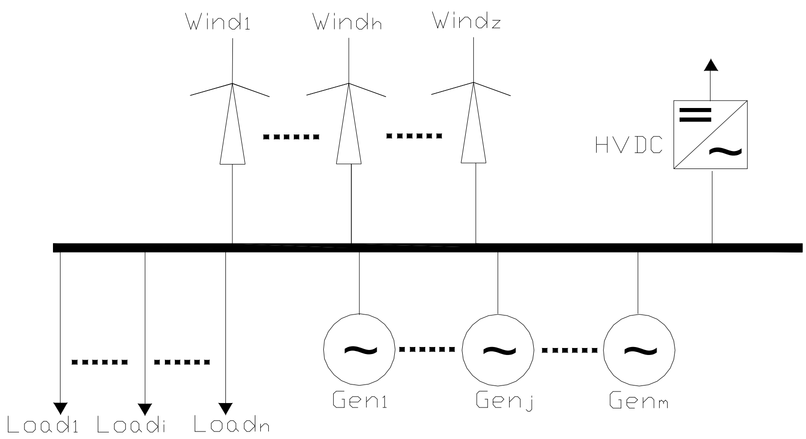

Fig. 3-1 – Single Bus Bar configuration – example with non-dispatchable RES generation represented by wind.

3.1 Adopted hypotheses

In this paragraph all the hypotheses adopted to obtain peak and minimum scenarios, used both in static and dynamic analyses, are described.
<u>The results reported in this document are valid only considering all these assumptions: CESI do not warrant the validity of the results reported if these hypotheses are not fulfilled.</u>

Hypotheses used both in peak and minimum load scenario:

1. ELMED Power Plant located in Skhira, as from results of Task 2 [2].

2. No further grid reinforcement beside those defined for the "solution A1" (ELMED power plant in Skhira) in Task 2 [2].
3. International interconnections:
   - Libya: out of service.
   - Algeria: connected, but with a non-null import/export balance only during particular transients.
4. Traditional reserve considered equal to 8% of total load (comprehensive of both Secondary and Tertiary reserve)
5. Additional reserve depending on the penetration of non-dispatchable RES generation, determined by a linear interpolation of the values reported in the table below (Tab. 3-1). The additional reserve has been considered with reference to wind power since it represents the most fluctuating form of RES generation.

Tab. 3-1 – Additional reserve depending on RES penetration (referred to wind).

RES penetration %	Additional reserve (in % of the RES generation)
5	6,5
10	9
15	11,5
20	14
25	16,5

To calculate the additional reserve, the following steps are necessary:

- assume a certain amount of RES productions;
- calculate the RES penetration in percentage with respect to the total load;
- calculate the additional reserve according to Tab. 3-1[1]: the traditional generation will must be at least equal to the sum of: total technical minimum, tertiary and additional reserves;
- check if the RES amount assumed at the beginning is coherent, i.e. the constraints on the reserves are fulfilled: if not, change it repeat the calculation.

6. For what concerns redispatching, the following hypotheses have been considered:
   - HVDC connection with a regulation bandwidth of 5% (referred to rated power), which means a maximum deliverable power of 950 MW out of 1000 MW: 950 MW is the exportation to Italy in both scenarios.
   - Redispatching of exceeding generated power according to merit-order criterion.
   - No generating unit can be shut down, but at most reduced to their technical minimum, increased by a regulation bandwidth of 5% (of its rated power).
   - Skhira power plant generation has been considered differently in the two scenarios analysed:
     i. 1000 MW is the production in peak load condition

[1] These values have been adopted considering international studies, i.e. the IEA Wind Task 25 study "*Design and operation of power systems with large amounts of wind power*", as reported in the report of Task A.

ii. 400 MW (its technical minimum) plus its regulating bandwidth is the production in minimum load condition: the generating level of Skhira may decrease down to 400 MW plus its regulating bandwidth to give priority to the RES generation.

Note 1: the merit order criterion followed in this study is based on the data provided by STEG and reported in detail in [1]. In presence of the new ELMED power plant, these data should be brought into question and the redispatching based on the merit order criterion may be different in respect to the one followed in this study also in function of the adopted technology of the new ELMED power plant (i.e. gas, coal).

Note 2: with reference to the redispatching in minimum load conditions (par. 4.2.2), the adopted hypotheses to decrease the power production in Skhira down to a value close to its technical minimum to give priority to RES generation can have an adverse impact on the efficiency of the Skhira units, particularly if the technology for the ELMED power plant is based on coal.
On the other hand, it is worth mentioning that this very binding operating mode refers to the worst possible condition for the Tunisian system, i.e. maximum non-dispatchable generation at the minimum loading conditions.

7. For what concern RES generators:
   - We always refer to generated power (a power really injected in the Tunisian electric system and not to the installed capacity)
   - generation rate of 80% of rated power[2].

As described in [1], the maximum acceptable gradients in increasing/decreasing RES generated power must be considered as a further possible constraint for the connection of RES generation plants. Also this restriction has been considered in the analyses but, thanks to the fast frequency regulation of the HVDC system, an estimated variation of a few MW/min in renewable production (as experienced in country with even higher wind power penetration such as Spain) can be easily covered and it not represents a problem for Tunisian electric system.

[2] This assumption has been done taking into account the situation of Sicily that can be considered, for many reasons (i.e. geographical extension and location, size and type of installed wind power plants) quite similar to the Tunisian situation and it is supported by the fact that the wind farms on Tunisia will be likely concentrated in a smaller area than Sicily. This value is in line with the evaluation of similar systems, e.g. Ireland. Moreover, referring to Sicily, which is characterised by wind regime similar to Tunisia, the records show that the maximum contemporary factor has never been greater than 70% .The assumption to consider this parameter equal to 80% for the Tunisian system is a conservative hypothesis to verify security conditions.

3.2 Peak Load Scenario

The starting point with the total absence of renewable generation is represented in Fig. 3-2.

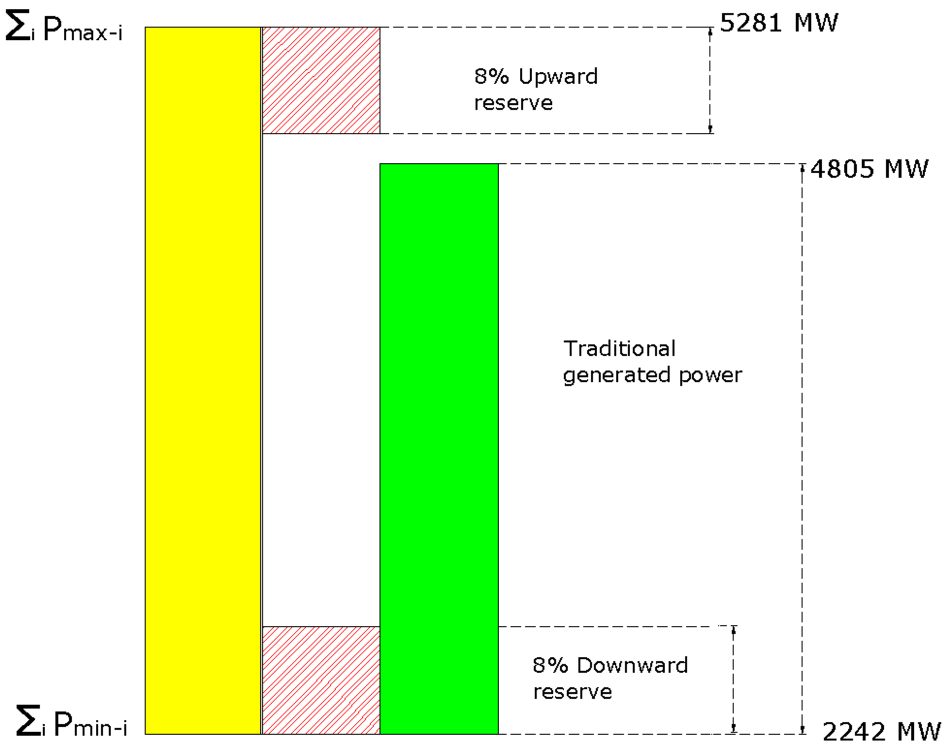

Fig. 3-2 –Load and reserve in peak load condition without renewable power generation.

From Fig. 3-2 it is possible see that in starting point conditions the total load is totally covered by traditional generated power: part of this production will be substituted with renewable generation.
As the load is kept constant, next step consists in reducing traditional generated power, substituting it with RES generating power, and adding the additional reserve depending on the non-dispatchable penetration.
The RES penetration could be theoretically increased till the total upward or downward available reserve is greater than the requested reserve (tertiary and additional).
Actually, since no traditional generating unit is turned off, the upward reserve would never become a limit: being the additional reserve always a little percentage of the renewable generation, the upward reserve of the traditional units will be greater than the requested additional reserve as it’s at least equal to RES generation.
Therefore, the downward reserve represents the unique constraint for the non-dispatchable RES penetration in this “single bus-bar” analysis, and in peak condition it doesn’t appear to be a restrictive situation as the generating units are far from their technical minimum.
However, a limitation will surely derive from minimum load scenario analysis.

3.3 Minimum Load Scenario

The starting point with the total absence of renewable generation is showed in Fig. 3-3.

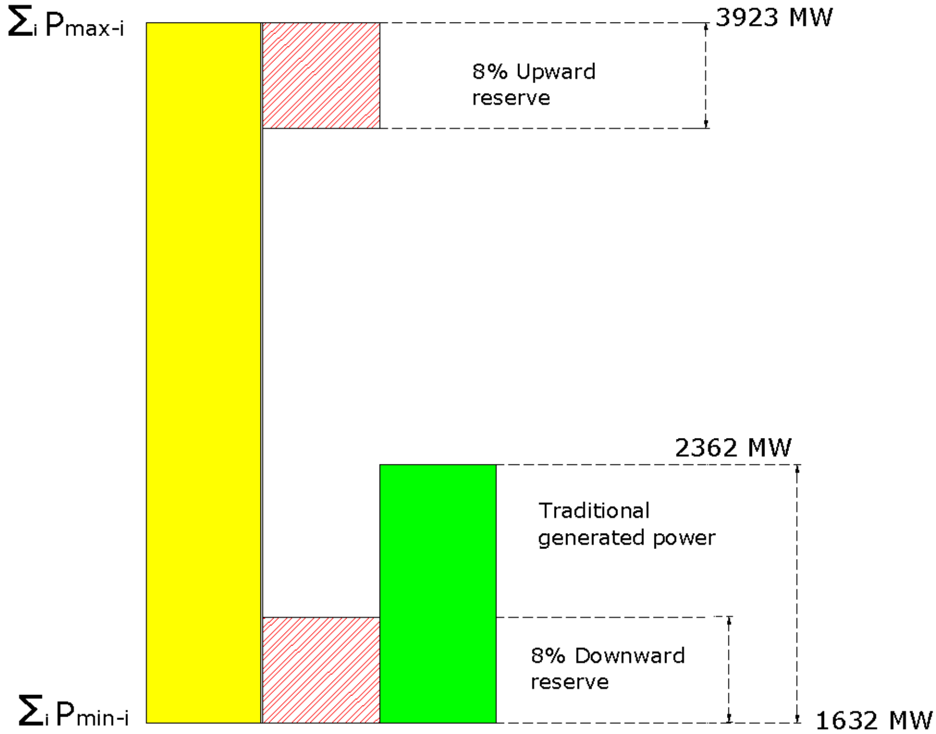

Fig. 3-3 –Load and reserve in minimum load condition without renewable power generation.

The more restrictive situation of the minimum load condition is immediately evident. The downward regulating power results to be pretty low, and it derives almost entirely from ELMED power plant, which is supposed to be able to reduce its production till its technical minimum (400 MW) increased by 5% regulation bandwidth (20 MW)[3]. Thus, the non-dispatchable power generation connectable to the Tunisian grid needs to be limited.

Through an iterative calculation[4], a final result has been obtained (Fig. 3-4):

- renewable power generation: 530 MW (penetration of 22 %)

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[3] It is important to always ensure a regulating bandwidth to allow the frequency regulation in case of necessity: to this purpose, the effective minimum production of the power plant is considered equal to its technical minimum increased by 20 MW (5%, i.e. the regulating bandwidth).

[4] The iterative calculation is summarized as follows, considering:

a) secondary reserve = $\sqrt{10 \cdot L_{min} + 150^2} - 150 = \sqrt{10 \cdot 1412 + 150^2} - 150 = 41.4\,MW$

b) tertiary reserve = $0.08 \cdot L_{min}$ = 0.08*1412 = 113 MW.

First step: we suppose 500 MW of RES. We calculate:

- The RES penetration: 500/2362 = 21.2% → percentage of additional reserve equal to 14.6% of RES
- Additional reserve: 0.146*500 = 73 MW
- Check: 1632+113+73+500 = 2318 MW The demand is greater (2362 MW), so it is possible to increase the RES generation.

Second step: we suppose 530 MW of RES. We calculate:

- The RES penetration: 530/2362 = 22.5% → percentage of additional reserve equal to 15.3% of RES
- Additional reserve: 0.153*530 = 81 MW
- Check: 1632+113+81+530 = 2356 MW (about equal to the demand). → So we confirm the limit of 530 MW of RES.

- additional reserve: 81.0 MW (15.3 % of generated renewable power)
- traditional generated power : 1832 MW

Since the HVDC connection is able to regulate frequency, it doesn't need any reserve; thus, the 8% reserve is calculated on the total load decreased by 950 MW (i.e. 1412 MW)[5].
The power reduction of 530 MW has been entirely covered by ELMED power plant, which without non-dispatchable RES generation would produce 1000 MW, while its technical minimum, increased by the regulation bandwidth, reaches 420 MW[6].
With a generating power rate of 80% of the rated power, the total installed renewable power would reach about 660 MW[7].

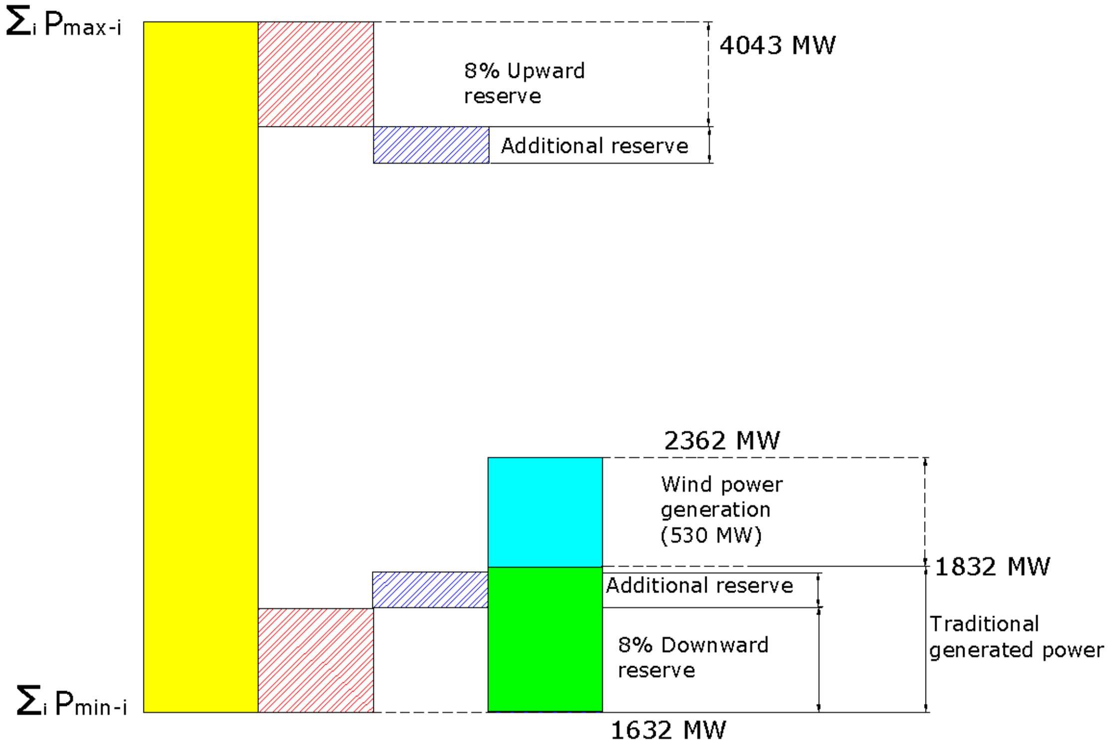

Fig. 3-4 – Load and reserve in minimum load condition with renewable power generation.

It is very important to point out that for this scenario, being all Tunisian generators to their technical minimum, also ELMED power plant must decreases its production: the ELMED power plant is considered as the last power plant that can decrease its production.

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[5] The power export through the HVDC link is part of the demand because it can be considered like an additional power required by the system: for this reason the power export is taken into account in the calculation of RES penetration. However, the behaviour of the HVDC system can not be considered strictly as a load, because it has the possibility to regulate the frequency: for this reason, the power export through the HVDC link is not considered in the tertiary reserve calculation.

[6] In minimum load conditions, the ELMED power plant is the only power plant that can decrease its production to give priority to RES generation in this condition. To have a minimum amount of frequency regulation bandwidth for this plant, its production doesn't decrease under 420 MW.

[7] The value of wind power equal to 530 MW must not be obtained as the difference between the values of 950 MW and 420 MW because also the additional reserve must be considered, as pointed out in the iterative calculation.

In conclusion, from single bus bar analysis based on the reserve criterion reported in this chapter, a non-dispatchable RES generation equal to 530 MW appears adequate for the Tunisian system: this value that has to be verified with static and dynamic analyses, has been determined considering the minimum load scenario being the most restrictive condition.

3.3.1 Non-dispatchable RES modulation in function of the ELMED power plant technical minimum

In the previous analysis a global technical minimum of the ELMED power plant equal to 400 MW has always been considered.
However, considering that the ELMED power plant is still at a planning stage, all its technical characteristics cannot be known with certainty. For this reason in this paragraph the maximum non-dispatchable RES generation in function of the ELMED power plant technical minimum (or limitation in the downward modulation) is reported[8].
The values indicated below are calculated adopting the same methodology illustrated above based on the total amount of available reserve for Tunisian system.

<u>CASE 1: ELMED technical minimum equal to 500 MW</u>

- Technical minimum total sum: $\sum_i P_{\min\_i} = 1732 \text{ MW}$
- Additional reserve: 61 MW
- **Non-dispatchable RES power <u>generation</u>: 450 MW**
- Traditional generated power: 1912 MW

<u>CASE 2: ELMED technical minimum equal to 600 MW</u>

- Technical minimum total sum: $\sum_i P_{\min\_i} = 1832 \text{ MW}$
- Additional reserve: 44 MW
- **Non-dispatchable RES power <u>generation</u>: 370 MW**
- Traditional generated power: 1992 MW

<u>CASE 3: ELMED technical minimum equal to 700 MW</u>

- Technical minimum total sum: $\sum_i P_{\min\_i} = 1932 \text{ MW}$
- Additional reserve: 29 MW
- **RES Non-dispatchable power <u>generation</u>: 285 MW**
- Traditional generated power: 2077 MW

[8] These considerations are necessary because the technical minimum of a power plant depends not only on its size, but also on the adopted technology (e.g.. coal, gas).

In conclusion, from the reported values it is possible point out that if technical minimum of the ELMED power plant increases of 100 MW, the non-dispatchable renewable power generation must decreases of about 80 MW in linear way.

The most problematic situation for the Tunisian system is that one showing the highest amount of non-dispatchable RES power generation. For this reason, all the analyses reported in the next sections are referred to the base scenario with renewable power generation equal to 530 MW.

4 NEW TUNISIAN SCENARIOS WITH NON-DISPATCHABLE RENEWABLE GENERATION

In this chapter the criteria adopted to build the new scenarios for Tunisian grid are reported. As already described in the previous section, both for maximum and minimum conditions the amount of non-dispatchable RES power generation is considered equal to 530 MW.
Starting from this value it is necessary:

1. to define the RES generation plants to be connected to the grid;
2. to define the best connection solution (in term of minimum costs) for the RES generation plants selected in point 1;
3. to redispach the conventional units in operation: "redispatching" is executed according to the "merit order" of the units, but without changing the unit commitment,

The solution proposed here will be then verified with static and dynamic analyses to ensure the compliance with the security criteria.

4.1 Non dispatchable RES power plants connection to the Tunisian grid

The connection solutions identified in this paragraph do not change in the two scenarios considered: they are the same both for minimum and for peak load conditions.
Tab. 4-1 reports the RES sites identified by STEG with the capacity factor assessed for a generator unit of 1500 kW. The data in Tab. 4-1 refers to the wind generation technology, lacking more detailed information on the siting of other RES generation. The RES generation plants have been selected according to the following criteria:

- First of all, the power plant already commissioned or in construction have been considered (Sidi Daoued, Metline and Kechabta);
- The second criterion is based on the capacity factor: the ones with the highest parameter have been chosen: this is an appropriate criterion because in this way the RES plants with the highest ratio between produced energy and producible energy are chosen.

Then, the most convenient solutions to connect RES generation plants to Tunisian grid have been selected among the candidate substations provided by STEG.

Tab. 4-1 – Non-dispatchable RES power plant sites identified by STEG.

Name of site	Region	Capacity factor assessed for a generator unit of 1500 kW (%)	Exploitable RES power (MW)
Sidi Daoued (1)	Cap Bon	30	54
Metline (2)	Bizerte	38	97
Kechabta (2)	Bizerte	35	93
Ben Aouf	Bizerte	37	25
Jebel Abderrahmen	Cap Bon	39	200
Ferkik	Kerkennah	-	40
Akarit	Gabés	-	50
Sidi Mechreg	Bizerte	-	40
Jbel Tbaga	Kébili	-	150
Thala	Kasserine	22	60
Zonkar	Bizerte	32	200

(1): Power plants already commissioned.
(2): Power plant in construction (in service at the end of 2012).

Tab. 4-2, provided by STEG, shows the candidate stations to connect the correspondent non-dispatchable RES power plants.

Tab. 4-2 – Connection stations identified by STEG.

Name of site	Region	Candidate station for connection
Sidi Daoued (1)	Cap Bon	Menzel Temime 90 kV: **29 km**
Metline (2)	Bizerte	Menzel Jemil 90 kV: **11 km**
Kechabta (2)	Bizerte	E/S sur la ligne existante 90 kV Menzel Jemil-Menzel Bourguiba: **6 km**
Ben Aouf	Bizerte	Menzel Jemil 225 kV, 90 kV: **28 km** Menzel Bourguiba 225 kV,90 kV : **25 km** Bizerte 90 kV : 1**2 km** Mateur 225 kV, 90 kV : **43 km**
Jebel Abderrahmen	Cap Bon	Menzel Temime 90 kV: **20 km** Grombalia 225 kV, 90 kV: **43 km** Korba 90 kV : **39 km** Hammamet 150 kV, 90 kV : **65 km** E/S sur la ligne existante 90 kV Grombalia-Menzel Temime: **11 km**
Ferkik	Kerkennah	Sidi Mansour 225 kV, 150 kV: **52 km** Sfax 150 kV: **68 km** Thyna 150 kV: **76 km**
Akarit	Gabés	Skhira : 150 kV : **35 km** Bouchemma 225 kV, 150 kV : **35 km** Ghannouch 225 kV, 150 kV : **36 km**
Sidi Mechreg	Bizerte	Mateur 225 kV, 90 kV : **72 km** Menzel Bourguiba 225 kV,90 kV : **78 km** Tabarka 225 kV,90 kV : **56 km** Beja 90 kV : **70 km**
Jbel Tbaga	Kébili	Kebeli 150 kV : **20 km** Mdhilla 150 kV : **91 km**
Thala	Kasserine	Tajerouine 225 kV, 150 kV, 90 kV: **46 km** Kasserine Nord 150 kV: **52 km** Kasserine 150 kV: **59 km**
Zonkar	Bizerte	Menzel Jemil 225 kV, 90 kV: **42 km** Menzel Bourguiba 225 kV, 90 kV: **30 km** Mateur 225 kV, 90 kV: **41 km** Bizerte 90 kV: **28 km**

(1): Active power plant.
(2): Power plant in construction (in service at the end of 2012).

Tab. 4-3 reports the solutions adopted in the study.
Considering the information reported in Tab. 4-2, the best connection solution for the RES power plants of Ben Aouf, Jebel Abderrahem and Zonkar has been selected. The connections of the other power plants already in service or in construction are already defined.
The motivations for the solutions proposed are the following:

- Ben Aouf power plant has a power equal only to 25 MW: the natural connection is at 90 kV voltage level.
- Because of the high power of Jebel Abderrahem and Zonkar plants, the connections have been chosen at 225 kV voltage level.

Tab. 4-3 – Connection adopted for Tunisian RES power plants.

Name of site	Region	Connection stations	Exploitable RES power (MW)
Sidi Daoued	Cap Bon	Menzel Temime **90 kV: 29 km**	54
Metline	Bizerte	Menzel Jemil **90 kV: 11 km**	97
Kechabta	Bizerte	E/S on existing line **90 kV** Menzel Jemil-Menzel Bourguiba: **6 km** *(1)*	93
Ben Aouf	Bizerte	Bizerte **90 kV: 12 km**	25
Jebel Abderrahmen	Cap Bon	Grombalia **225 kV: 43 km**	200
Zonkar	Bizerte	Menzel Bourguiba **225 kV: 30 km**	200

(1) lenght Menzel Jemil – E/S: 7 km; length E/S – Menzel Bourguiba: 8.5 km

The parameters of the new lines used to connect RES power plants to the Tunisian grid are reported in Tab. 4-4.

Tab. 4-4– Transmission capacity and electrical characteristics of the new lines (source STEG)[9]

Voltage and mechanical characteristics	R (Ω/km)	X (Ω/km)	C (nF/km)	In (A)	S (MVA)
225 kV -411 mm^2 Alu-Ac	**0,088**	**0,417**	**8,28**	**620**	**242**
90 kV -411 mm^2 Alu-Ac	**0,088**	**0,417**	**8,28**	**620**	**97**

[9] Data sent via e-mail on July 16th, 2010 by STEG

4.2 Conventional unit redispatching

The introduction of 530 MW of non-dispatchable renewable production in the Tunisian system implies necessarily a redispatching of the other units to maintain the balance between generation and load, while avoiding modifications of the exchanges with Algeria.
The redispatching is carried out considering the merit order of the units and it is different in the two scenarios considered because the generating unit commitment is different.
For both scenarios the exportation to Sicily with the HVDC interconnection is always considered equal to 950 MW.

4.2.1 Peak load conditions

In this scenario we have to consider the following assumptions:

- 530 MW of new non-dispatchable generation;
- power export to Sicily through the HVDC link increased from 800 MW to 950 MW (with a regulating bandwidth of 5% referred to the rating of the cable).

This means that there are 180 MW of RES generation that replace the traditional production according to the merit order criterion.

Tab. 4-5 – Generation redispatching in peak load scenario.

Power plant	Unit	C S M [Tep/GWh]	Initial production [MW]	Final Production [MW]	Variation [MW]	Pmin [MW]
EL BIBENE	TG1	400	24.0	12.0	-12.0	12
BIR MCHERGUA	TG1	300	107.0	82.3	-23.7	40
BIR MCHERGUA	TG2	300	107.0	82.3	-23.7	40
BOUCHEMMA	TG1	300	107.0	82.3	-23.7	40
FERIANA	TG1	300	97.0	76.5	-19.5	40
FERIANA	TG2	300	97.0	76.5	-19.5	40
THYNA	TG1	300	105.0	80.8	-23.2	40
THYNA	TG2	300	107.0	81.9	-24.1	40
THYNA	TG3	300	107.0	81.9	-24.1	40
TOTAL			**858.0**	**656.5**	**-201.5***(1)*	

(1) This value is greater than 180 MW due to losses variation caused by different power flows distribution.

Tab. 4-5 reports the power modifications for the most expensive generating units. It is possible to point out that:

- For the generator of El Bibene the production has been put equal to its minimum value because it is the most expensive unit;
- For the other generators the productions have been reduced proportionally to their initial active power. This is a hypothesis adopted to consider in the same way all generating units with the same merit order.

4.2.2 Minimum load conditions

In this scenario the active power redispatching has to consider the same assumptions adopted in the peak load conditions:

- 530 MW of new non-dipatchable power generation;
- power export to Sicily through the HVDC link set at 950 MW to warrant the downward regulating margin (a regulating bandwidth of 5% referred to the rating of the cable);

Moreover, the production of the ELMED power plant can decrease to its minimum value, equal to 400 MW (plus its regulating bandwidth).

This means that there are about 580 MW of power (including both 530 MW of RES generation and 50 MW of the HVDC link regulating bandwidth) that replace the traditional production according to the merit order criterion.
In this case, considering that one hypothesis is the reduction of the ELMED power plant production to its minimum value, the redispatching in minimum loading conditions has been completed decreasing only the power of these two generating units.

This choice has been adopted on the basis of the considerations described below.

a) All generators in service are at their technical minimum: it is not possible to reduce their productions.
b) As discussed with STEG, this scenario has to be considered as an extreme minimum situation. The reserve provided by STEG is constituted by the productions of Sousse and Rades 2 power plants that can be decreased in the following way in case of necessity.

Sousse:	TG1	from	70 MW	to	80 MW
	TG2	from	70 MW	to	0 MW
	TV1	from	60 MW	to	50 MW
Rades 2:	TG1	from	50 MW	to	0 MW
	TG2	from	50 MW	to	50 MW
	TV1	from	120 MW	to	60 MW

The reserve assured by Sousse and Rades 2, provided by STEG, is not modified after the insertion of RES power plants because it is necessary for the possible necessities that can occur in Tunisian system.
Moreover, following the merit order criterion reported in [1], the two power plants of Sousse and Rades 2 are the cheapest ones.

For these reasons, we consider necessary to reduce the ELMED power plant to its technical minimum plus its regulating bandwidth. The need for decreasing the power production in the ELMED power plant down to a value close to its technical minimum to give priority to RES generation can have an adverse impact on the efficiency of the ELMED units.
On the other hand, it is worth mentioning that this very binding operating mode refers to the worst possible condition for the Tunisian system, i.e. maximum non-dispatchable RES generation at the minimum loading conditions.

5 MAXIMUM NON-DISPATCHABLE RES GENERATION: STATIC ANALYSES

The static analysis, the results of which are reported in this chapter, is the first step to examine the performances of the Tunisian system in the new operating point with 530 MW of non-dispatchable RES power generation. The objective of this analysis is to verify, through load flow calculations, whether the solution proposed in previous chapter respects the N-1 security criteria both for voltages and for components overloads.

5.1 Load flow results

For both scenarios the RES power plants produce the same power reported in Tab. 5-1. The ratio between the power injected into the grid and the exploitable value is considered equal to 0.8.

Tab. 5-1 – Production of RES power plants

Name of site	Region	Exploitable RES power (MW)	Produced power (MW)
Sidi Daoued	Cap Bon	54	43.2
Metline	Bizerte	97	77.6
Kechabta	Bizerte	93	74.4
Ben Aouf	Bizerte	25	20.0
Jebel Abderrahmen	Cap Bon	200	160.0
Zonkar	Bizerte	200	160.0
TOTAL		**669**	**535.2**

Obviously in static analyses the non-dispatchable RES productions are constant and the oscillations caused by RES power plants variations (namely wind) are not considered.

5.1.1 Peak load conditions

In the base case of peak load condition, total demand is 3960 MW while total losses are 96 MW, as Fig. 5.1 shows; total Tunisian generation is therefore slightly higher than 5000 MW.
The exportation to Italy is equal to 950 MW; since Tunisian grid is interconnected with Algeria, a small active and reactive loop flow is present. The reactive power, in particular, is linked to the very low loading level of the cross-border lines.

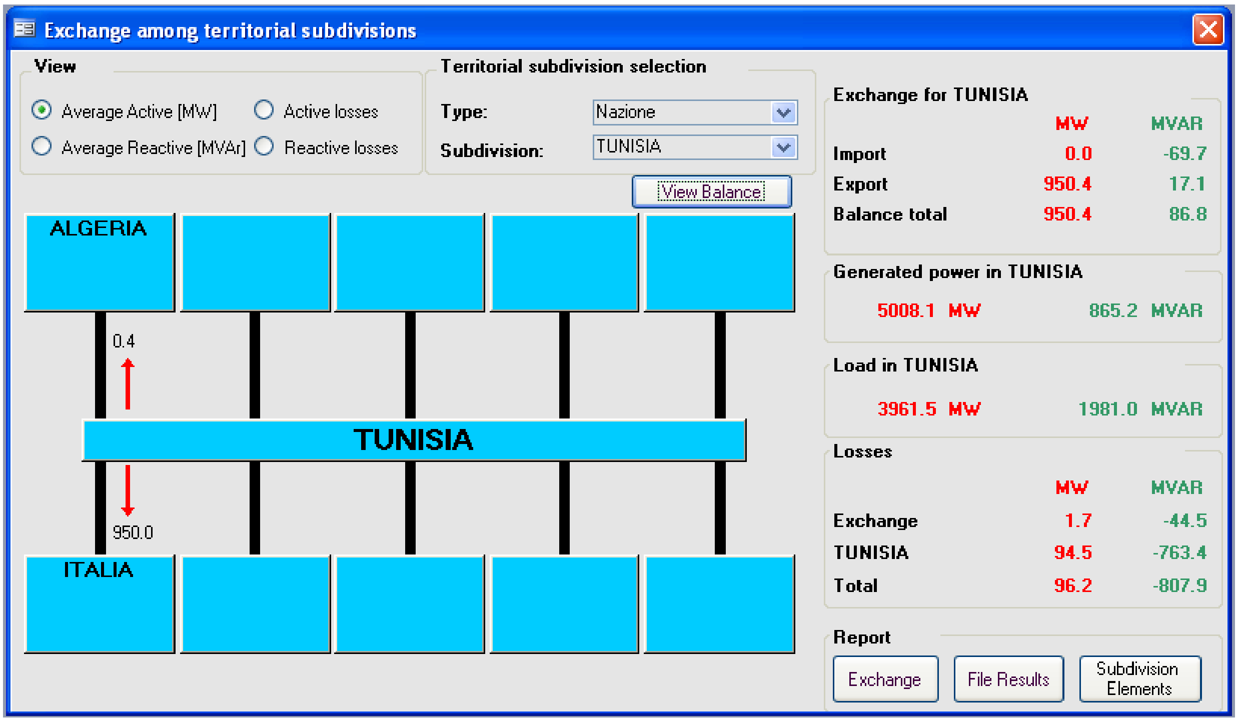

Fig. 5.1 - Peak condition, International exchanges and power balances for the Tunisian grid.

In sound network condition, no voltage violation or overloads are present on the Tunisian network.
In N-1 conditions Tab. 5-2 resumes the voltage violations: comparing these values with the ones of the base case ([2]), there is an additional violation after the tripping of the double circuit 90 line Grombalia-Korba: Sidi Daoued station goes to 79.7 kV. Anyway, these limited violations can be easily solved with local measures.
With reference to overloaded lines, only the line Rades 2 – Kram 225 kV has a load factor equal to 121% after the tripping of the double circuit Goulette – Rades 2 225 kV (Tab. 5-3)

Tab. 5-2 – Post-contingency voltage violations

Contingency		Vn (kV)	Violation	Vn (kV)	V_N (kV)	V_{N-1} (kV)	ΔV (%)
GROMBALI	**KORBA**	**90**	**M.TEMIME**	**90**	**90.1**	**79.2**	**-12.0**
GROMBALI	**KORBA**	**90**					
GROMBALI	**KORBA**	**90**	**KORBA**	**90**	**91.7**	**76.7**	**-14.8**
GROMBALI	**KORBA**	**90**					
GROMBALI	**KORBA**	**90**	**HAMMAMET**	**90**	**90.4**	**79.3**	**-11.9**
GROMBALI	**KORBA**	**90**					
GROMBALI	**KORBA**	**90**	**A.KMICHA**	**90**	**90.0**	**77.3**	**-14.1**
GROMBALI	**KORBA**	**90**					
GROMBALI	**KORBA**	**90**	**SIDI DAOUED**	**90**	**90.7**	**79.7**	**-11.4**
GROMBALI	**KORBA**	**90**					
HAMMAMET	**RADES**	**150**	**RADES**	**150**	**157.9**	**166.0**	**10.7**

Tab. 5-3 – Overloads in N-1 conditions

Contingency		Vn (kV)	Overload		Vn (kV)	I_{N-1} (kA)	I_{N-1} (p.u.)
GOULETTE	**RADES 2**	**225**	**RADES 2**	**KRAM**	**225**	**0.57**	**1.21**
GOULETTE	**RADES 2**	**225**					

5.1.2 Minimum load conditions

In the base case of minimum load condition, total demand is 1400 MW while total losses are 39 MW, as Fig. 5.2 shows; total Tunisian generation is therefore slightly lower than 2400 MW.

The exportation to Italy is equal to 950 MW; since Tunisian grid is interconnected with Algeria, a small active and reactive loop flow is present. The reactive power, in particular, is linked to the very low loading level of the cross-border lines.

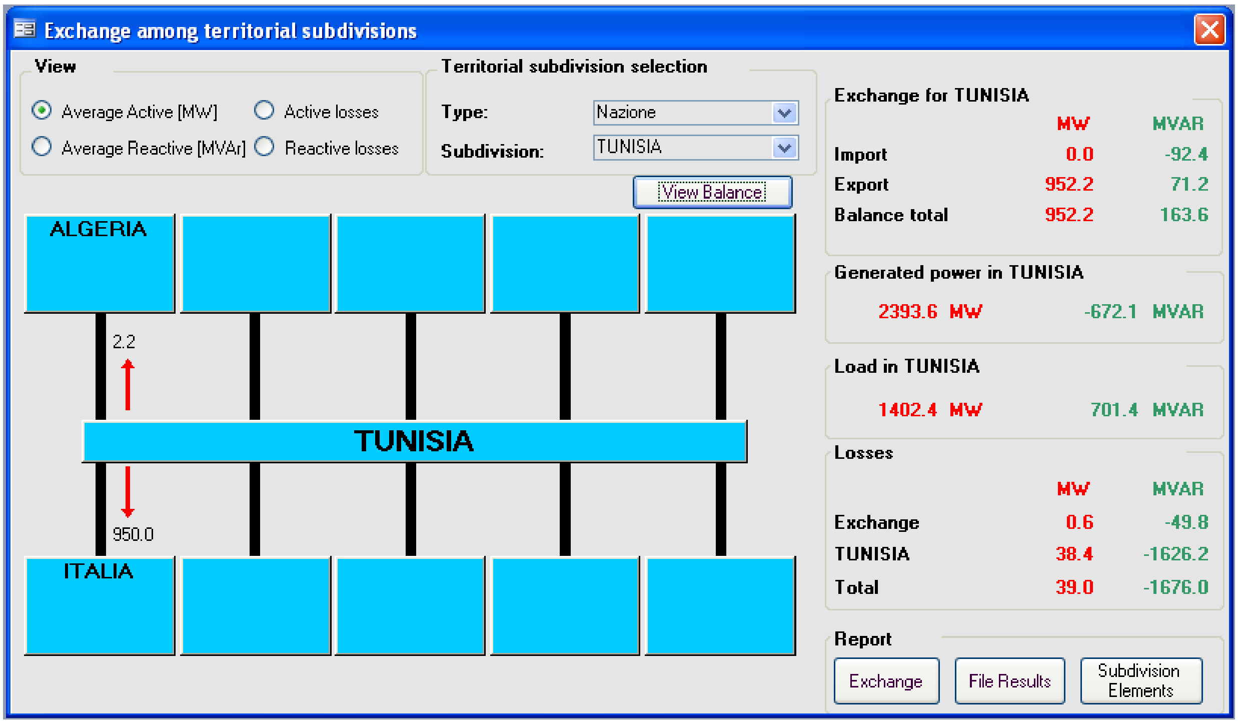

Fig. 5.2 - Minimum condition, International exchanges and power balances for the Tunisian grid.

In sound network condition, voltages are high but within the acceptable limit on all the voltage levels; no overloads are present on lines or transformers.

Neither voltage violations nor overloads are present in N-1 conditions.

5.1.3 Considerations

The results reported in this chapter show that with the connection of the mentioned RES power plants with a generation equal to 530 MW there are no particular changes for Tunisian network with respect to base case scenario. This is a reasonable conclusion because the productions of the new RES power plants are in substitution and not in addition to conventional production. This operation causes a different distribution of power flow on the network but it does not change the total amount of active power generation.

6 MAXIMUM NON-DISPATCHABLE RES GENERATION: DYNAMIC ANALYSES

This chapter addresses the detailed dynamic analyses applied to Tunisian electric system in presence of non-dispatchable renewable power generation (with particular reference to wind generation) with a total amount of 530 MW located in the following sites:

- Sidi Daoued
- Metline
- Kechabta
- Ben Aouf
- Jebel Abderrahmen
- Zonkar

Firstly, the main connection rules for non-dispatchable RES generation plants, suggested in [3], have been recalled.
Thereafter, the analyses have been reported; these can be classified into two categories:

1. sensitivity analyses;
2. fault analyses.

The most important aspect of ***sensitivity analyses*** consists in the examination of power flow fluctuations caused by the intermittent generation of RES power plants without faults and with all elements in operation. These analyses are aimed to:

- an evaluation of the fluctuations of the most important electric variables, such as frequencies, voltages, active power flows on tie-lines with Algeria;
- a calibration check of RES power plants protections;
- an evaluation of the effect of HVDC link on the fluctuations reduction.

The most important aspect of ***fault*** analyses consists of the evaluation of the network response in terms of voltage and frequency profiles, oscillations and stability margin in presence of important contingencies, particularly in case of three-phase short circuit without fault impedance occurring on different voltage levels: 400 kV, 225 kV and 90 kV. These analyses are aimed at:

- an evaluation of the dynamic behaviour of RES power plants;
- a calibration check of RES power plants protections, particularly the frequency derivative ones.

6.1 Connection rules for RES power plants

In CESI Report [3], several integrations of the Tunisian Grid Code have been suggested, with reference to the connection of wind power plants to the grid. These rules are applied more in general for the connection of non-dispatchable RES generation.
The most important ones, regarding wind generators operating parameters and protection settings, have been used for the simulations and are reported hereby:

- normal and exceptional functioning voltage and frequency variation range in figure below (Fig. 6-1). During perturbations the frequency variation limit is ±0.3 Hz.

Tension nominale	État normal	État exceptionnel
225 kV	±7,0 %	±10,0 %
150 kV	±7,0 %	±10,0 %
90 kV	±7,0 %	±10,0 %
Fréquence nominale	**État normal**	**État exceptionnel**
50 Hz	50±50 mHz	48÷52 Hz

Fig. 6-1 –Functioning voltage and frequency.

- wind farms should be able to vary their power factor from 0.95 (lead) to 0.95 (lag), measured at the connection point with the grid (Fig. 6-2).

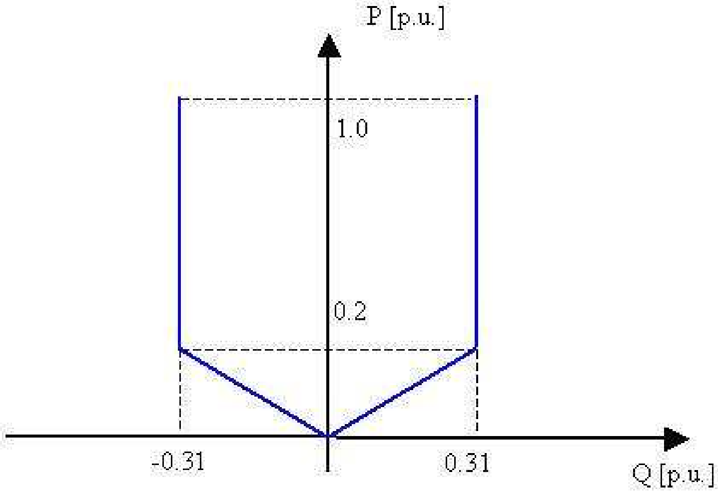

Fig. 6-2 –Functioning field in terms of active and reactive power.

- Wind farms are equipped with voltage, frequency and frequency derivative protections whose calibration thresholds are reported in Tab. 6-1.

Tab. 6-1 – Wind generators' protections

Protections	*Threshold*	*Delay*
Max Voltage	1.15 p.u.	0.2 s
Min Voltage	0.3 p.u.	0.4 s
	0.85 p.u.	3 s
Max Frequency	51.5 Hz	0.2 s
Min Frequency	47 Hz	0.2 s
Derivative Frequency	0.5 Hz/s	0.2 s

- To avoid unexpected wind farm disconnections in case of significant contingencies on the network (i.e. short circuits causing important voltage droops), the setting of voltage protections has to comply with the Fault Ride Through curve with two thresholds with different delays: this curve is depicted in Fig. 6-3.

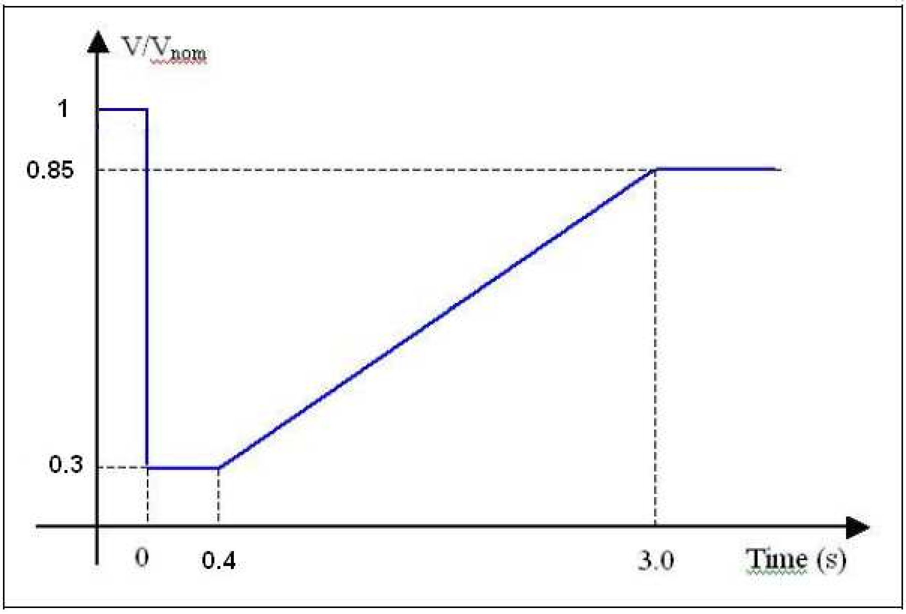

Fig. 6-3 – Fault Ride Through characteristic of wind farms.

In this case, if this characteristic is fulfilled, the disconnection of many RES power plants for under-voltages problems in case of network fault is avoided.

6.2 Hypotheses adopted for the simulations

All the results reported in this chapter have been obtained mainly considering the effect of wind power plans that are those causing the most important fluctuations on the network.
To execute the simulations reported in this chapter the following assumptions involving RES power plants have been considered.

Sensitivity analysis

- The fluctuations for each non dispatchable RES power plant, according to ELMED requests, is made by steps: the power productions of generators change consequently according to the inertia and to the limits of the machine;
- As from the very first simulations the voltage levels appear to be too high if the non-dispatchable RES generation plants work with a null reactive power exchange with the grid (power factor equal to 1): an absorption of reactive power equal to 20% of rated power has been settled for each RES generator. It means that the power factor would be about 0.97 (lag), which is admitted by the suggested connection rules.

Contingency analysis

- In this case a constant power profile has been considered: to analyse the consequences of network faults is not necessary to consider the power fluctuations.
- Three-phase short circuit without fault impedance is considered: this is a conservative hypothesis to assess the security level of the network (the effects of the other types of fault, such

as single-phase, are less binding for angle stability);
- Fault clearing is obtained opening both circuit breakers at the end of the line without simulating the protection relays;
- Auto-reclosing manoeuvres are not considered since we are simulating three-phase faults: when circuit breakers are opened the line is left out of service.

In addition to the previous assumptions, also the hypotheses already described in [2] involving Skhira power plant and the HVDC system to Italy have been considered. For completeness, they are reported below.

With reference to Skhira power plant:
1. both generators are equipped with Power System Stabilizer (PSS) components;
2. a Fast Valving (FV) device has been considered for each generator: it closes high and medium steam pressure valves during the transient;
3. both generators have been equipped with an independent excitation supply system.

With reference to HVDC system:
- the reactive compensation identified in static analyses has been applied also in dynamic simulations;
- typical values of time constants and control parameters (with reference to SAPEI[10] interconnection) have been adopted.

6.3 Variables analysed in the simulations

During the simulations the behaviours of the following variables have been monitored and reported in this document:
- electric and mechanical power of Skhira power plant (for sensitivity analysis only);
- active power of HVDC system;
- RES power generations;
- wind profile for each generator (for sensitivity analysis only);
- frequency of some important 400 kV substations of the network, such as Skhira, Bouchemma, Oueslatia and Mornaguia;
- voltages of the same substations;
- total active power exchanges between Tunisia and Algeria

The following table is the legend for the tie-lines codes used in the graphs showing the power exchanges between Tunisia and Algeria. Note that the first number in the code represents the voltage level: 1 – 400 kV; 2 – 225 kV; 3 – 150 kV and 5 – 90 kV.

[10] SAPEI is an acronym, which stands for: SArdegna – PEnisola Italiana. It is the HVDC link connecting Sardinia to continental Italy. In this study this DC link has been considered as a reference because it has the same characteristics of the one considered in the study: bipolar configuration, having a rating of 1000 MW.

Tab. 6-2 –Sicre Codes of interconnection lines between Algeria and Tunisia.

CODE	*LINE*
AT11001	El Hadja – Jendouba (400 kV)
AT20001	El Aouinet – Tajeroui (225 kV)
AT30001	Djeb Onk – Metlaoui (150 kV)
AT50001	El Aouinet – Tajeroui (90kV)
AT50002	El Kala – Fernana (90 kV)

6.4 Sensitivity analyses

In this chapter the most important results and considerations caused by RES generations' variations are reported. To point out the positive effects on the Tunisian transmission system of the HVDC link, this analysis is repeated in four different situations both for peak and minimum load conditions:

- Case 1: Tunisian grid connected to the rest of Maghreb (and Europe) and HVDC link with frequency regulation;
- Case 2: Tunisian grid connected to the rest of Maghreb (and Europe) and HVDC link without frequency regulation;
- Case 3: Tunisian grid isolated and HVDC link with frequency regulation;
- Case 4: Tunisian grid isolated and HVDC without frequency regulation.

Comparing particularly the results of Case 1 with Case 2 and Case 3 with Case 4, it is possible to highlight the positive effects that the HVDC link can have on the Tunisian system.

Note: the wind profile for each wind power plant is obtained using a random function that permits to have a casual distribution different for each power plant. For this reason the production profiles are different for each analysis reported.

6.4.1 Peak load scenario

Peak load scenario, as showed in the graphs reported, is the less disturbed case in comparison to minimum load condition, because the RES power fluctuations represent a minor percentage of the total generated power. However it is useful to investigate it, as done hereafter, to point out how different grid operational arrangements (presence/absence of HVDC frequency regulation and interconnections with Algeria) could improve or worsen the effects of RES generations' variations.

6.4.1.1 Case 1: Tunisia interconnected with the rest of Maghreb and HVDC system in frequency regulation

Case 1, reported from Fig. 6.4 to Fig. 6.13, is the scenario with the smallest oscillations and it represents the best grid setup in order to maintain the system variables within an acceptable range even in case of major RES power fluctuations. Both the interconnection lines with Algeria and frequency regulation of HVDC system contribute to keep voltage within the ±7% limit and frequency in the ±50mHz limit.
Fig. 6.4 and Fig. 6.5 represent, respectively, the generations and the wind speeds for every RES power plant. Comparing the figures it is possible note that, because of the inertia of the machines, after a step variation of wind speed the generated power change following an exponential behaviour because it

cannot change instantaneously. This behaviour, even if with different profiles, is equal for every case considered in sensitivity analyses.

Comparing Fig. 6.6 to Fig. 6.7 it is possible to highlight the frequency control of HVDC connection: when the frequency decreases the exportation to Italy decreases and vice-versa; in particular it could happen that, if the frequency increases, the HVDC has a saturation with an exportation fixed to 1000 MW: in this case the DC link can not control the frequency. For this reason it’s important to have an adequate frequency control margin.

Fig. 6.8 and Fig. 6.9 report respectively the power flow variations on all tie-lines Tunisia-Algeria and the total amount of active power exchange with Algeria. The fluctuations of RES generation plants cause, as reported in Fig. 6.9, variations from about 90 MW in importation to 70 MW in export.

The other grid variables, such as voltages of some 400 kV or RES stations, change consequently.

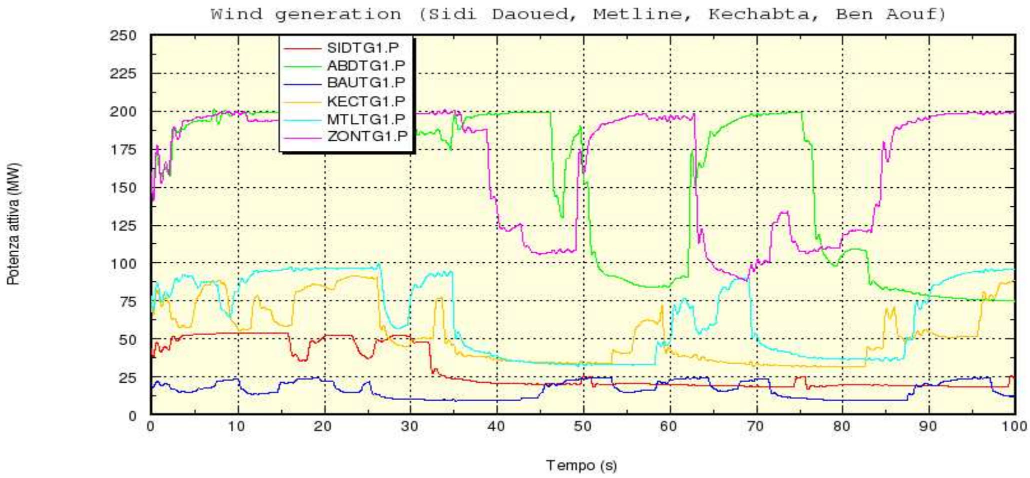

Fig. 6.4 - Peak condition, sensitivity analysis, RES generations (Sidi Daoued, J. Abderrahmen, Ben Aouf, Kechabta, Metline, Zoncar)

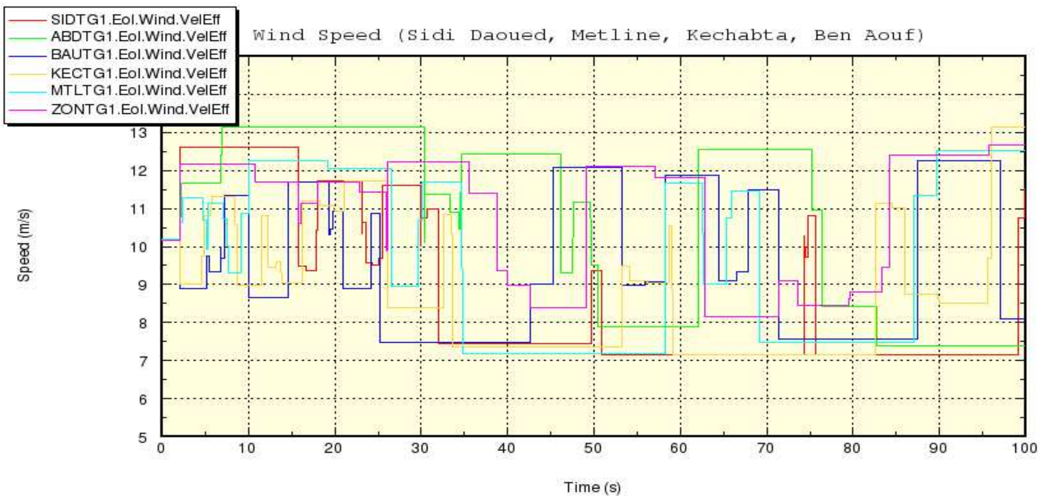

Fig. 6.5 - Peak condition, sensitivity analysis, wind speeds (Sidi Daoued, J. Abderrahmen, Ben Aouf, Kechabta, Metline, Zoncar)

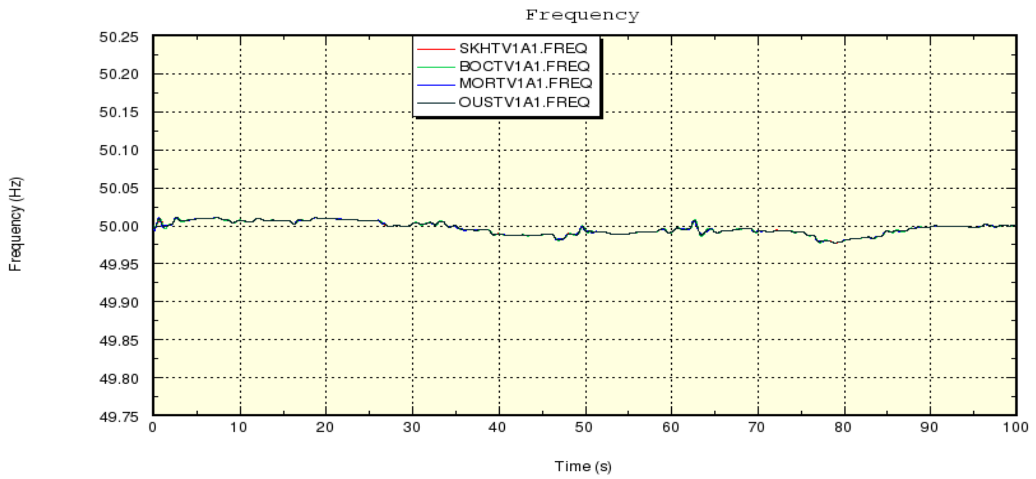

Fig. 6.6 - Peak condition, sensitivity analysis, frequencies (Skhira, Bouchemma, Mornaguia, Oueslatia)

Fig. 6.7 - Peak condition, sensitivity analysis, HVDC active power flow

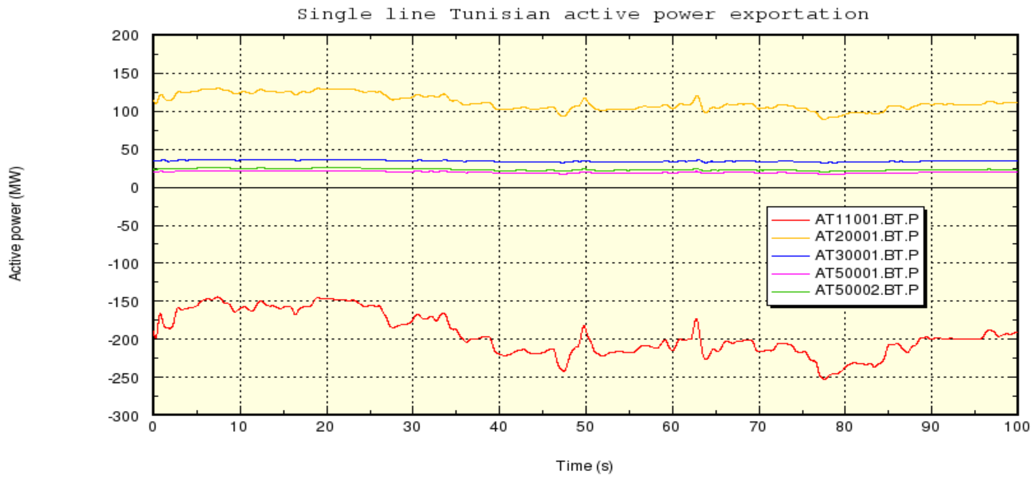

Fig. 6.8 - Peak condition, sensitivity analysis, single line active power exchanges.

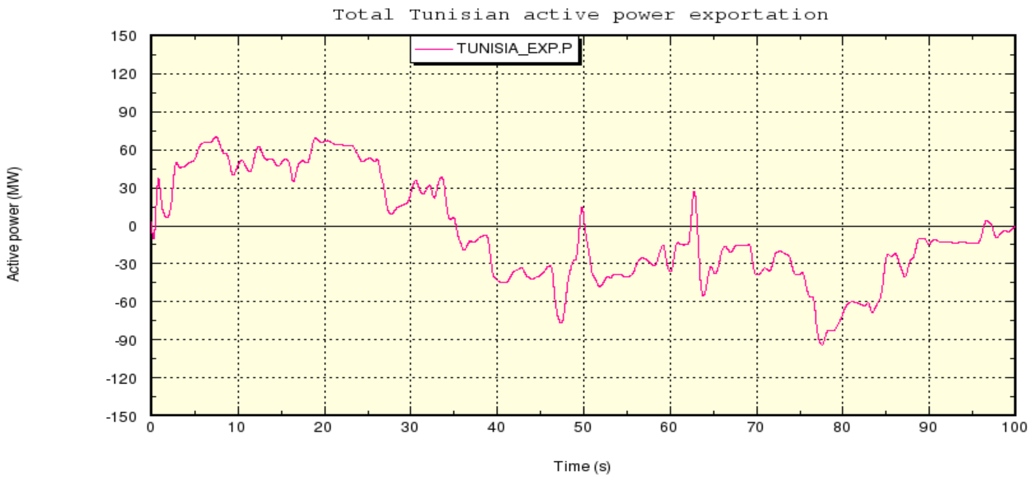

Fig. 6.9 - Peak condition, sensitivity analysis, total active power exchange with Algeria only.

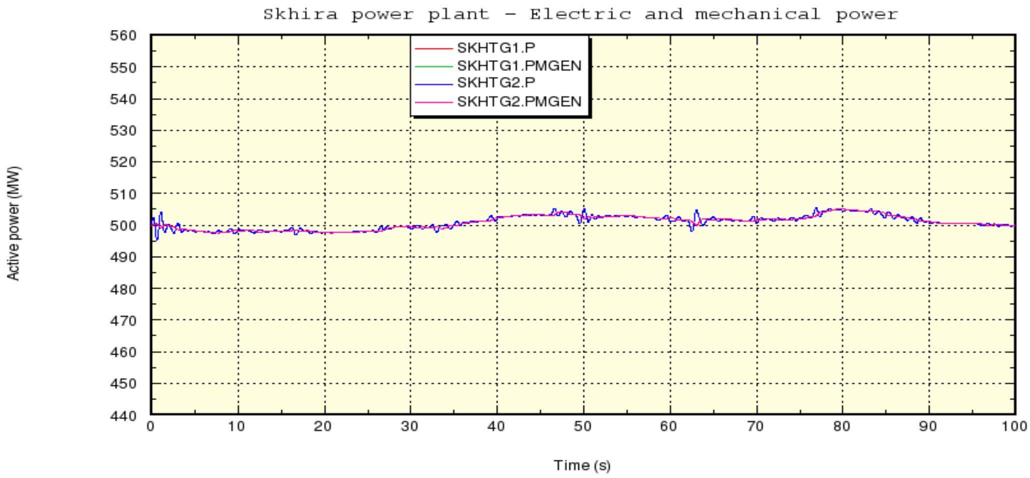

Fig. 6.10 - Peak condition, sensitivity analysis, electric and mechanical power of Skhira.
Legend: P – Electric Power; PMGEN – Mechanical Power

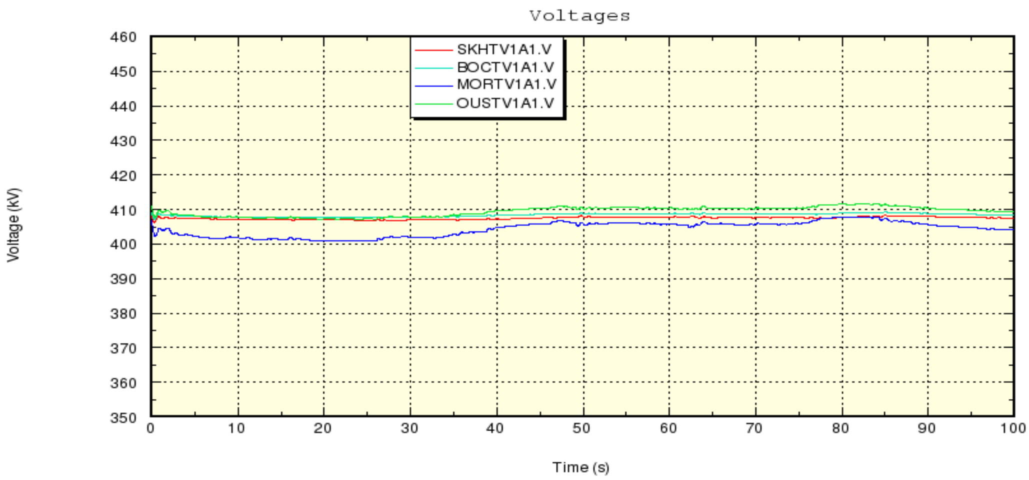

Fig. 6.11 - Peak condition, sensitivity analysis, 400 kV voltages (Skhira, Bouchemma, Mornaguia, Oueslatia).

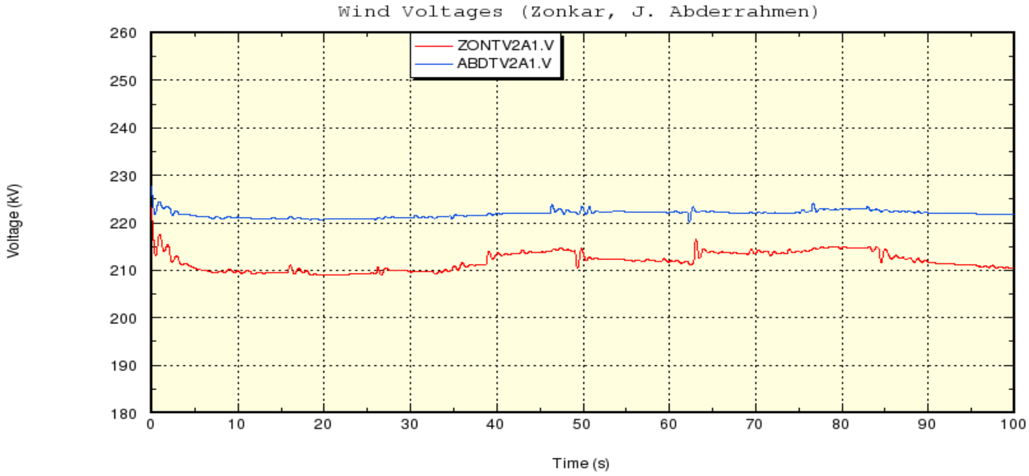

Fig. 6.12 - Peak condition, sensitivity analysis, 225 kV RES station voltages (Zonkar, J. Abderrahmen).

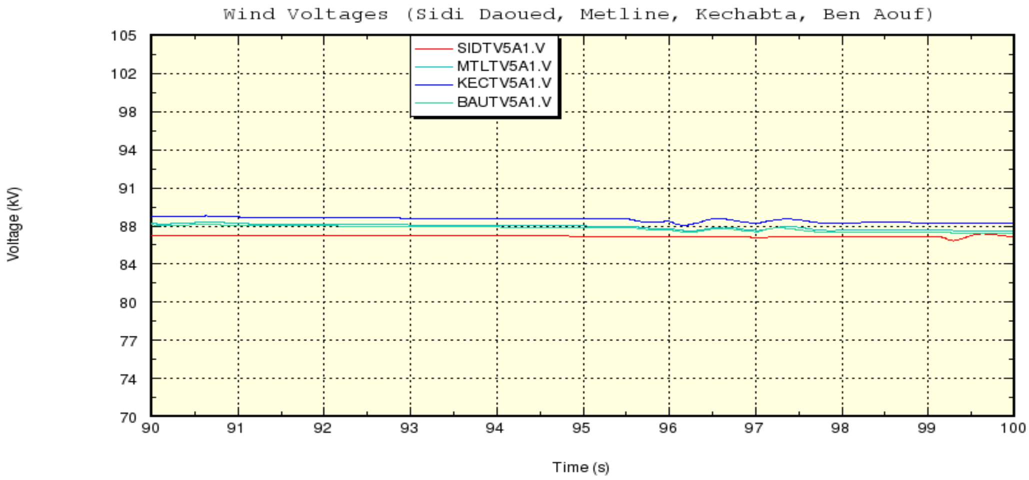

Fig. 6.13 - Peak condition, sensitivity analysis, 90 kV RES station voltages (Sidi Daoued, Metline, Kechabta, Ben Aouf).

6.4.1.2 Case 2: Tunisia interconnected with the rest of Maghreb and HVDC system without frequency regulation

In case 2, reported from Fig. 6.14 to Fig. 6.23, the HVDC interconnection is not equipped with frequency regulation (Fig. 6.17 shows that HVDC export is constant and equal to 950 MW): in this case all non-dispatchable RES power variations are corrected changing only power flows with Algeria and with Tunisian generation. A consequence of this, as reported in Fig. 6.16, in this scenario frequency fluctuations are larger than those reported in Case 1, even if they remain into ±50mHz limit. Moreover, fluctuations of renewable productions cause, as reported in Fig. 6.19, active power variations from about 110 MW in import to 110 MW in export between Algeria and Tunisia.

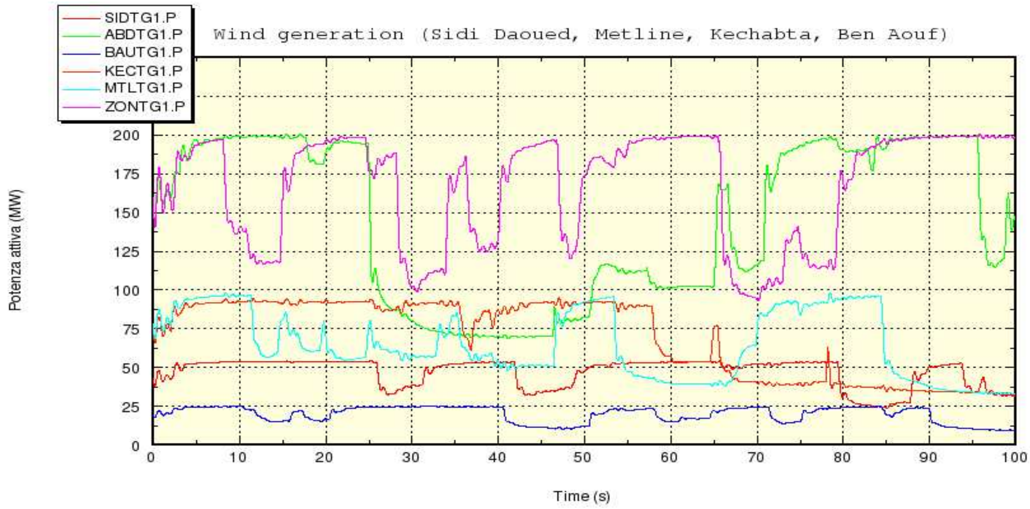

Fig. 6.14 - Peak condition, sensitivity analysis, RES generations (Sidi Daoued, J. Abderrahmen, Ben Aouf, Kechabta, Metline, Zoncar)

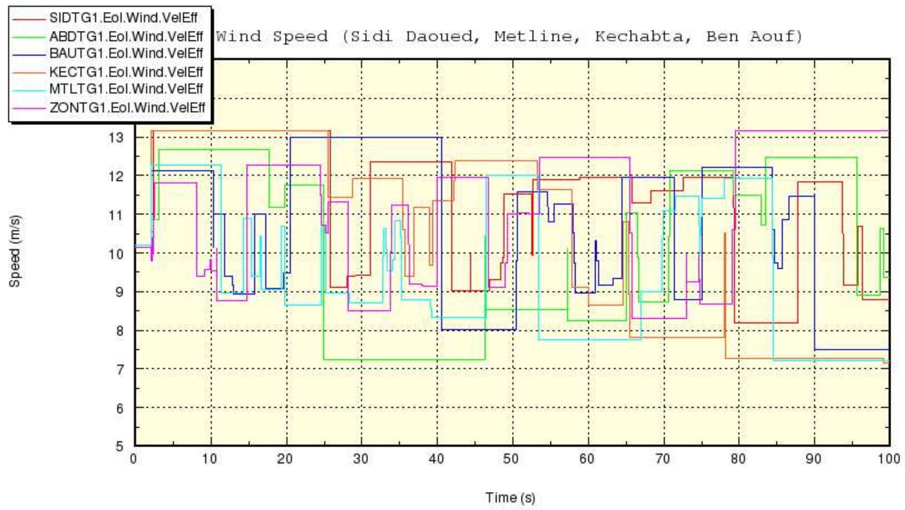

Fig. 6.15 - Peak condition, sensitivity analysis, wind speeds (Sidi Daoued, J. Abderrahmen, Ben Aouf, Kechabta, Metline, Zoncar)

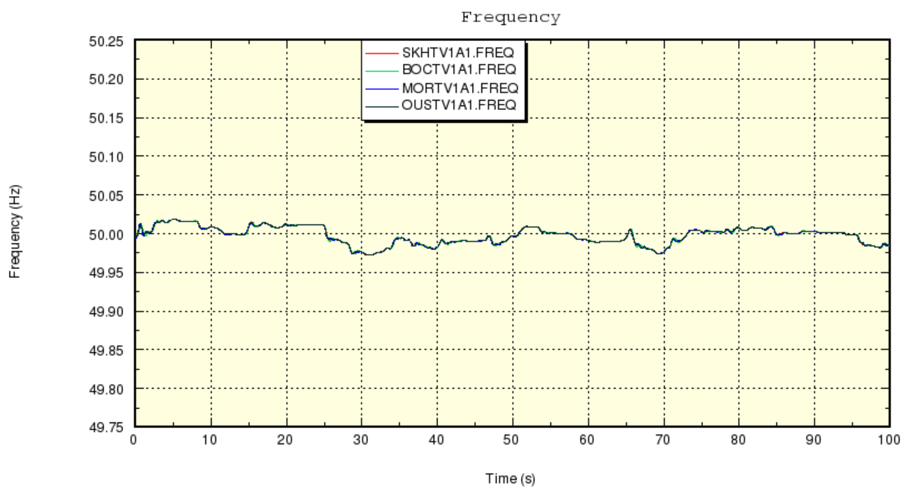

Fig. 6.16 - Peak condition, sensitivity analysis, frequencies (Skhira, Bouchemma, Mornaguia, Oueslatia)

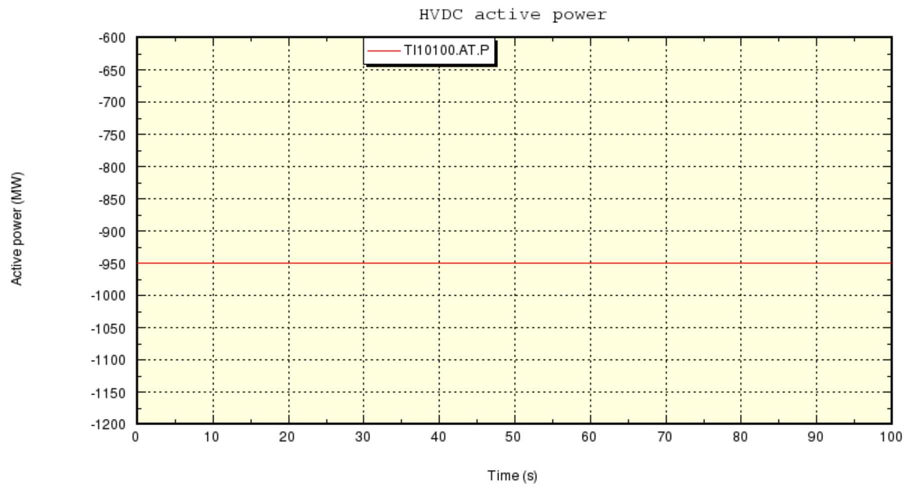

Fig. 6.17 - Peak condition, sensitivity analysis, HVDC active power flow

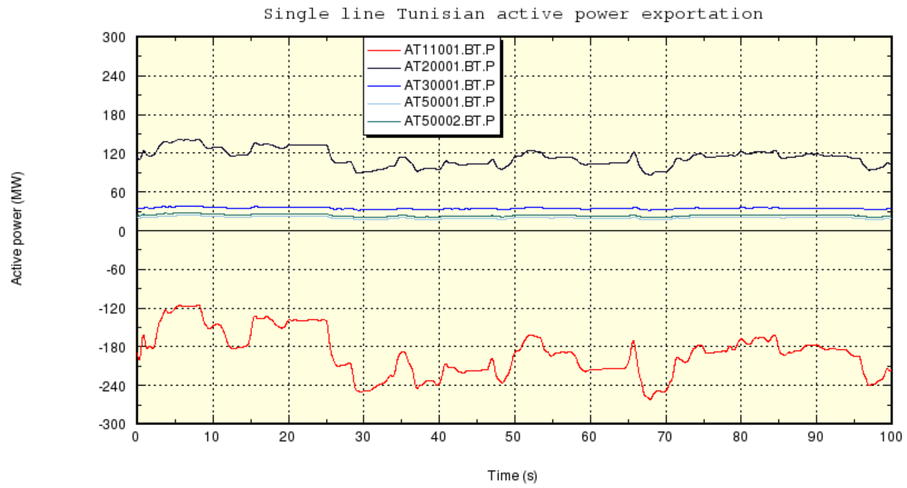

Fig. 6.18 - Peak condition, sensitivity analysis, single line active power exchanges.

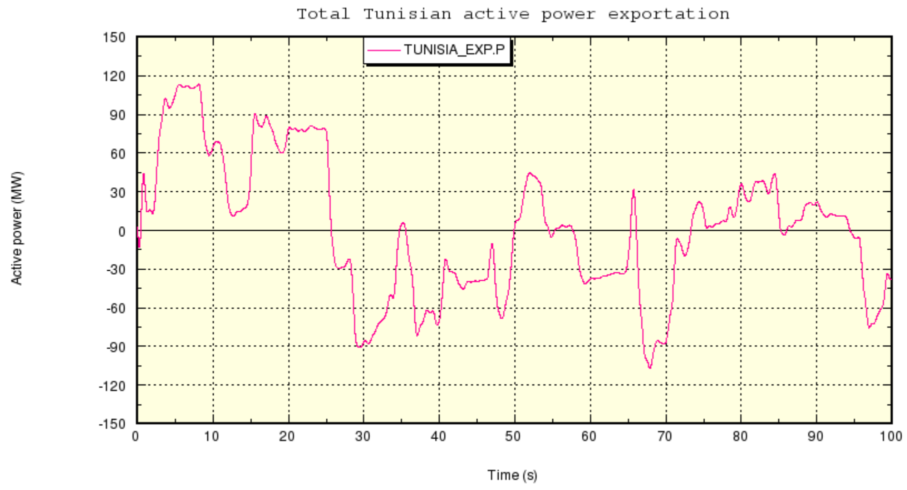

Fig. 6.19 - Peak condition, sensitivity analysis, total active power exchange with Algeria only.

Fig. 6.20 - Peak condition, sensitivity analysis, electric and mechanical power of Skhira. Legend: P – Electric Power; PMGEN – Mechanical Power

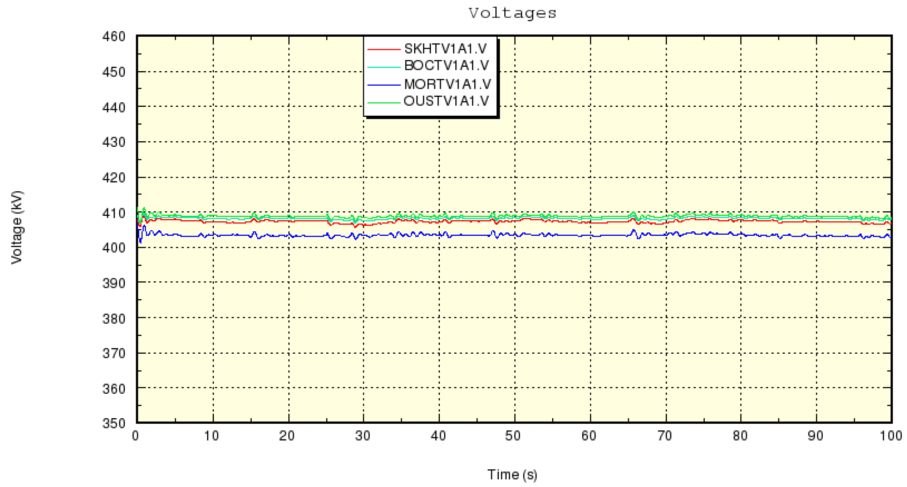

Fig. 6.21 - Peak condition, sensitivity analysis, 400 kV voltages (Skhira, Bouchemma, Mornaguia, Oueslatia).

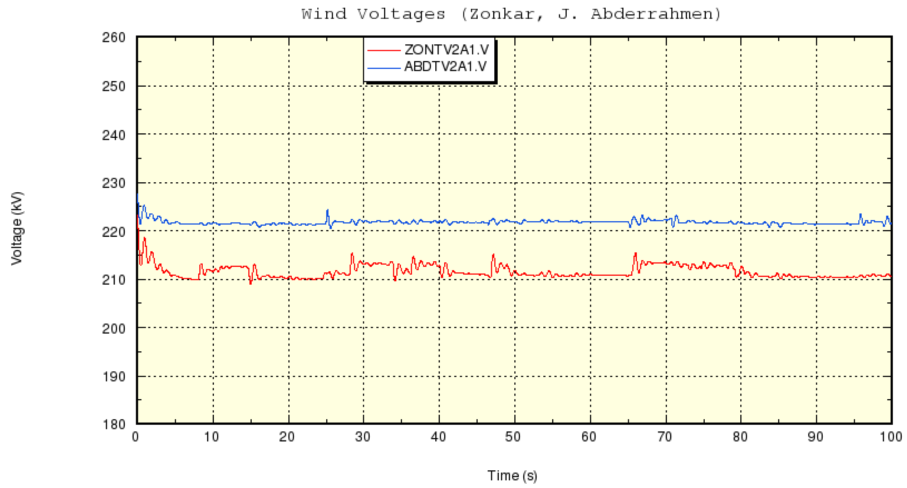

Fig. 6.22 - Peak condition, sensitivity analysis, 225 kV RES station voltages (Zonkar, J. Abderrahmen).

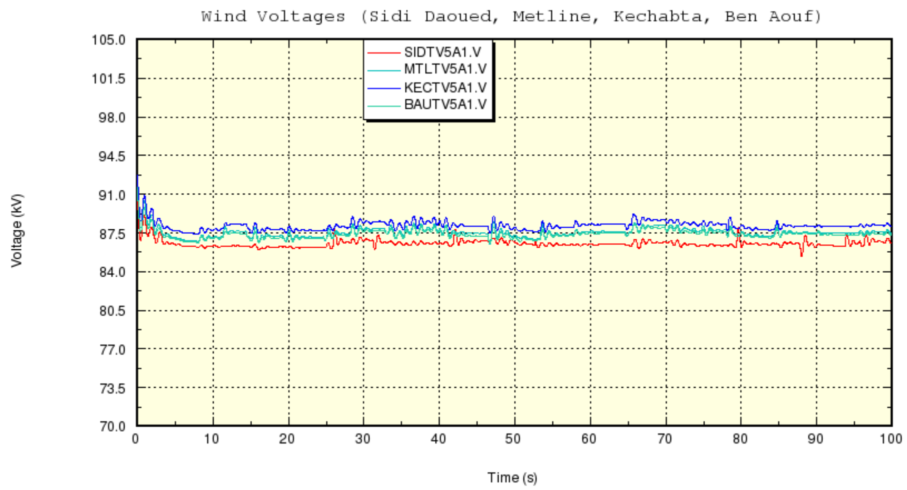

Fig. 6.23 - Peak condition, sensitivity analysis, 90 kV RES station voltages (Sidi Daoued, Metline, Kechabta, Ben Aouf).

6.4.1.3 Case 3: Tunisia isolated and HVDC system in frequency regulation

Case 3, reported from Fig. 6.24 to Fig. 6.31, shows the importance of the frequency regulation at the HVDC converter station, since in this scenario it is the only element, together with the Tunisian generation, able to control frequency deviations caused by non-dispatchable RES generation. In particular, an instantaneous RES generation reduction of more than 200 MW causes a reduction in the system frequency below 49.95 Hz[11]. However the quick intervention of the HVDC system, which reduces its power export, leads to an acceptable recovering of the frequency values. From the behaviour reported in Fig. 6.26 it is possible to note that also in this case frequency variations are almost all within a range of ±50mHz. rare

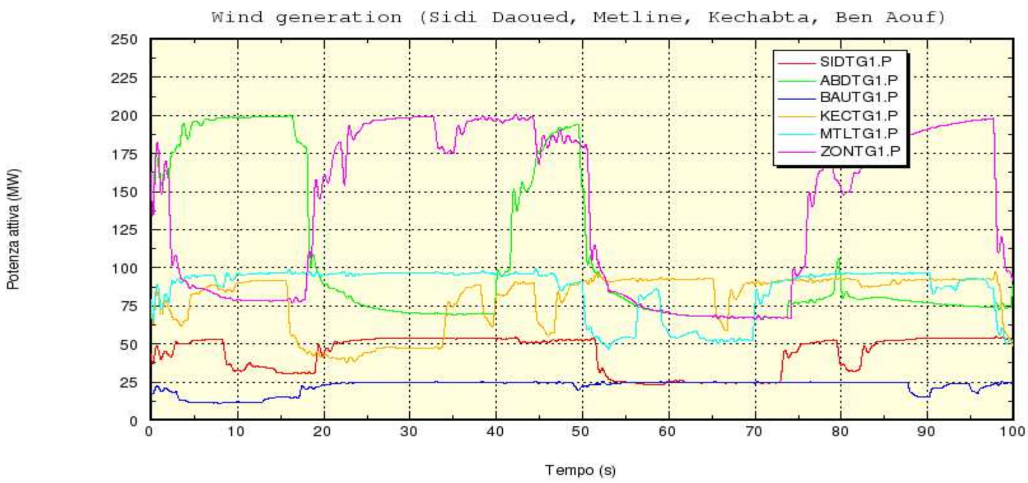

Fig. 6.24 - Peak condition, sensitivity analysis, RES generations (Sidi Daoued, J. Abderrahmen, Ben Aouf, Kechabta, Metline, Zoncar)

[11] This is certainly an unusual, but not impossible, event. It is true that the duration of the phenomenon is short (less than 5 seconds) and it does not cause problems for the network, but it is an indicator that the electric system is operating close to its limits.

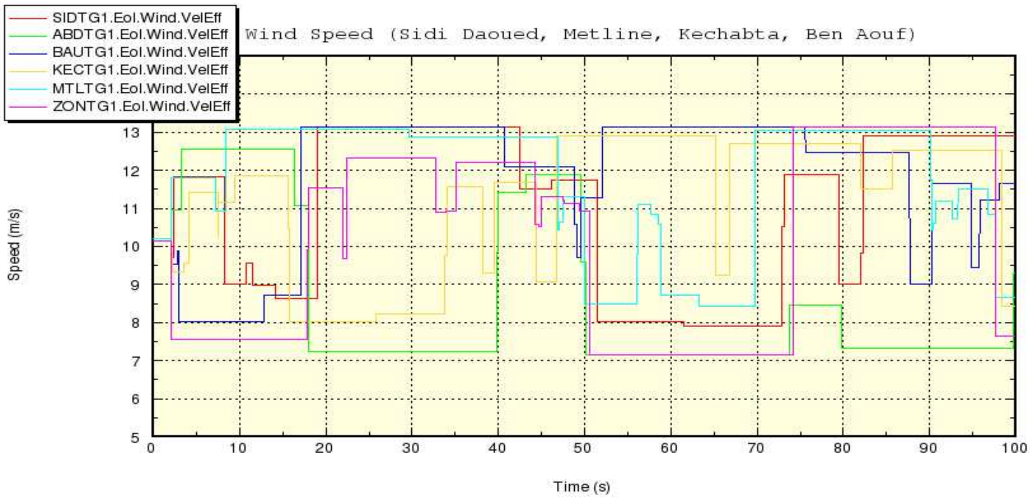

Fig. 6.25 - Peak condition, sensitivity analysis, wind speeds (Sidi Daoued, J. Abderrahmen, Ben Aouf, Kechabta, Metline, Zoncar)

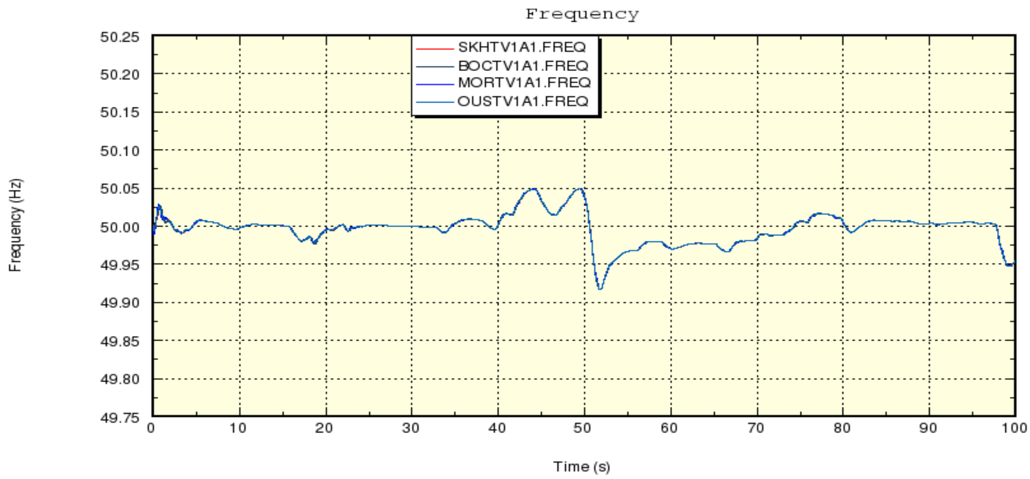

Fig. 6.26 - Peak condition, sensitivity analysis, frequencies (Skhira, Bouchemma, Mornaguia, Oueslatia)

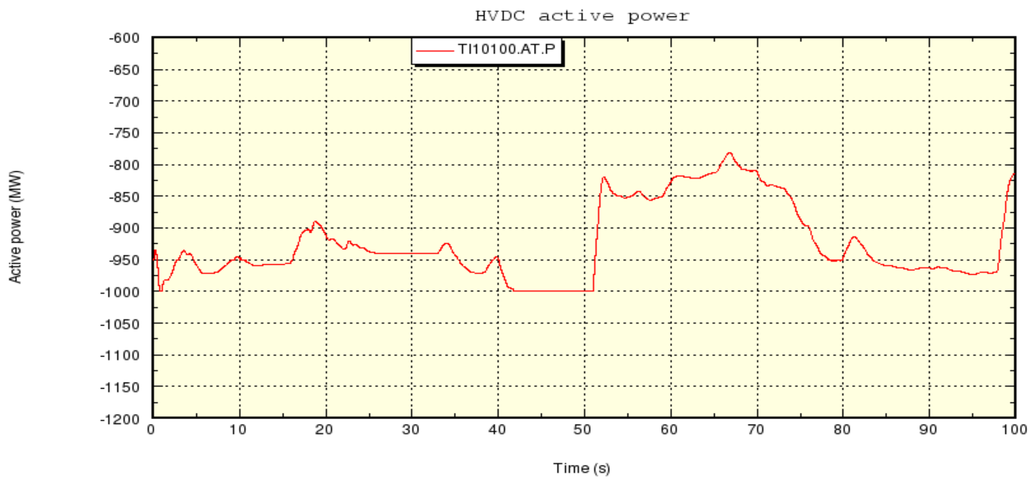

Fig. 6.27 - Peak condition, sensitivity analysis, HVDC active power flow

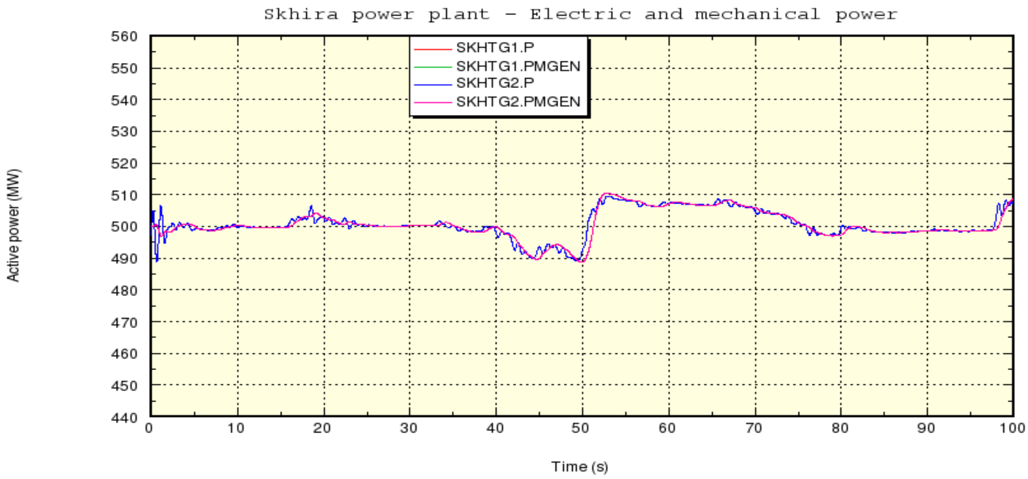

Fig. 6.28 - Peak condition, sensitivity analysis, electric and mechanical power of Skhira. Legend: P – Electric Power; PMGEN – Mechanical Power

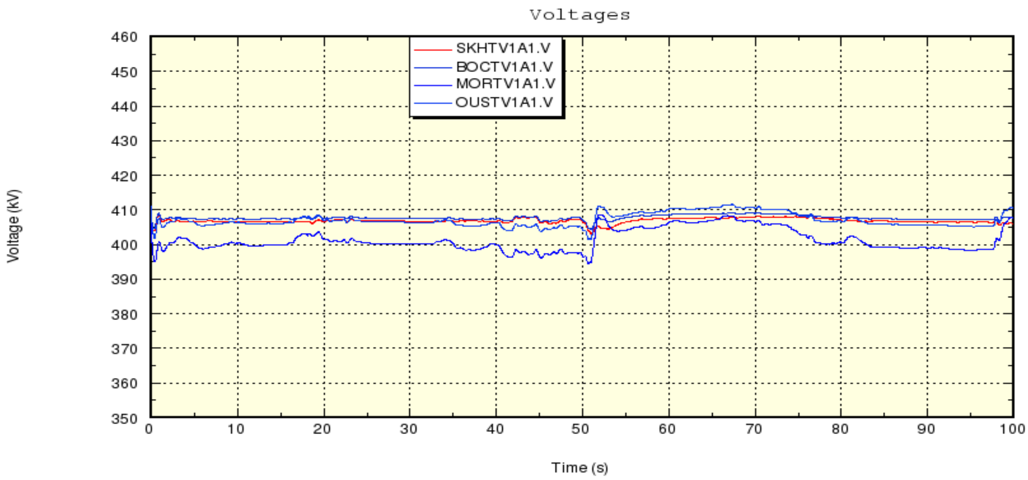

Fig. 6.29 - Peak condition, sensitivity analysis, 400 kV voltages (Skhira, Bouchemma, Mornaguia, Oueslatia).

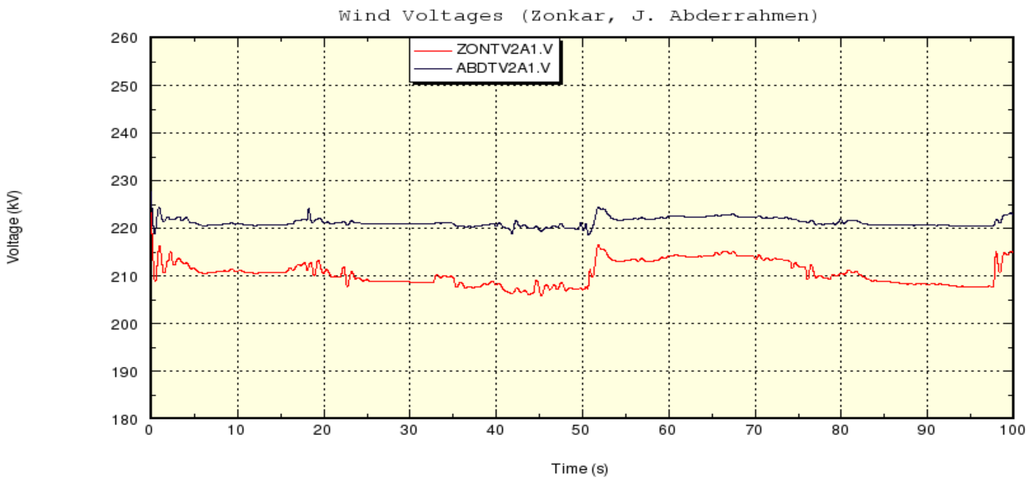

Fig. 6.30 - Peak condition, sensitivity analysis, 225 kV RES station voltages (Zonkar, J. Abderrahmen).

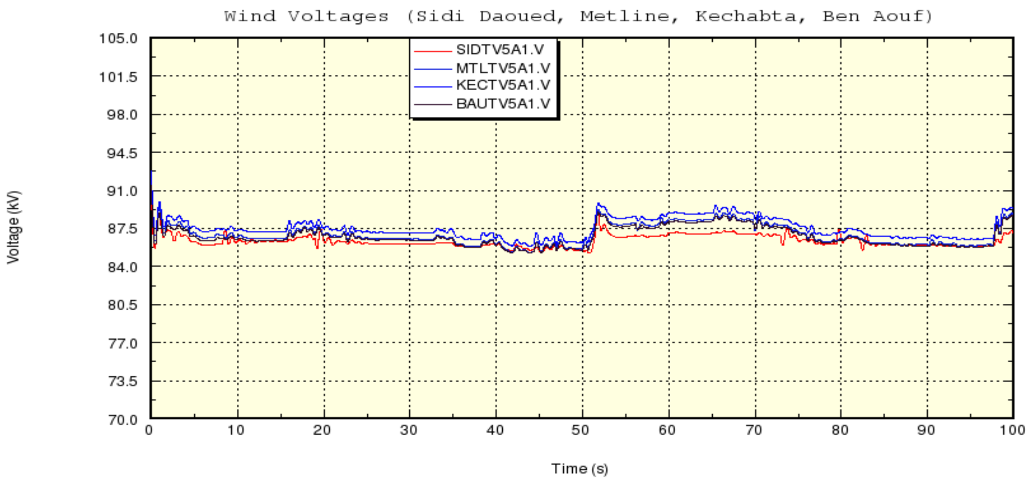

Fig. 6.31 - Peak condition, sensitivity analysis, 90 kV RES station voltages (Sidi Daoued, Metline, Kechabta, Ben Aouf).

6.4.1.4 Case 4: Tunisia isolated and HVDC system without frequency regulation

Case 4 is the worst scenario: all RES power variations are compensated only with Tunisian generators. Compared with the other ones reported above, this case demonstrates that the effects of renewable power fluctuations are not acceptable, lacking the support of interconnection with Algeria and the frequency regulation of the HVDC system: for example, frequency fluctuations are always larger than the ±50mHz limit.
In this case the variations of ELMED power plant production are larger than those of other scenarios (Fig. 6.36)

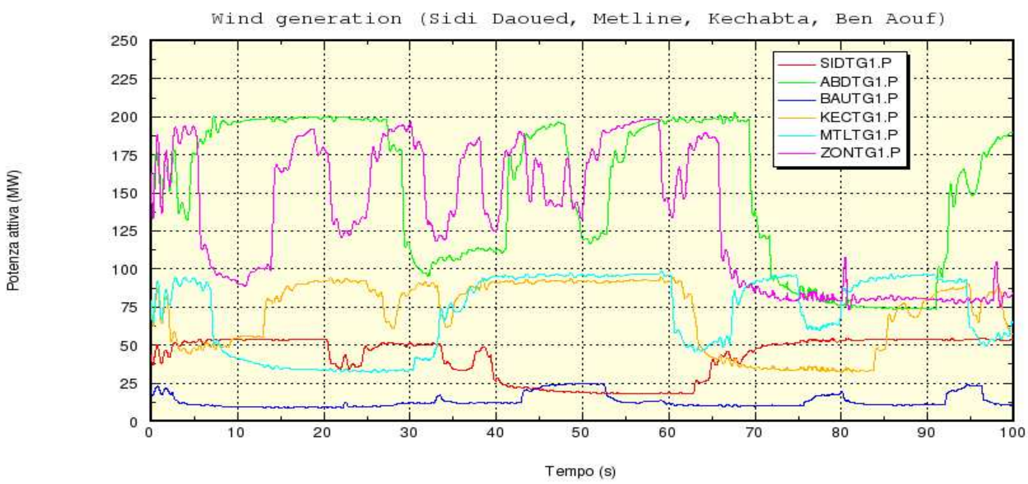

Fig. 6.32 - Peak condition, sensitivity analysis, RES generations (Sidi Daoued, J. Abderrahmen, Ben Aouf, Kechabta, Metline, Zoncar)

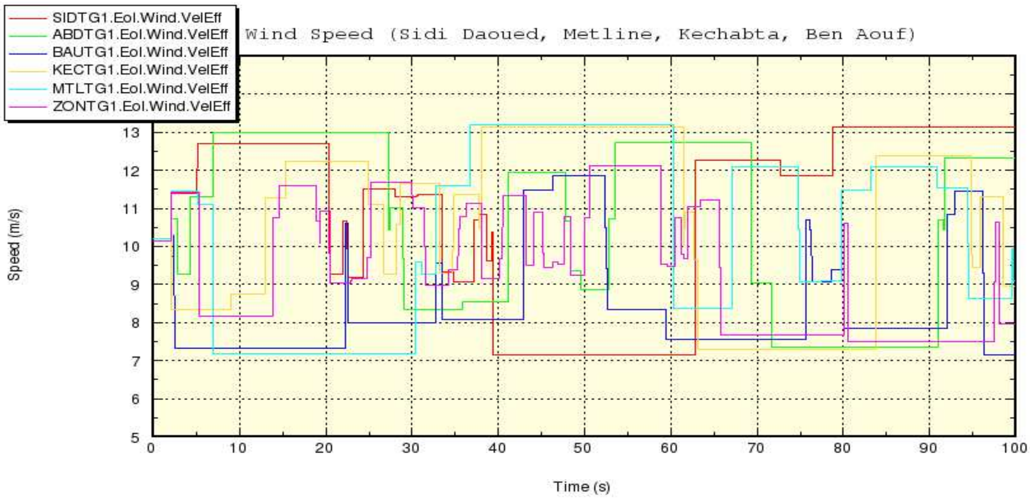

Fig. 6.33 - Peak condition, sensitivity analysis, wind speeds (Sidi Daoued, J. Abderrahmen, Ben Aouf, Kechabta, Metline, Zoncar)

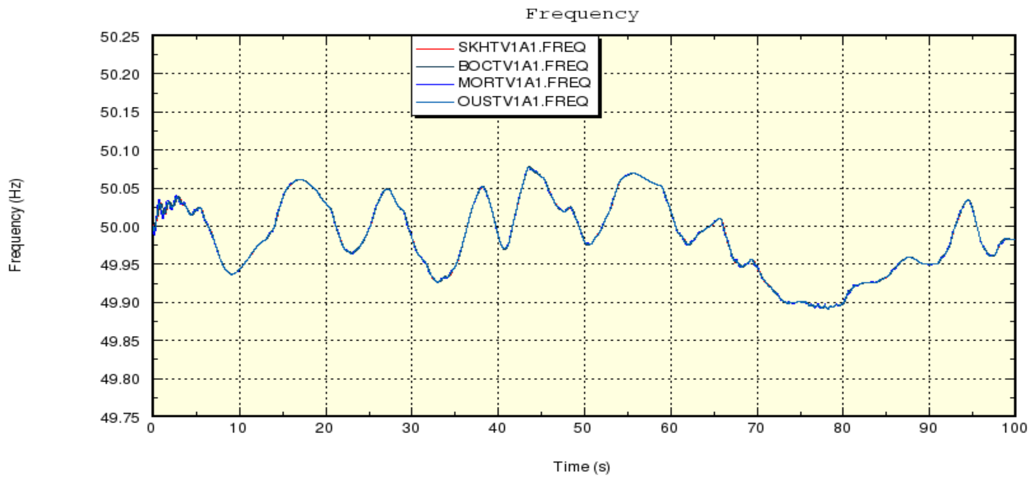

Fig. 6.34 - Peak condition, sensitivity analysis, frequencies (Skhira, Bouchemma, Mornaguia, Oueslatia)

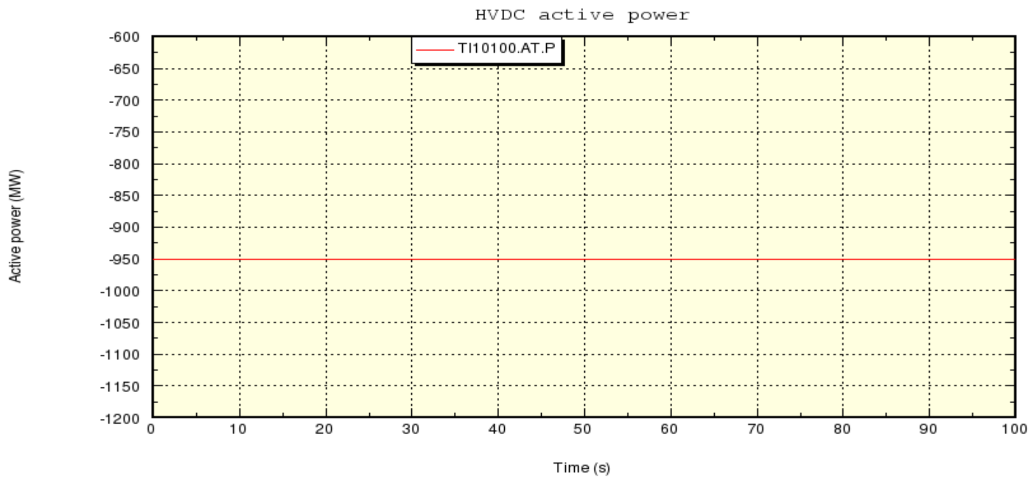

Fig. 6.35 - Peak condition, sensitivity analysis, HVDC active power flow

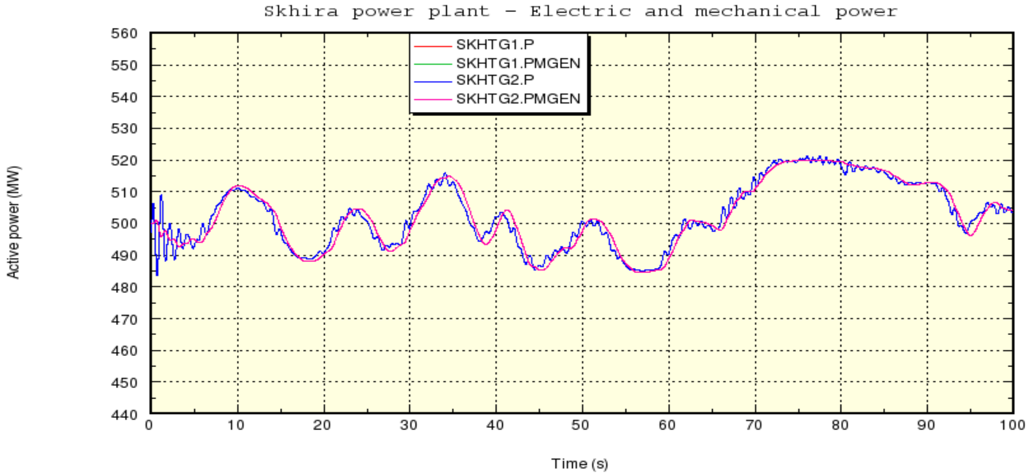

Fig. 6.36 - Peak condition, sensitivity analysis, electric and mechanical power of Skhira. Legend: P – Electric Power; PMGEN – Mechanical Power

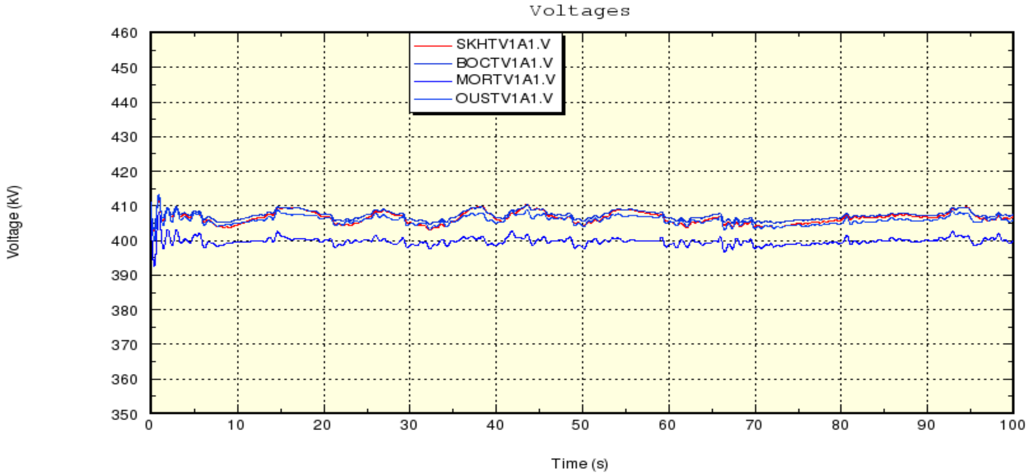

Fig. 6.37 - Peak condition, sensitivity analysis, 400 kV voltages (Skhira, Bouchemma, Mornaguia, Oueslatia).

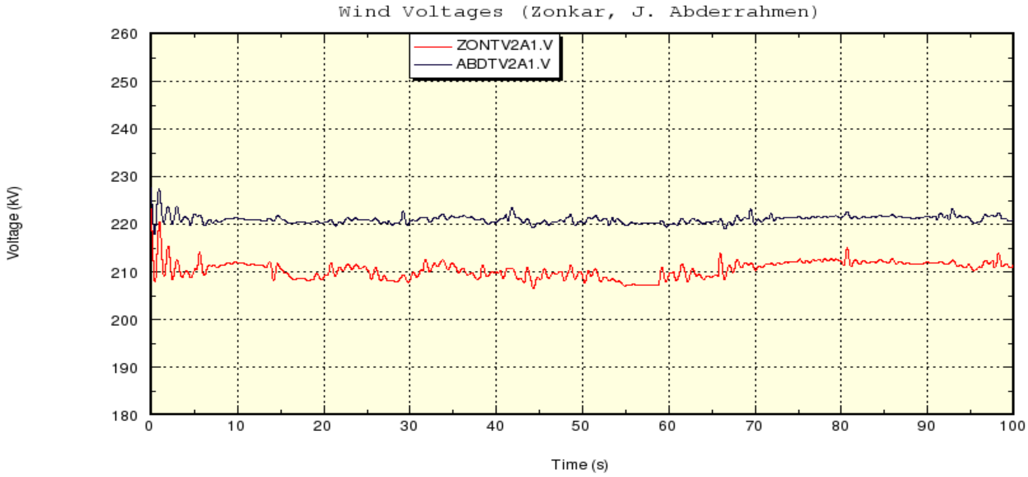

Fig. 6.38 - Peak condition, sensitivity analysis, 225 kV RES station voltages (Zonkar, J. Abderrahmen).

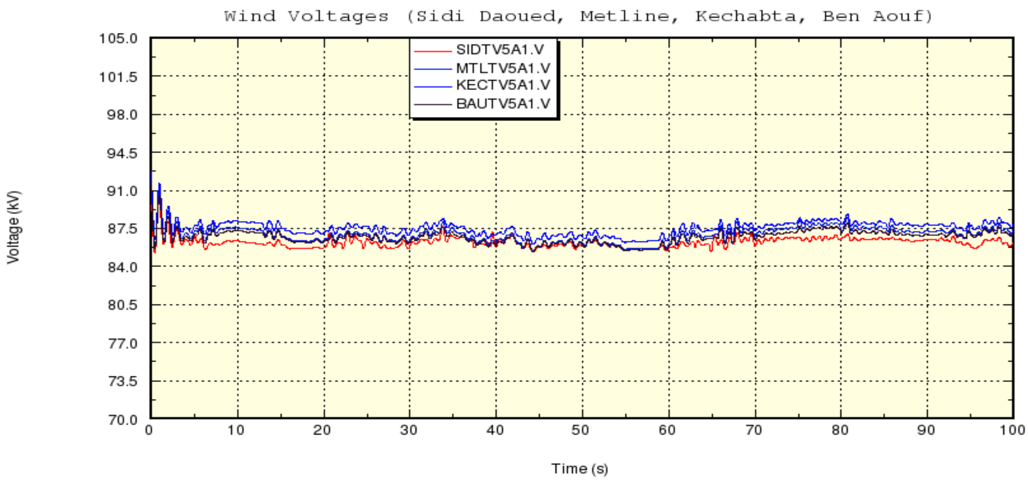

Fig. 6.39 - Peak condition, sensitivity analysis, 90 kV RES station voltages (Sidi Daoued, Metline, Kechabta, Ben Aouf).

6.4.2 Minimum load scenario

As already mentioned, minimum load scenario represents the worst condition in case of non-dispatchable RES fluctuations. Also in this case the presence of HVDC system's frequency regulation has a really beneficent effect for the system.

6.4.2.1 Case 1: Tunisia interconnected with the rest of Maghreb and HVDC system in frequency regulation

Case 1, reported from Fig. 6.40 to Fig. 6.49, shows that in normal operation also in minimum load condition the presence of HVDC system's frequency regulation and of interconnections with Algeria permits to have very good system performances even for important renewable power production variations. Also in this case frequency variations are always included in the ±50mHz limit and voltage oscillations are not particularly high. Moreover, the power flow variations on tie-lines with Algeria are quite small and, like reported in Fig. 6.45, included from about 60 MW in import to 50 MW in export.

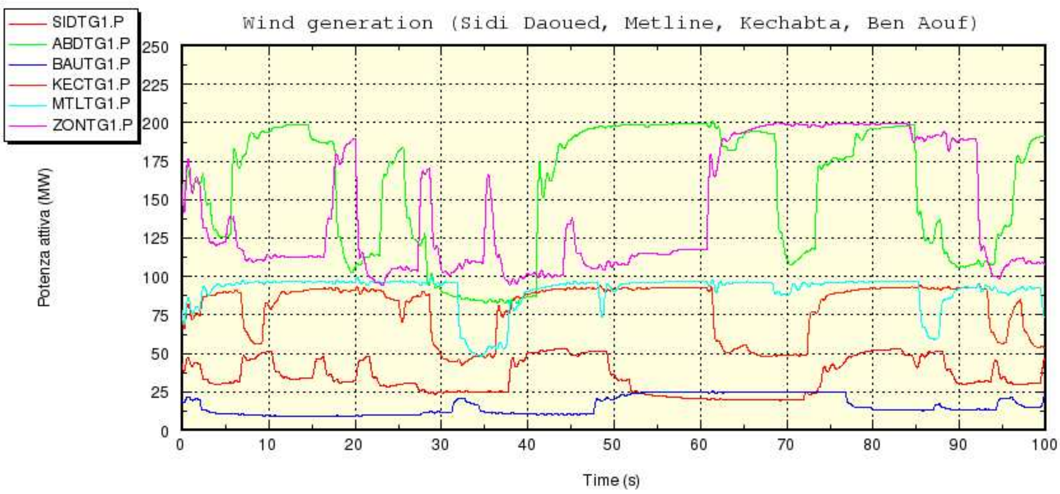

Fig. 6.40 – Minimum load condition, sensitivity analysis, RES generations (Sidi Daoued, J. Abderrahmen, Ben Aouf, Kechabta, Metline, Zoncar)

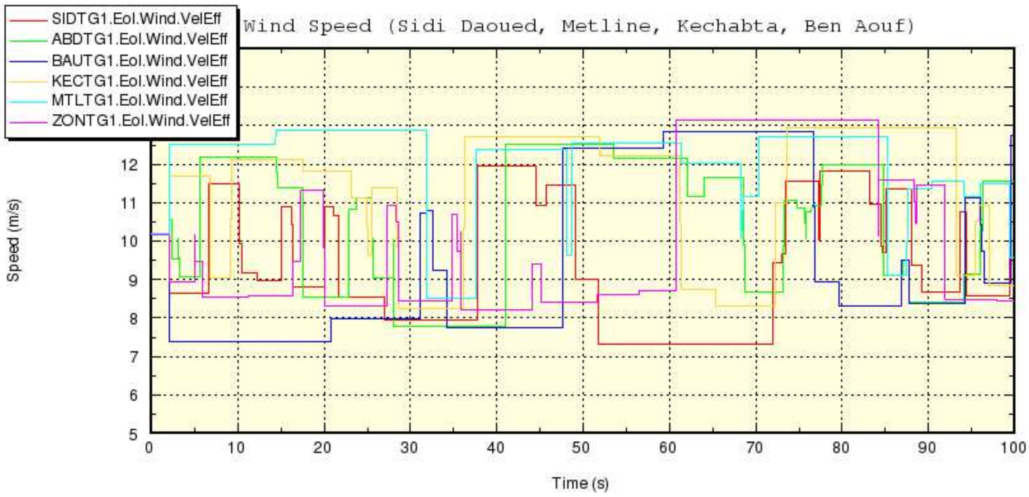

Fig. 6.41 - Minimum load condition, sensitivity analysis, wind speeds (Sidi Daoued, J. Abderrahmen, Ben Aouf, Kechabta, Metline, Zoncar)

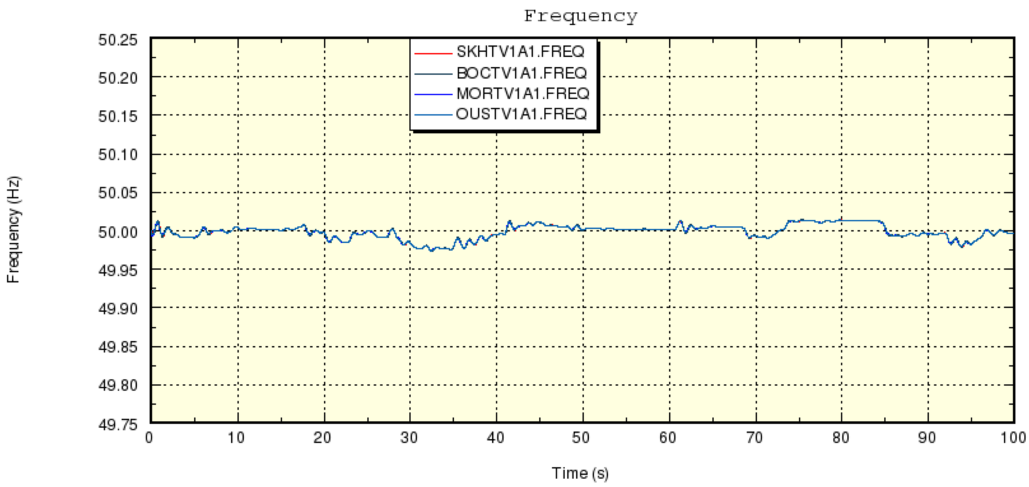

Fig. 6.42 - Minimum load condition, sensitivity analysis, frequencies (Skhira, Bouchemma, Mornaguia, Oueslatia)

Fig. 6.43 - Minimum load condition, sensitivity analysis, HVDC active power flow

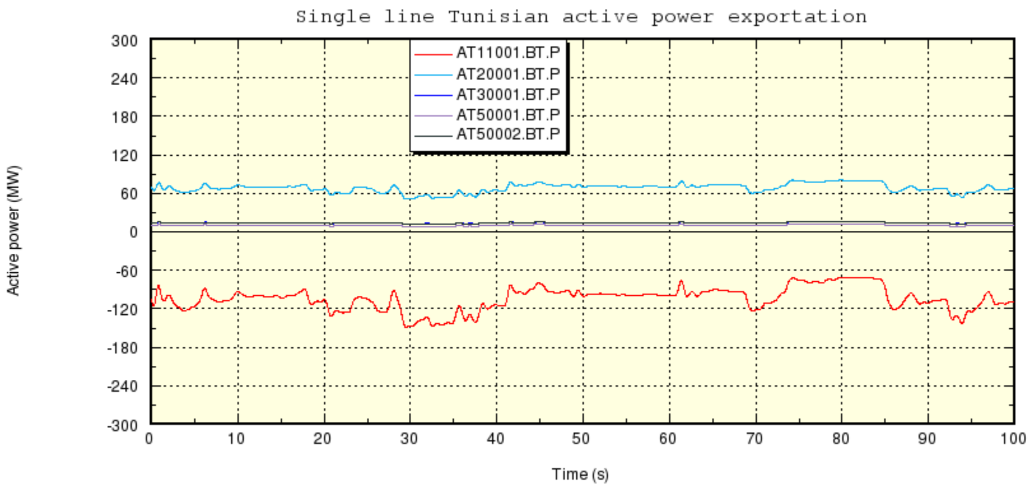

Fig. 6.44 - Minimum load condition, sensitivity analysis, single line active power exchanges.

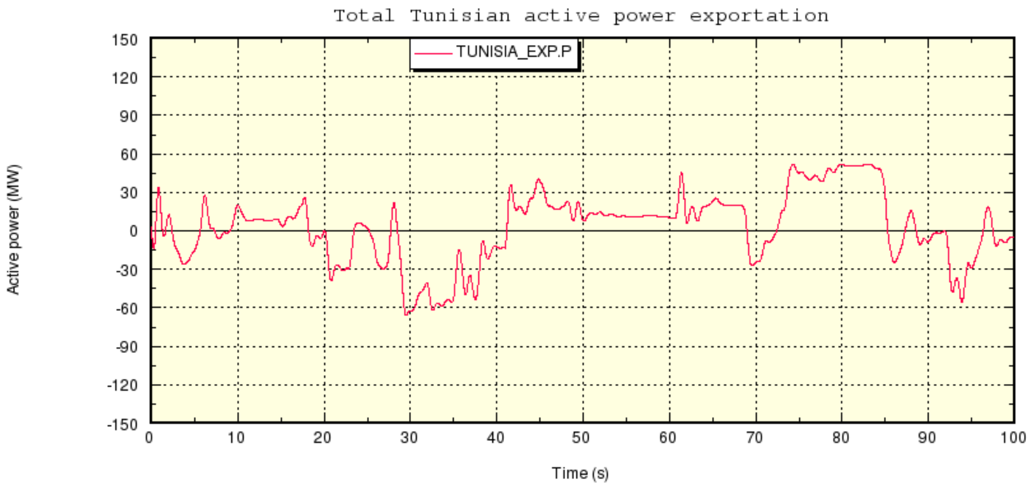

Fig. 6.45 - Minimum load condition, sensitivity analysis, total active power exchange with Algeria only.

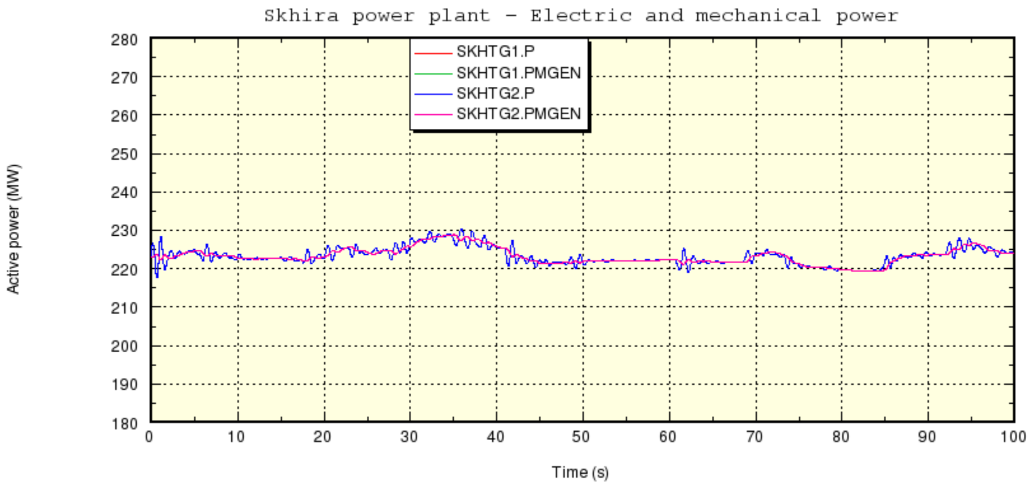

Fig. 6.46 - Minimum load condition, sensitivity analysis, electric and mechanical power of Skhira.
Legend: P – Electric Power; PMGEN – Mechanical Power

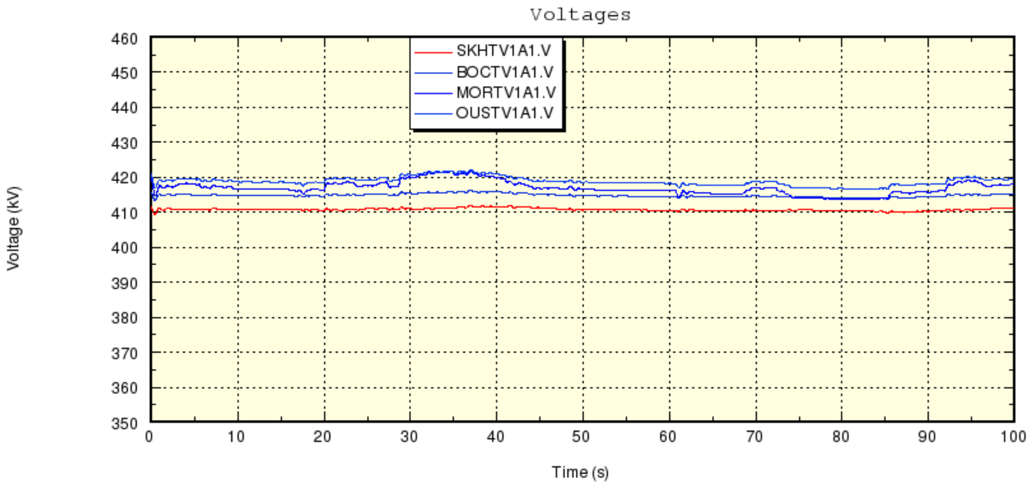

Fig. 6.47 - Minimum load condition, sensitivity analysis, 400 kV voltages (Skhira, Bouchemma, Mornaguia, Oueslatia).

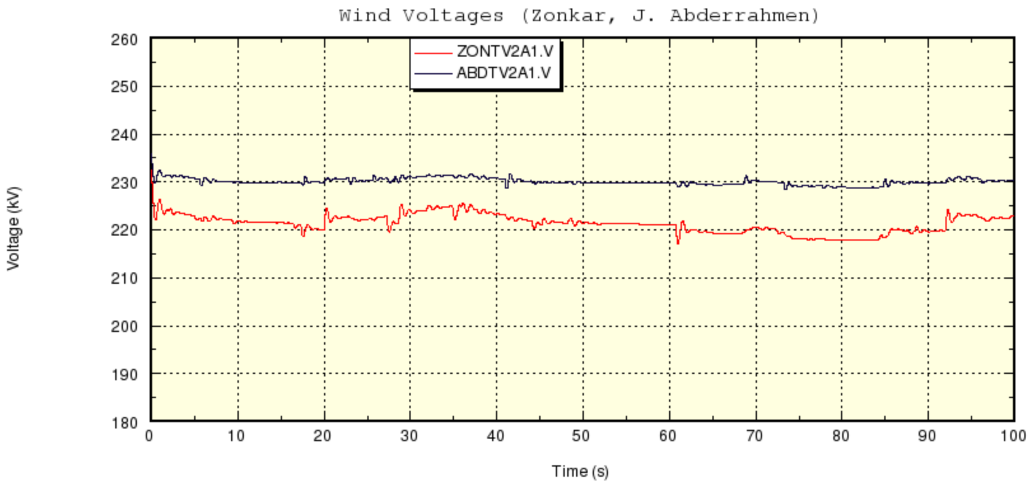

Fig. 6.48 - Minimum load condition, sensitivity analysis, 225 kV RES station voltages (Zonkar, J. Abderrahmen).

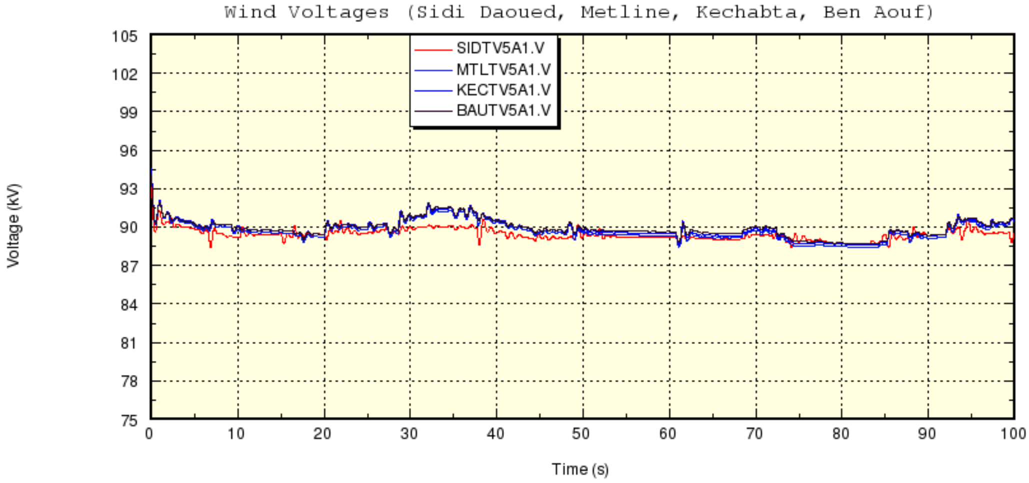

Fig. 6.49 - Minimum load condition, sensitivity analysis, 90 kV RES station voltages (Sidi Daoued, Metline, Kechabta, Ben Aouf).

6.4.2.2 Case 2: Tunisia interconnected with the rest of Maghreb and HVDC system without frequency regulation

In case 2, reported from Fig. 6.50 to Fig. 6.59, the HVDC interconnection is not equipped with frequency regulation (Fig. 6.53 shows that HVDC exportation is constant and equal to 950 MW): in this case all RES power variations are corrected changing power flows with Algeria and thanks to the Tunisian generation. A consequence of this, as reported in Fig. 6.52, is that frequency fluctuations are larger than those reported in Case 1, even if they remain into ±50mHz limit. Moreover, as reported in Fig. 6.55, fluctuations of non-dispatchable RES productions cause active power variations from about 120 MW in import to 60 MW in export.

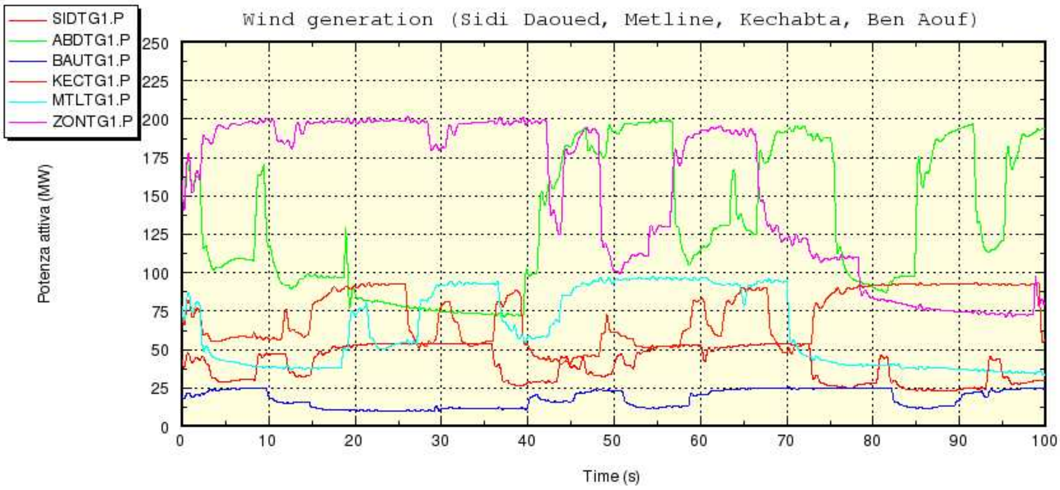

Fig. 6.50 – Minimum load condition, sensitivity analysis, RES generations (Sidi Daoued, J. Abderrahmen, Ben Aouf, Kechabta, Metline, Zoncar)

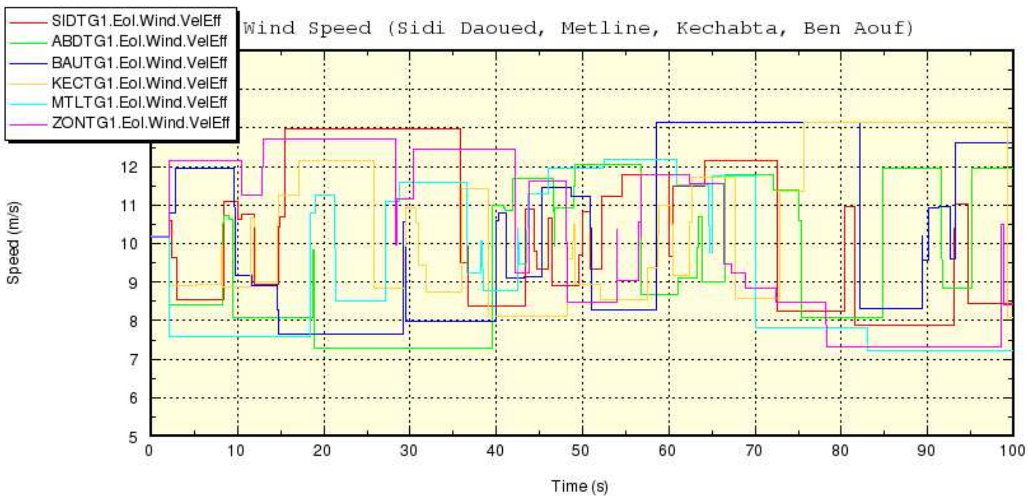

Fig. 6.51 - Minimum load condition, sensitivity analysis, wind speeds (Sidi Daoued, J. Abderrahmen, Ben Aouf, Kechabta, Metline, Zoncar)

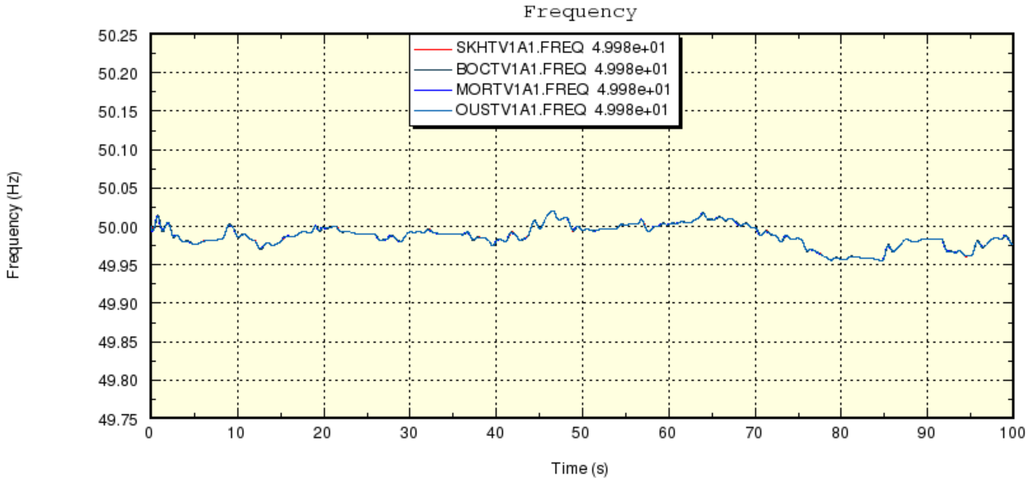

Fig. 6.52 - Minimum load condition, sensitivity analysis, frequencies (Skhira, Bouchemma, Mornaguia, Oueslatia)

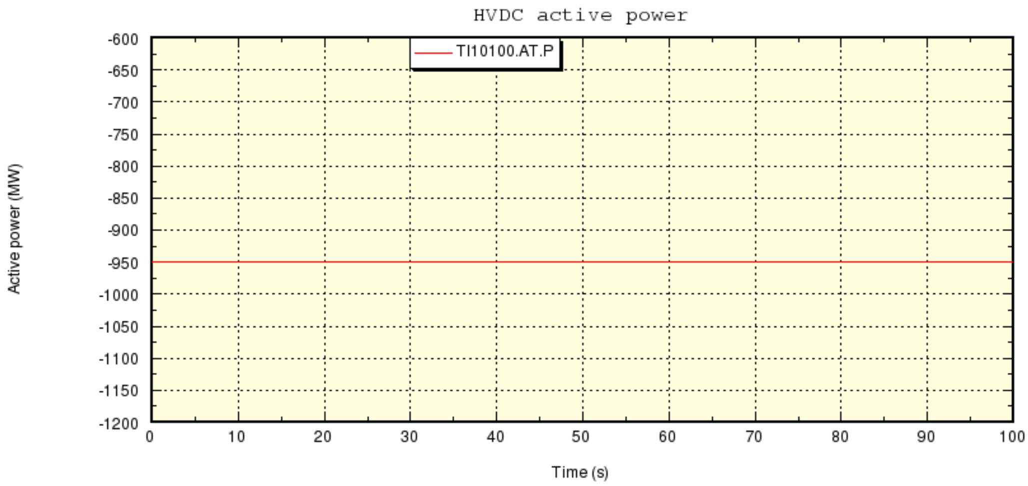

Fig. 6.53 - Minimum load condition, sensitivity analysis, HVDC active power flow

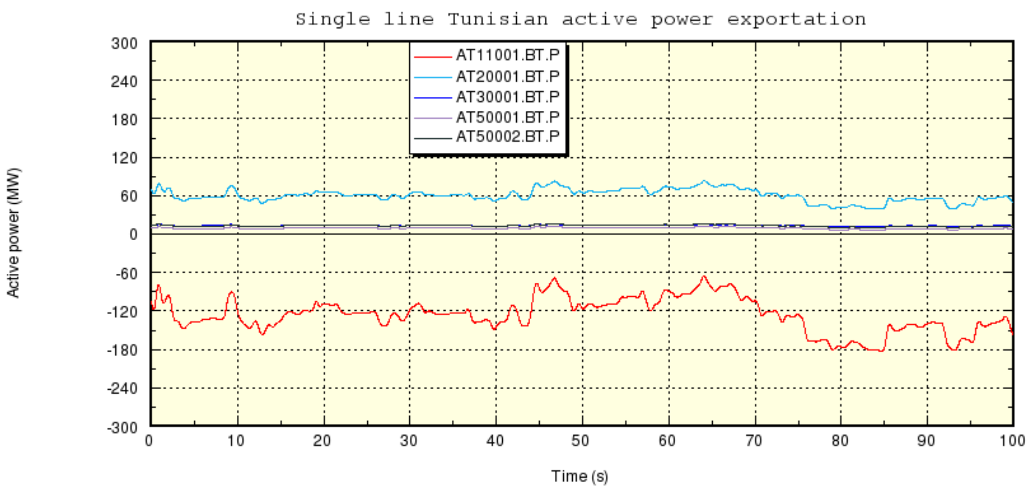

Fig. 6.54 - Minimum load condition, sensitivity analysis, single line active power exchanges.

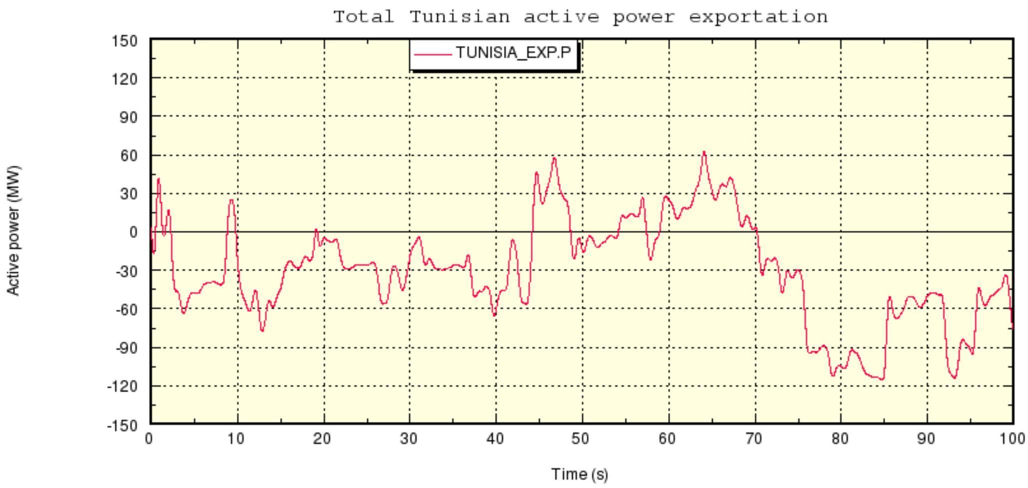

Fig. 6.55 - Minimum load condition, sensitivity analysis, total active power exchange with Algeria only.

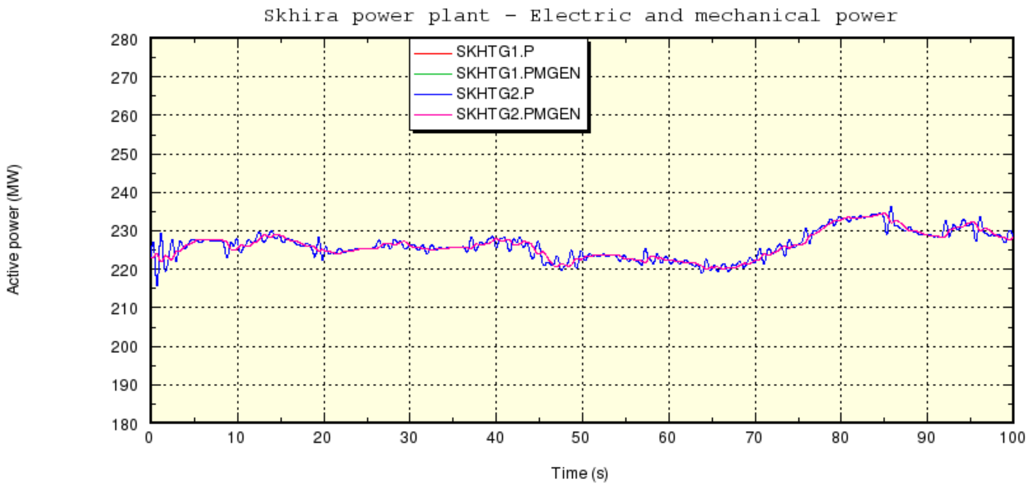

Fig. 6.56 - Minimum load condition, sensitivity analysis, electric and mechanical power of Skhira. Legend: P – Electric Power; PMGEN – Mechanical Power

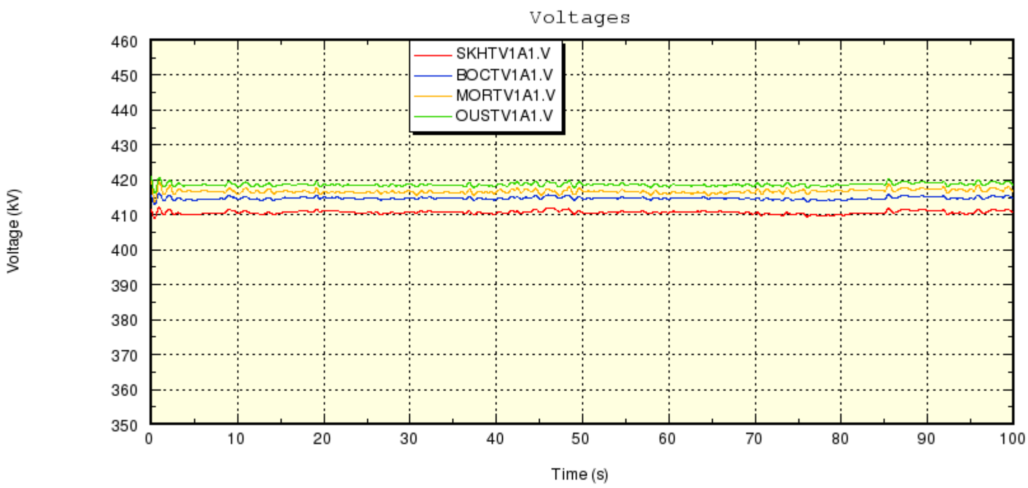

Fig. 6.57 - Minimum load condition, sensitivity analysis, 400 kV voltages (Skhira, Bouchemma, Mornaguia, Oueslatia).

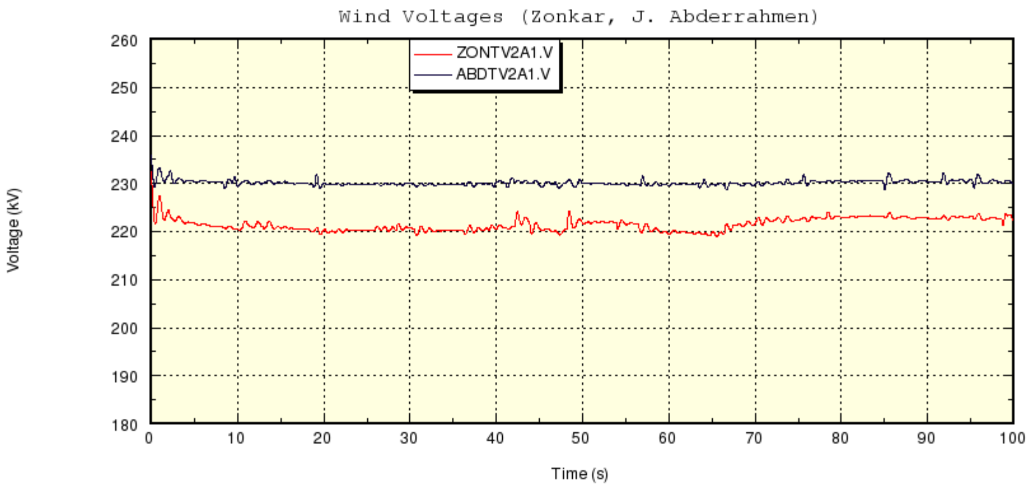

Fig. 6.58 - Minimum load condition, sensitivity analysis, 225 kV RES station voltages (Zonkar, J. Abderrahmen).

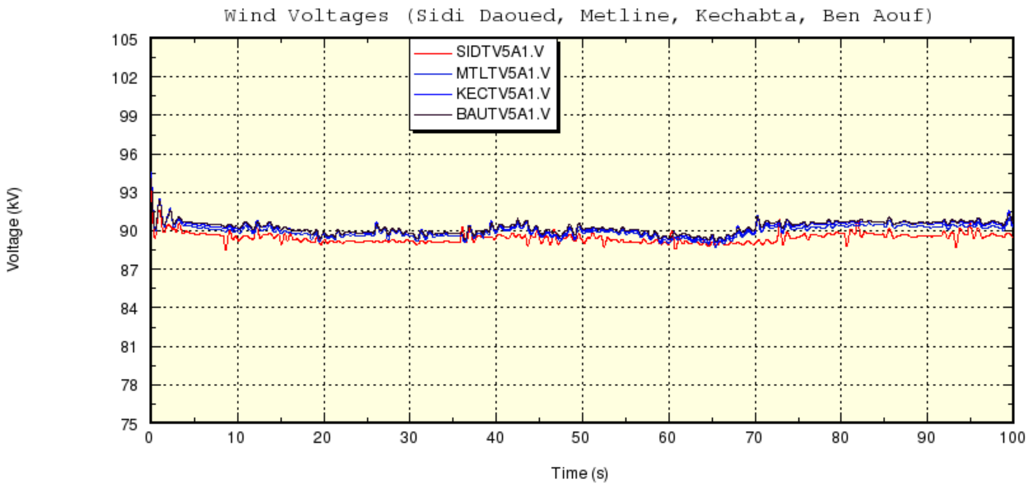

Fig. 6.59 - Minimum load condition, sensitivity analysis, 90 kV RES station voltages (Sidi Daoued, Metline, Kechabta, Ben Aouf).

6.4.2.3 Case 3: Tunisia isolated and HVDC system in frequency regulation

Case 3, reported from Fig. 6.60 to Fig. 6.67, highlights the importance of the frequency regulation of HVDC system because in this scenario it is the only element, together with Tunisian generation, capable to control frequency deviations caused by non-dispatchable generation. From the behaviour reported in Fig. 6.62 it is possible note that also in this case frequency variations are almost all included into ±50mHz limit.

Fig. 6.60 – Minimum load condition, sensitivity analysis, RES generations (Sidi Daoued, J. Abderrahmen, Ben Aouf, Kechabta, Metline, Zoncar)

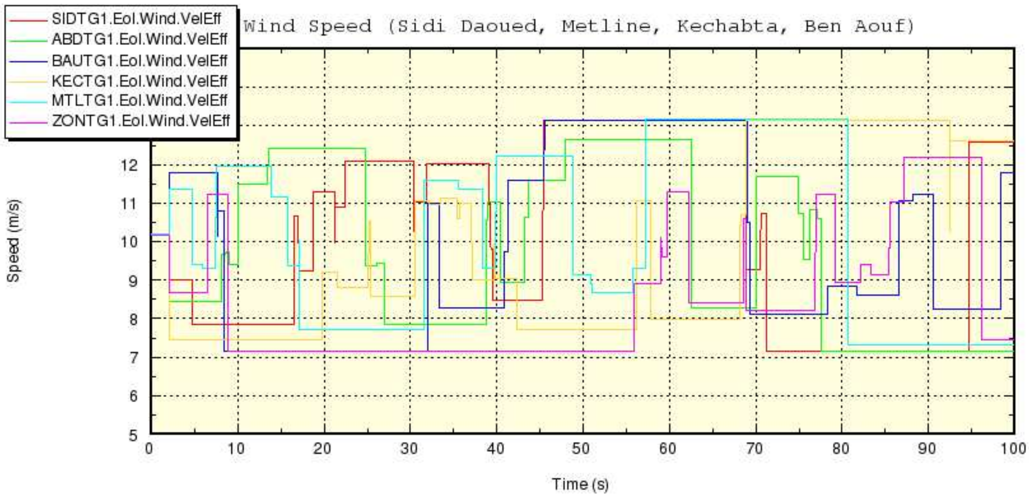

Fig. 6.61 - Minimum load condition, sensitivity analysis, wind speeds (Sidi Daoued, J. Abderrahmen, Ben Aouf, Kechabta, Metline, Zoncar)

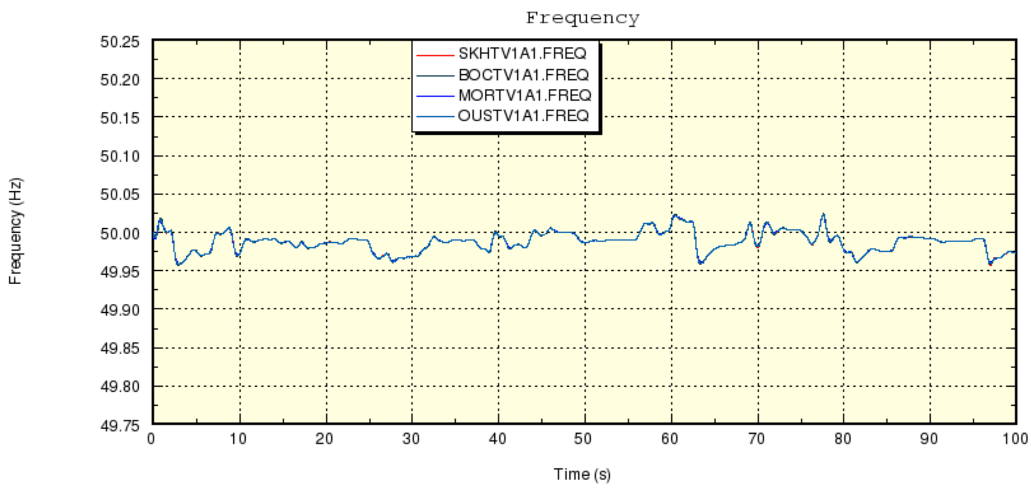

Fig. 6.62 - Minimum load condition, sensitivity analysis, frequencies (Skhira, Bouchemma, Mornaguia, Oueslatia)

Fig. 6.63 - Minimum load condition, sensitivity analysis, HVDC active power flow

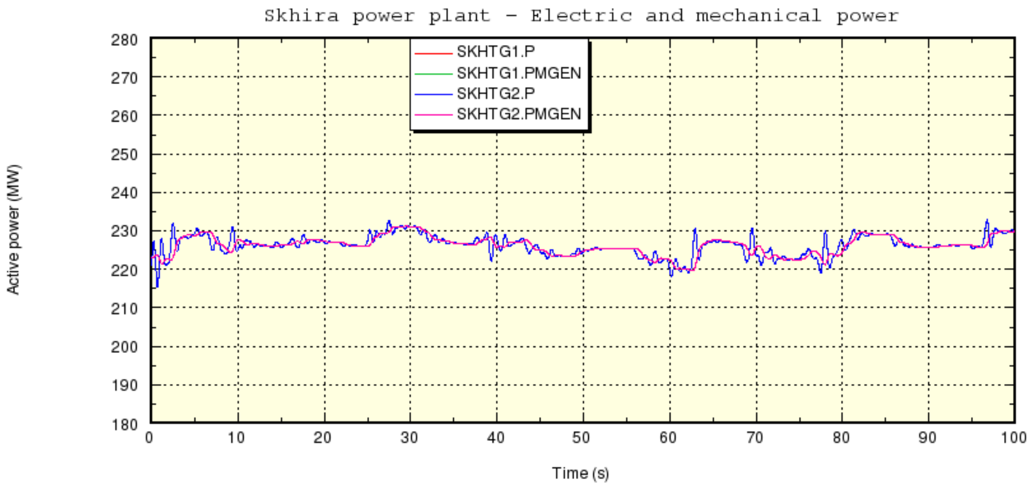

Fig. 6.64 - Minimum load condition, sensitivity analysis, electric and mechanical power of Skhira. Legend: P – Electric Power; PMGEN – Mechanical Power

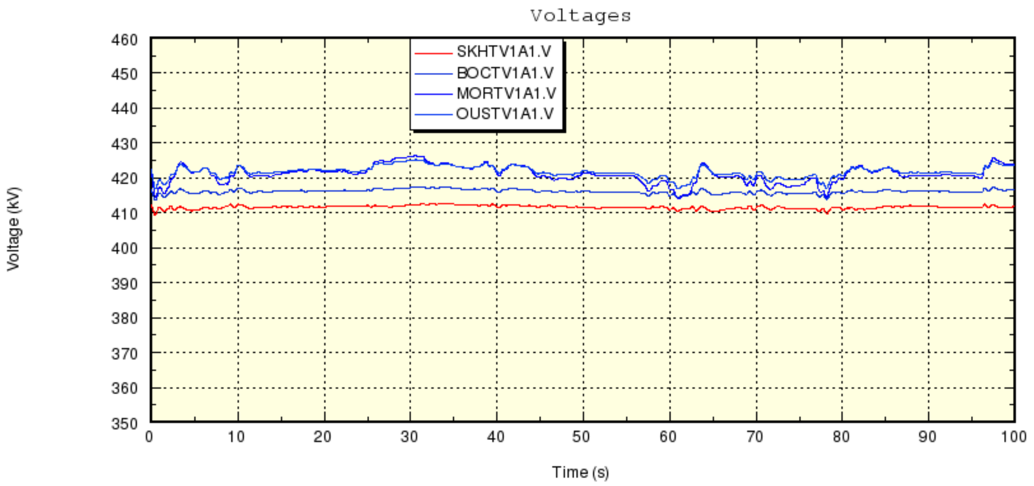

Fig. 6.65 - Minimum load condition, sensitivity analysis, 400 kV voltages (Skhira, Bouchemma, Mornaguia, Oueslatia).

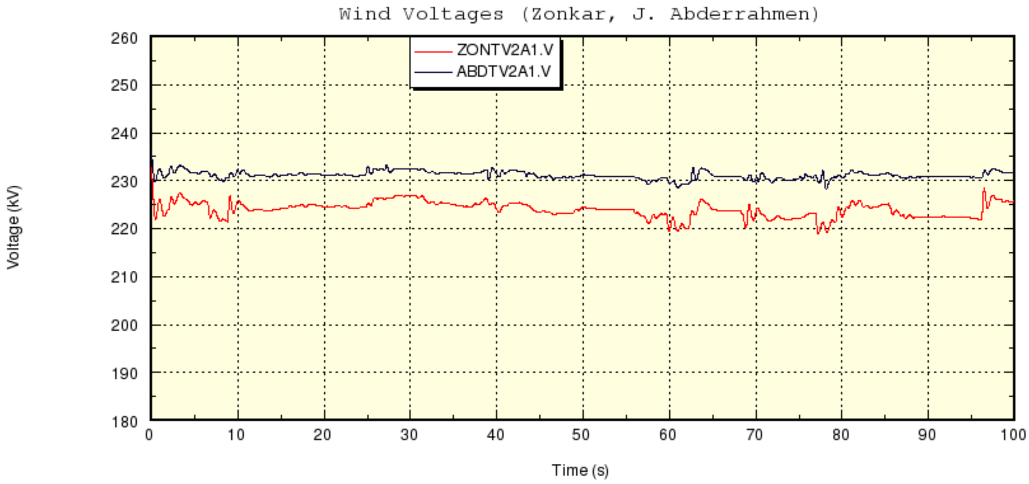

Fig. 6.66 - Minimum load condition, sensitivity analysis, 225 kV RES station voltages (Zonkar, J. Abderrahmen).

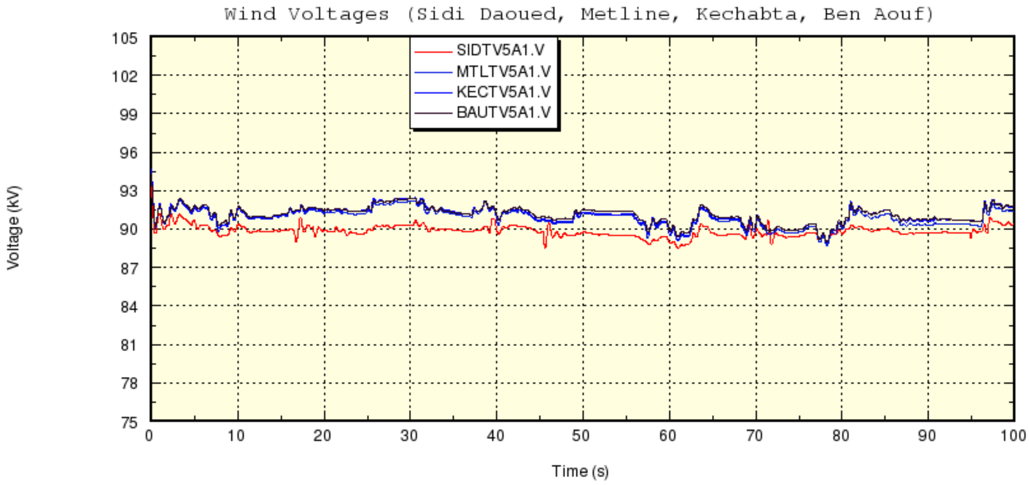

Fig. 6.67 - Minimum load condition, sensitivity analysis, 90 kV RES station voltages (Sidi Daoued, Metline, Kechabta, Ben Aouf).

6.4.2.4 Case 4: Tunisia isolated and HVDC system without frequency regulation

Case 4 is the worst scenario: all RES power variations are compensated only with Tunisian generators. Compared with the other ones reported above, this case demonstrates that the effects of non-dispatchable power fluctuations are not acceptable and they are greater than those reported in the correspondent scenario in peak load conditions, lacking the support of the interconnection with Algeria and the frequency regulation at the HVDC converter station: for example, frequency fluctuations are always much wider than ±50mHz limit. Indeed, as could be observed in the figures below, system frequency presents a pretty low value (49.75 Hz), approaching frequency maximum admitted variation during perturbations (±0.3 Hz)

Fig. 6.68 – Minimum load condition, sensitivity analysis, RES generations (Sidi Daoued, J. Abderrahmen, Ben Aouf, Kechabta, Metline, Zoncar)

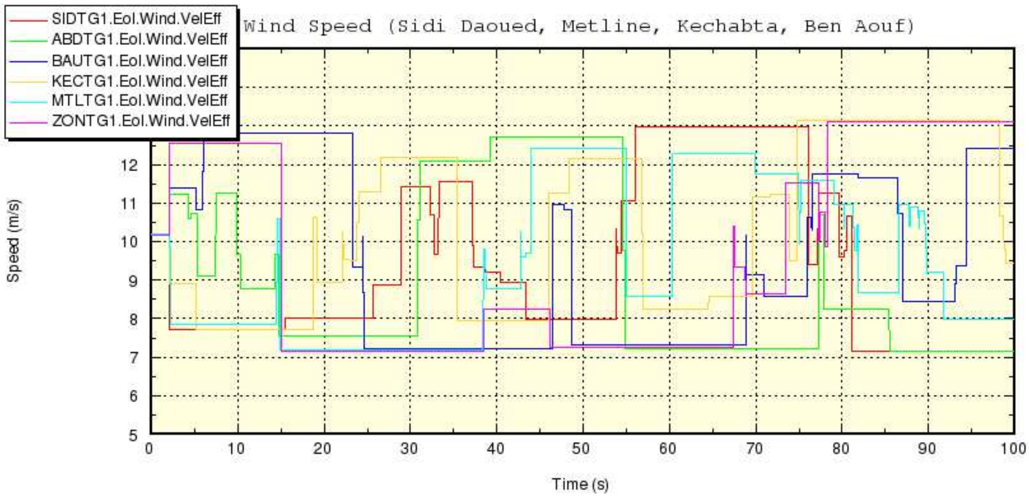

Fig. 6.69 - Minimum load condition, sensitivity analysis, wind speeds (Sidi Daoued, J. Abderrahmen, Ben Aouf, Kechabta, Metline, Zoncar)

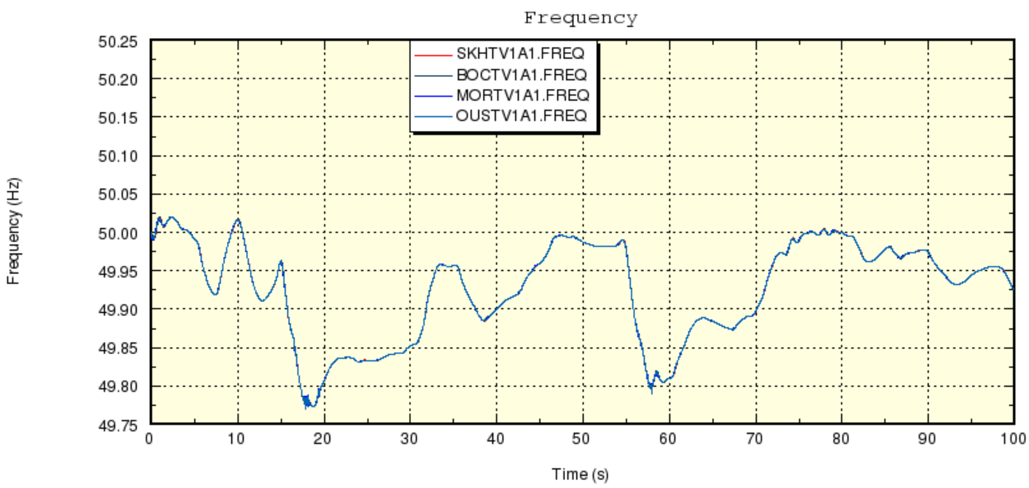

Fig. 6.70 - Minimum load condition, sensitivity analysis, frequencies (Skhira, Bouchemma, Mornaguia, Oueslatia)

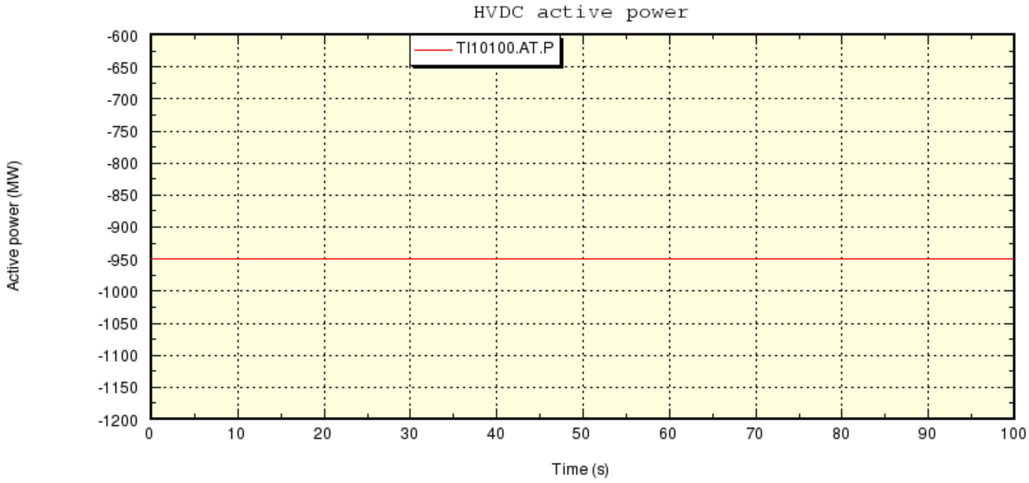

Fig. 6.71 - Minimum load condition, sensitivity analysis, HVDC active power flow

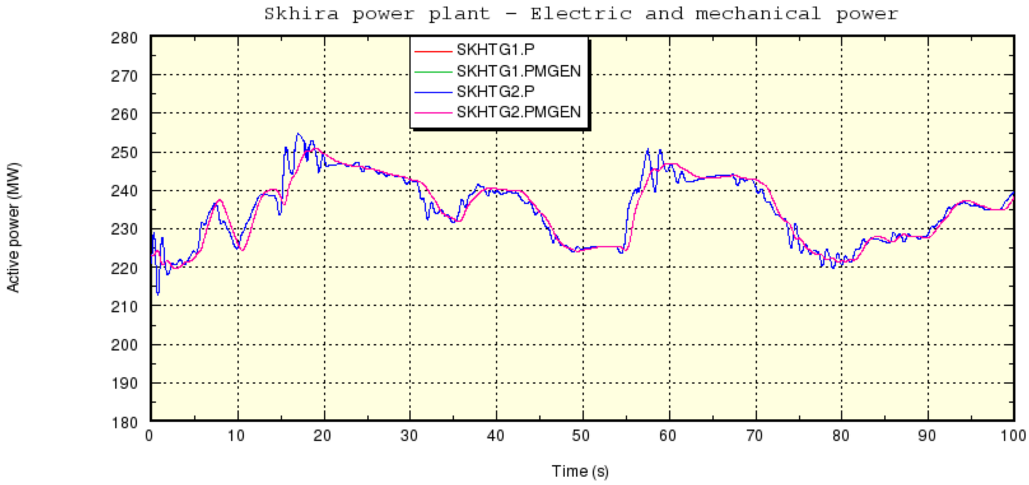

Fig. 6.72 - Minimum load condition, sensitivity analysis, electric and mechanical power of Skhira. Legend: P – Electric Power; PMGEN – Mechanical Power

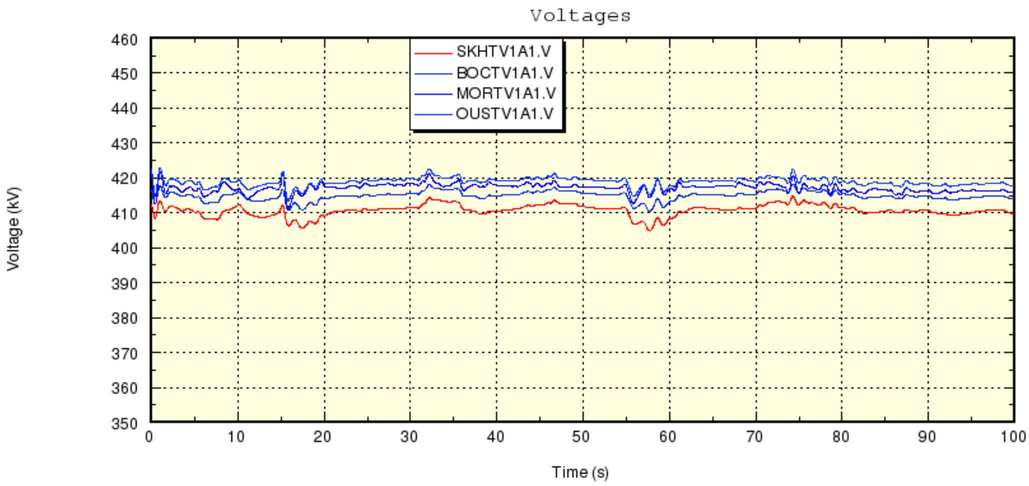

Fig. 6.73 - Minimum load condition, sensitivity analysis, 400 kV voltages (Skhira, Bouchemma, Mornaguia, Oueslatia).

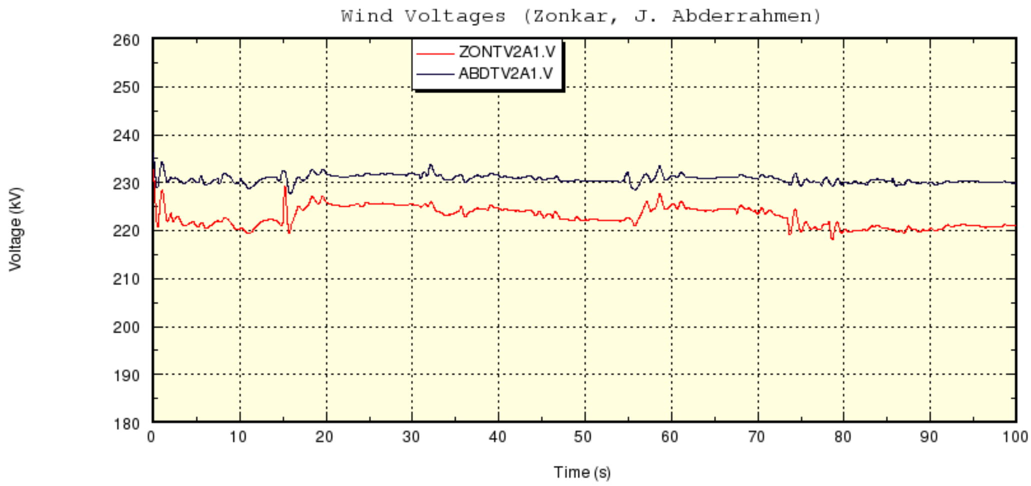

Fig. 6.74 - Minimum load condition, sensitivity analysis, 225 kV RES station voltages (Zonkar, J. Abderrahmen).

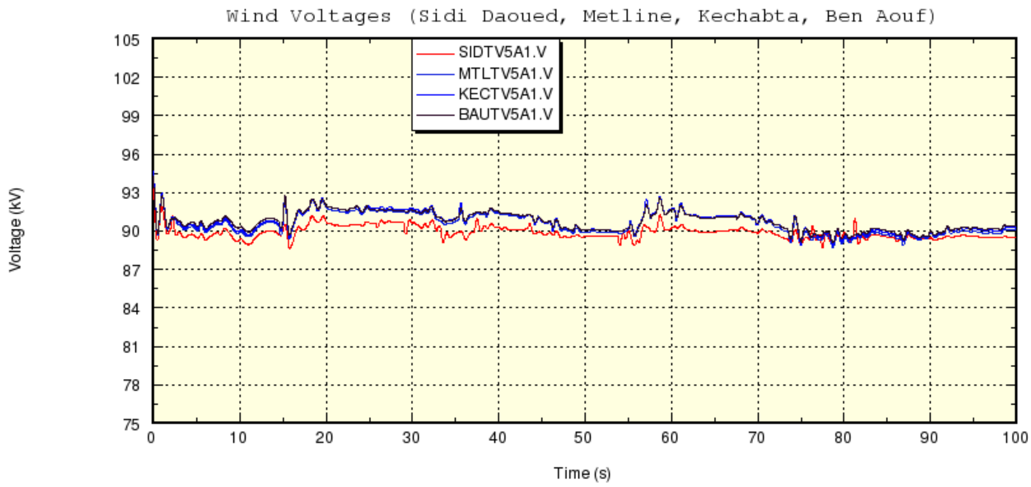

Fig. 6.75 - Minimum load condition, sensitivity analysis, 90 kV RES station voltages (Sidi Daoued, Metline, Kechabta, Ben Aouf).

6.5 Fault analyses

In this chapter three faults have been analysed, representing different types of contingencies that can occur and for whom the system stability has to be investigated:

- Fault on a 400 kV line, i.e. high power transportation connection, far from the connection points of RES power plants: Skhira – Maknassy 400 kV, Oueslatia – Mornaguia 400 kV.
- Fault on a 90 kV line near RES generation plants: Menzil Jemine – Bizerte 90 kV.

All these events have been simulated in peak and minimum load scenarios with and without frequency derivative protections: the choice to repeat the simulations considering or not this protection is due to its effect on RES generation plants connections.
The simulated faults present the same features:

- Three phase short circuit;

- Fault at mid-point of the line;
- Line protection delay of 0.18 s;
- No fault impedance.

The aims of these analyses are the following:
- Verify the effect on Tunisian electric system of important faults in presence of non-dispatchable RES generations;
- Check RES power plant protections.

For all these tests renewable productions are constant: the effect of non-dispatchable RES variations are not considered because the are not relevant for the scopes of the simulations.

6.5.1 Peak load scenario

6.5.1.1 <u>Short circuit on Skhira – Maknassy 400 kV line</u> ***<u>with frequency derivative protections</u>***

As reported in the figures below, the presence of frequency derivative protections causes the disconnection from the grid of all the RES power plants in case of grid fault, even if it occurs far from their connection points. This causes the loss of about 530 MW in Tunisian system: this is an important loss compensate both increasing the importation from Algeria and reducing the exportation to Italy, in addition to an increase of internal generation.
Voltages and frequency variables maintain acceptable values even after such events.

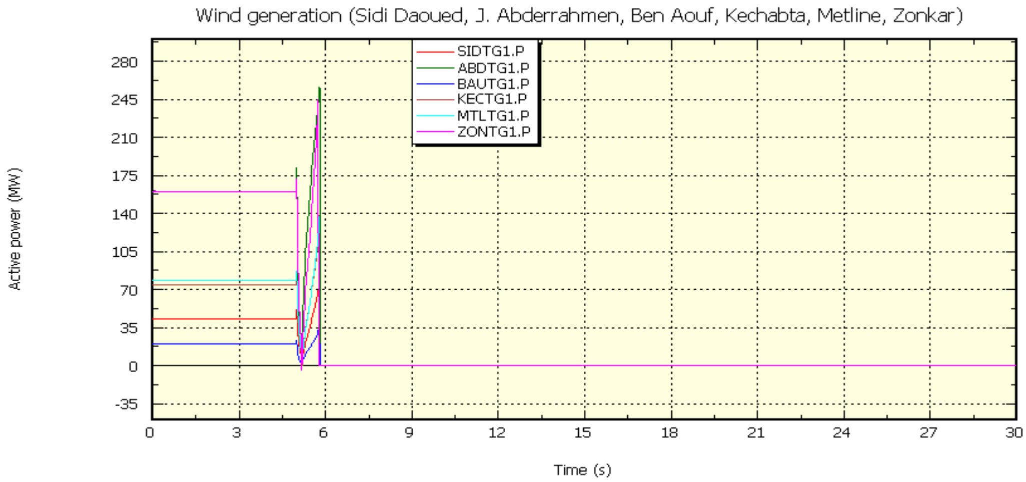

Fig. 6.76 – Peak load condition, fault analysis, RES power production.

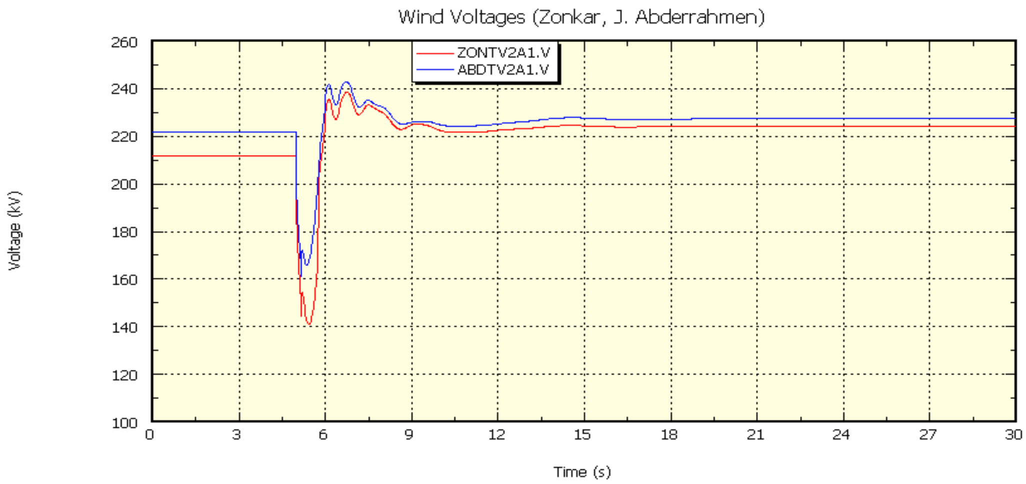

Fig. 6.77 – Peak load condition, fault analysis, RES power plants' voltages (225 kV).

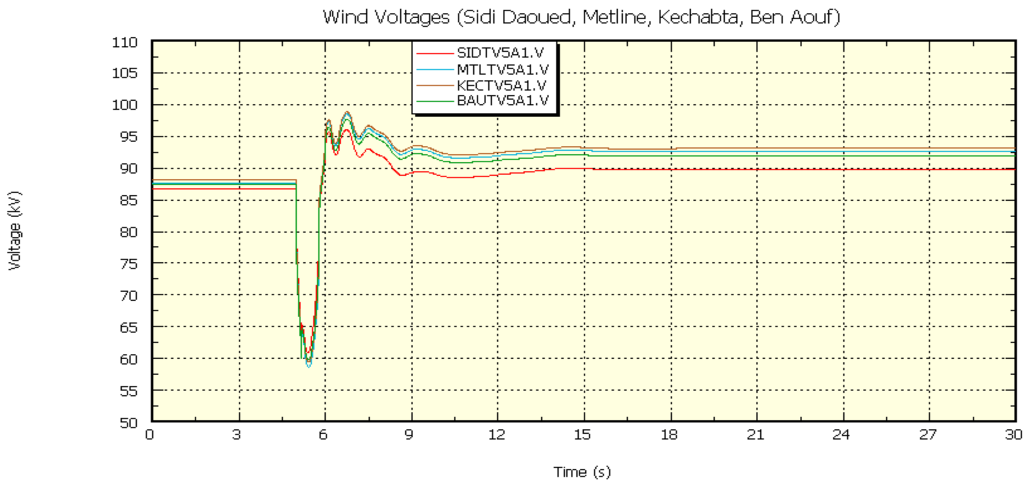

Fig. 6.78 – Peak load condition, fault analysis, RES power plants' voltages (90 kV).

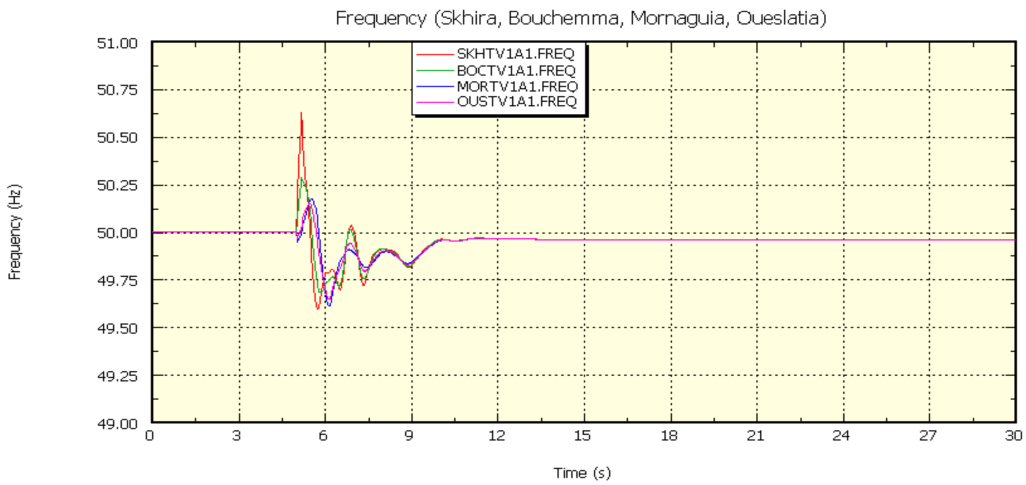

Fig. 6.79 – Peak load condition, fault analysis, system nodes' frequency.

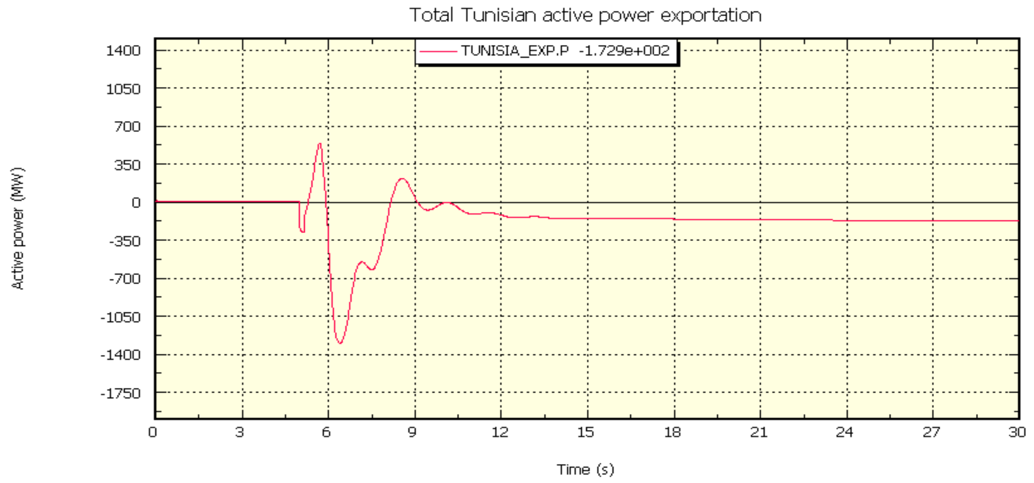

Fig. 6.80 – Peak load condition, fault analysis, total active power exchange with Algeria only.

Fig. 6.81 – Peak load condition, fault analysis, single line active power exchanges.

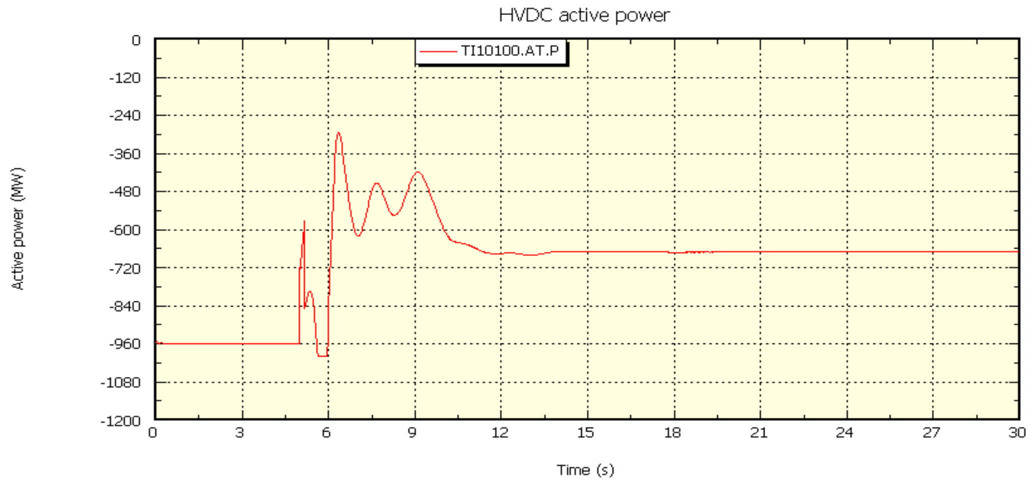

Fig. 6.82 – Peak load condition, fault analysis, HVDC active power flow.

6.5.1.2 *Short circuit on Skhira – Maknassy 400 kV line **without frequency derivative protections***

The same grid fault repeated without frequency derivative protections doesn't show any heavy consequences for the network: all RES generation plants remain connected to the grid. This avoids the loss of internal generation and the oscillations are lower if compared with those of previous case. Moreover, from the graphs reported below, we note that voltages and frequency values after fault are almost the same of those before the contingency.

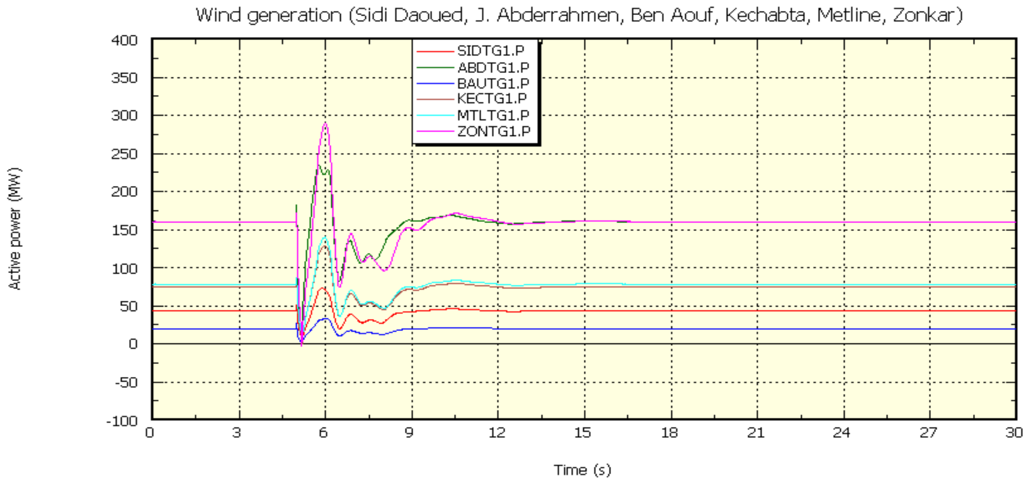

Fig. 6.83 – Peak load condition, fault analysis, RES power production.

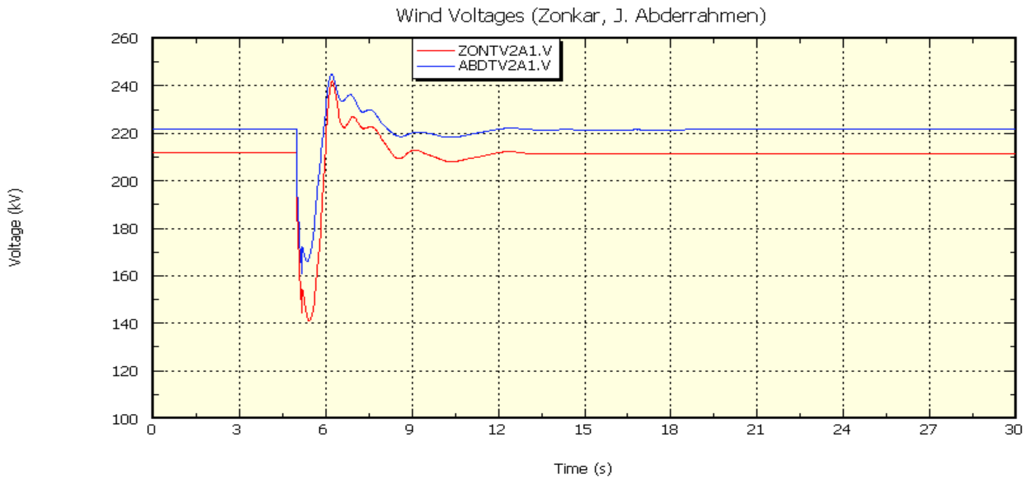

Fig. 6.84 – Peak load condition, fault analysis, RES power plants' voltages (225 kV).

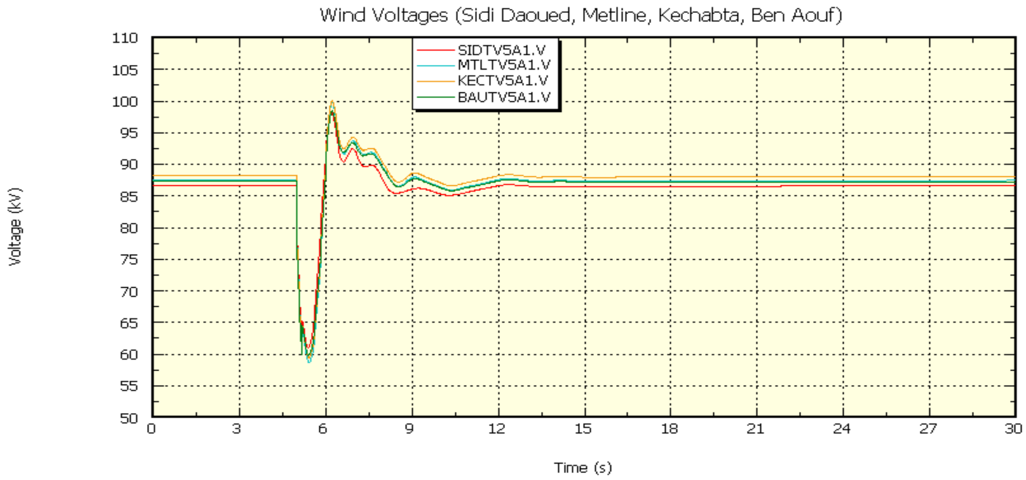

Fig. 6.85 – Peak load condition, fault analysis, RES power plants' voltages (90 kV).

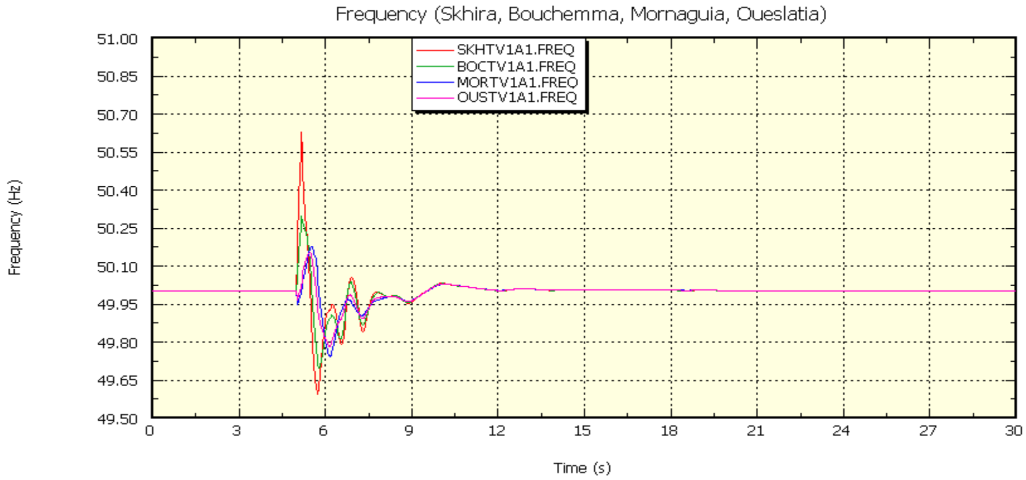

Fig. 6.86 – Peak load condition, fault analysis, system nodes' frequency.

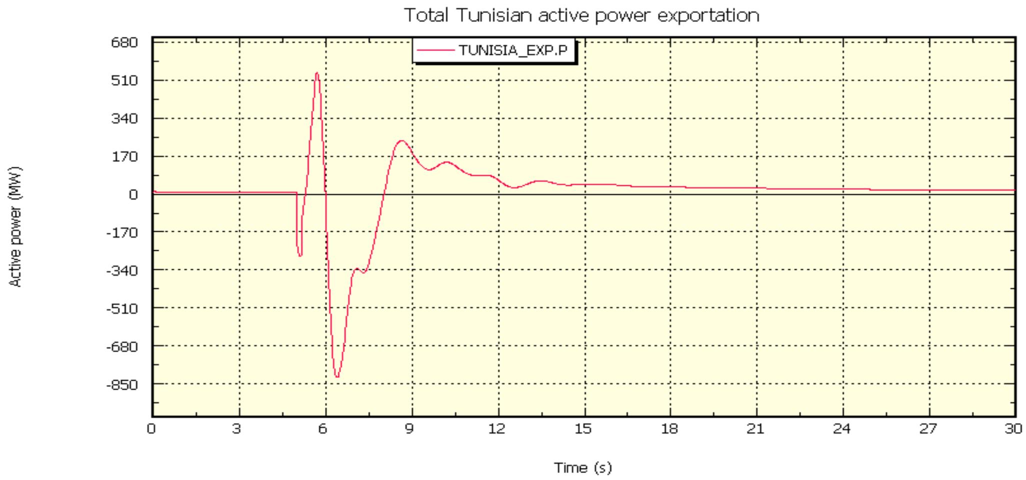

Fig. 6.87 – Peak load condition, fault analysis, total active power exchange with Algeria only.

Fig. 6.88 – Peak load condition, fault analysis, single line active power exchanges.

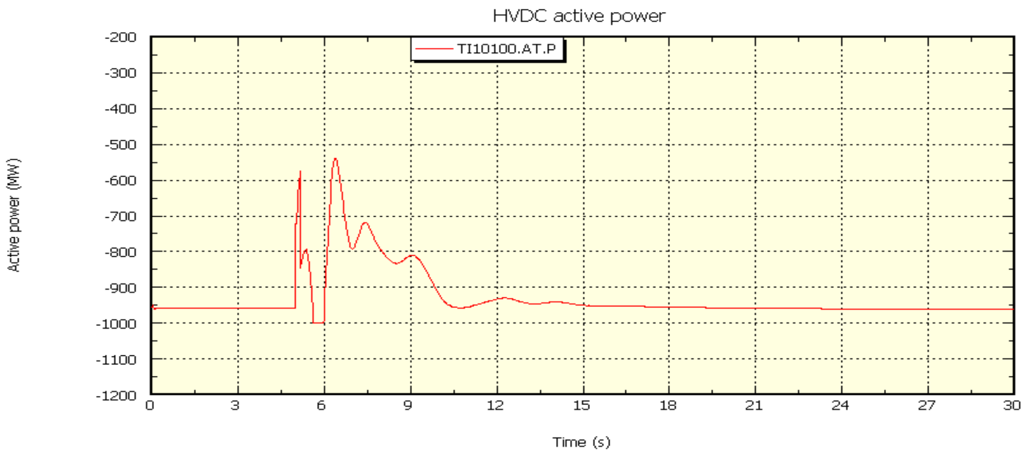

Fig. 6.89 – Peak load condition, fault analysis, HVDC active power flow.

6.5.1.3 <u>Short circuit on Oueslatia – Mornaguia 400 kV line</u> ***<u>with frequency derivative protections</u>***

Also this fault causes an intervention of the frequency derivative protections, which disconnects all the RES power plants from the grid. However, being the fault point not too close to ELMED power plant, the transients have less oscillations than previous ones and the power import from Algeria on the 400 kV line doesn't exceed 700 MW.

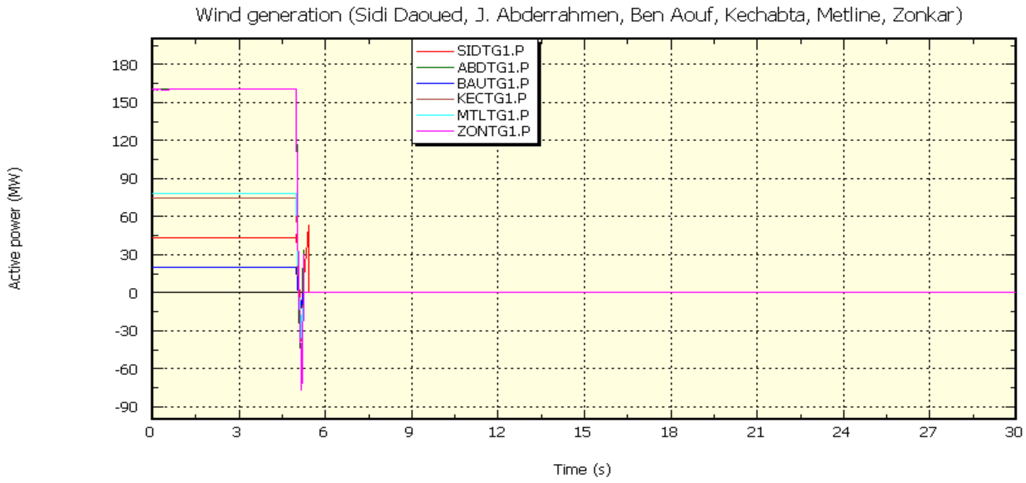

Fig. 6.90 – Peak load condition, fault analysis, RES power production.

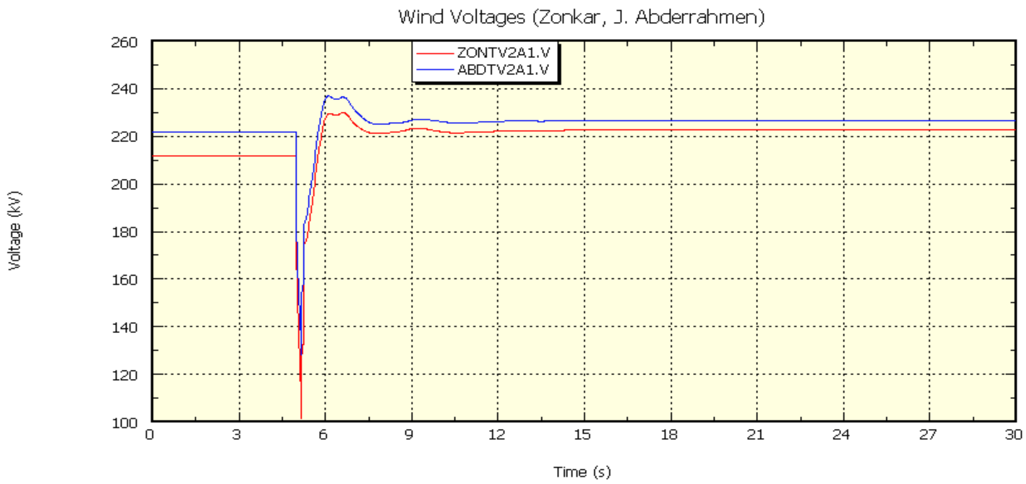

Fig. 6.91 – Peak load condition, fault analysis, RES power plants' voltages (225 kV).

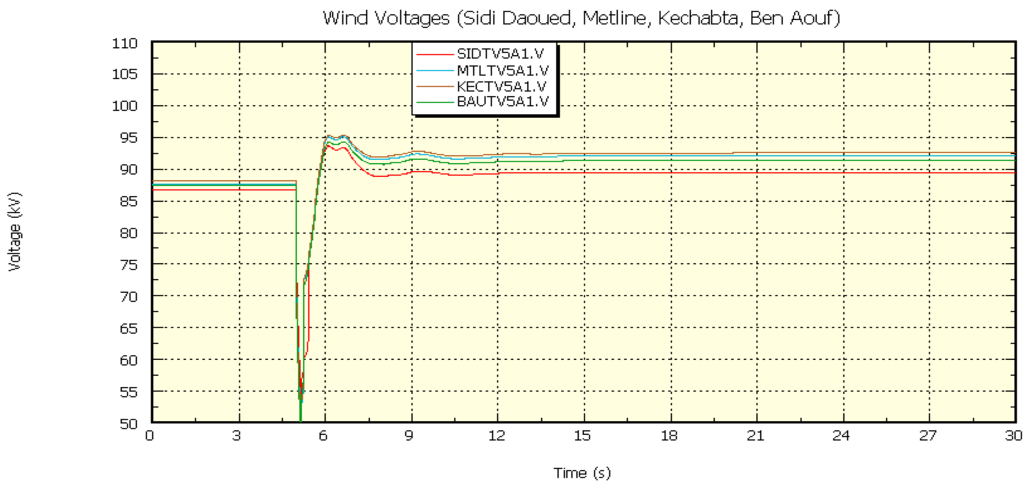

Fig. 6.92 – Peak load condition, fault analysis, RES power plants' voltages (90 kV).

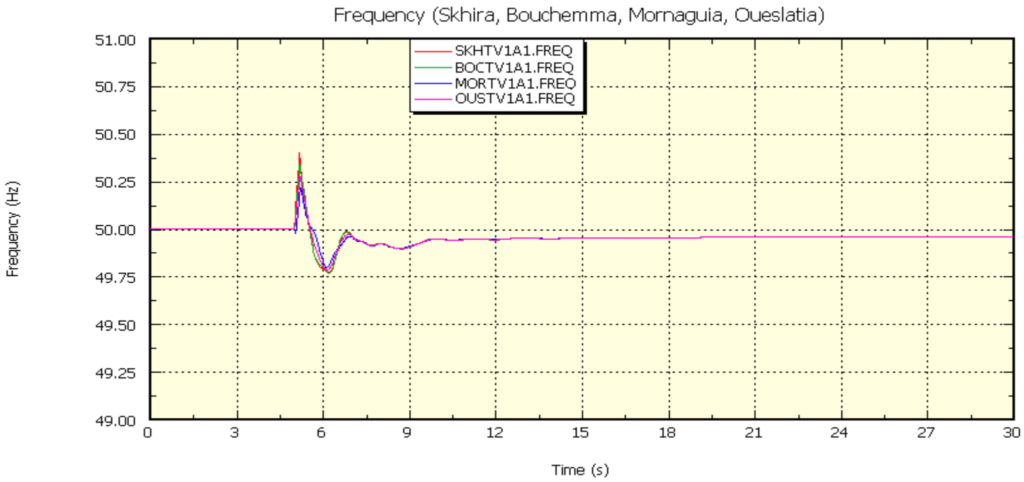

Fig. 6.93 – Peak load condition, fault analysis, system nodes' frequency.

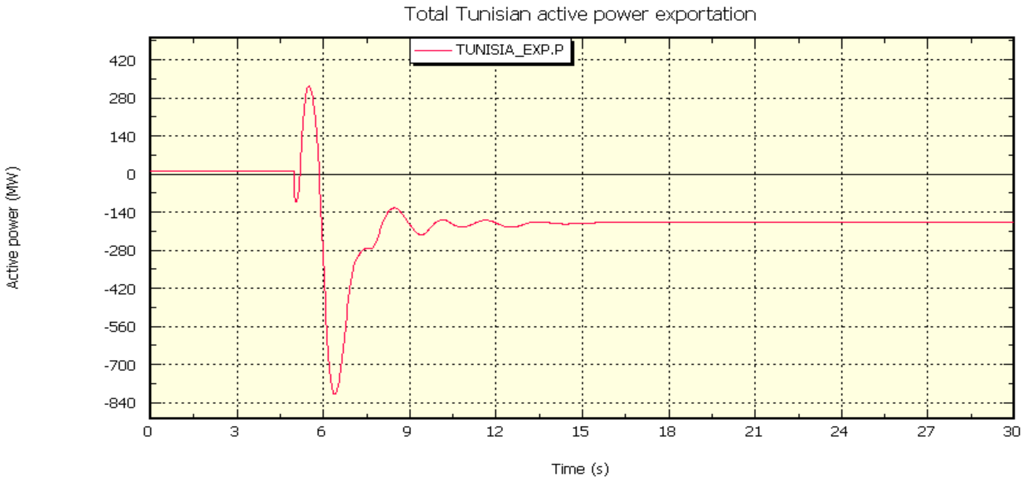

Fig. 6.94 – Peak load condition, fault analysis, total active power exchange with Algeria only.

Fig. 6.95 – Peak load condition, fault analysis, single line active power exchanges.

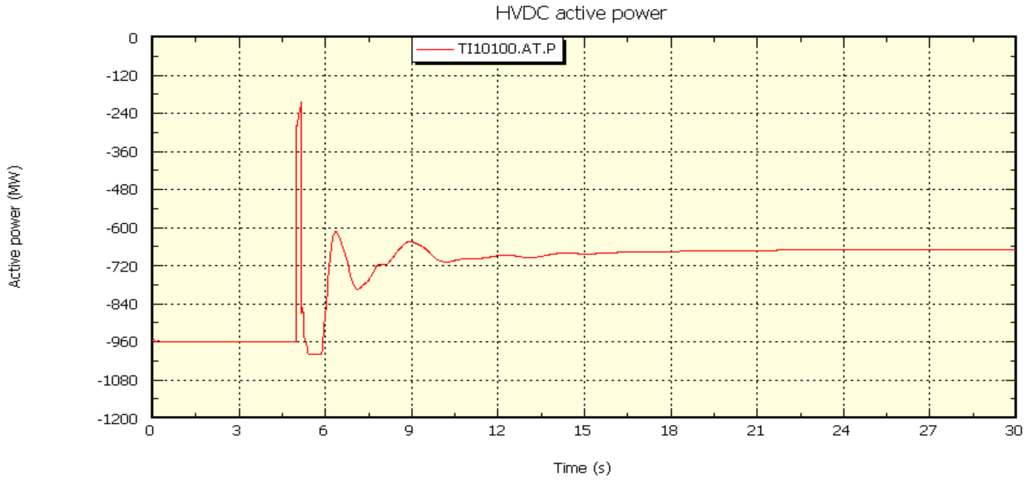

Fig. 6.96 – Peak load condition, fault analysis, HVDC active power flow.

6.5.1.4 *Short circuit on Oueslatia – Mornaguia 400 kV line* ***without frequency derivative protections***

The benefits of the absence of frequency derivative protections in the RES generation plants are evident in this simulation, too:

- No RES power plants disconnection (and no loss of power generation);
- Frequency within acceptable values even during the transient;
- Voltages and frequency values after fault almost the same of those before the contingency;
- Pretty low 400 kV interconnection line's exchange (below 500 MW during the transitory).

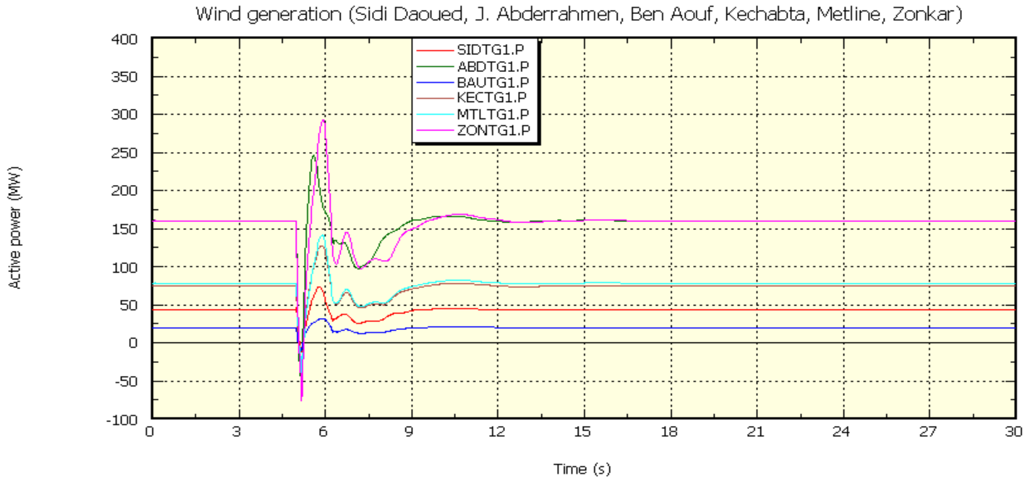

Fig. 6.97 – Peak load condition, fault analysis, RES power production.

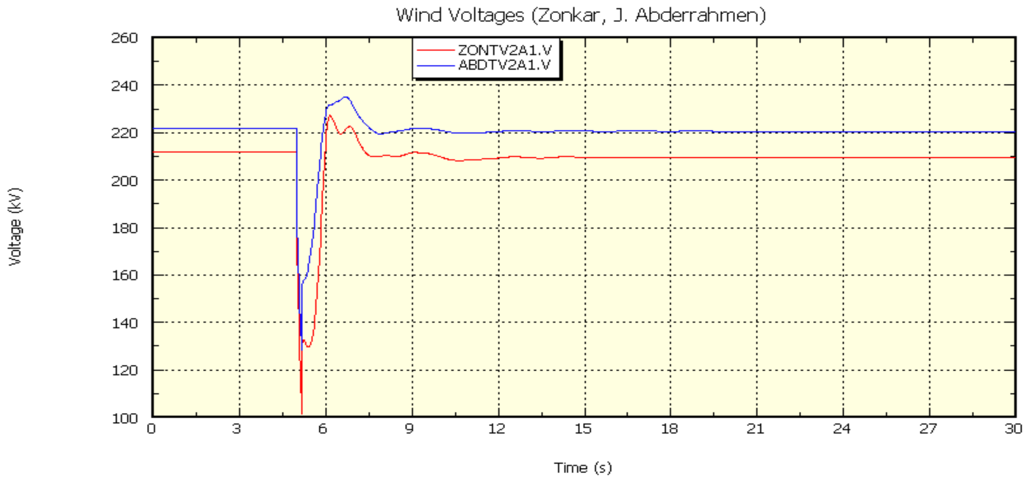

Fig. 6.98 – Peak load condition, fault analysis, RES power plants' voltages (225 kV).

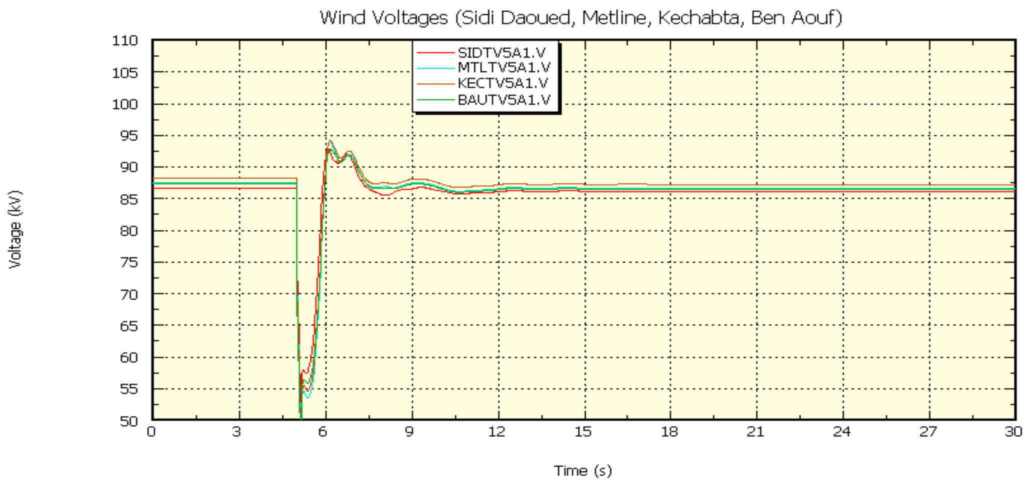

Fig. 6.99 – Peak load condition, fault analysis, RES power plants' voltages (90 kV).

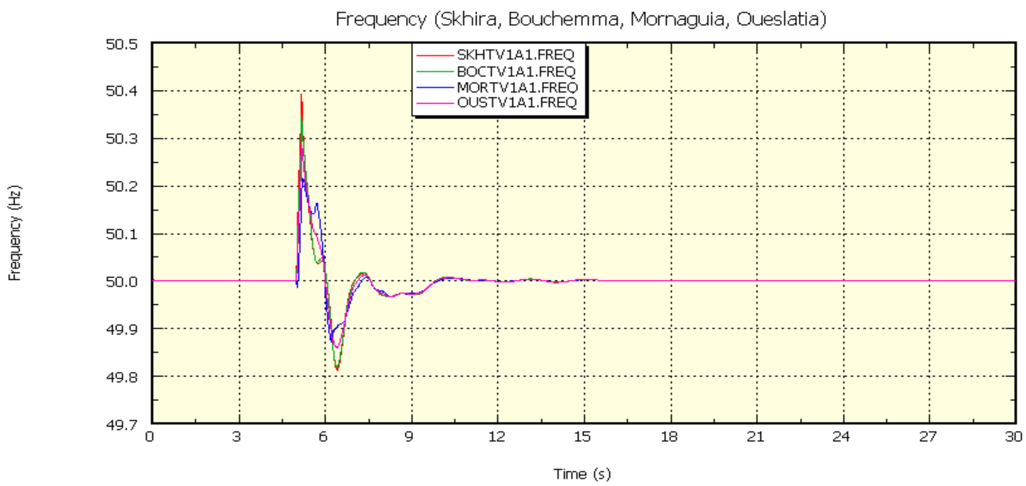

Fig. 6.100 – Peak load condition, fault analysis, system nodes' frequency.

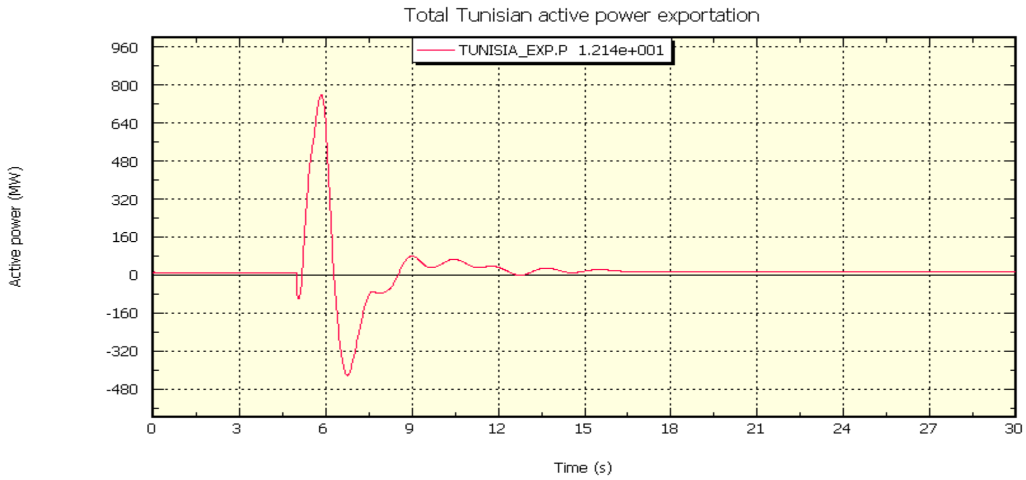

Fig. 6.101 – Peak load condition, fault analysis, total active power exchange with Algeria only.

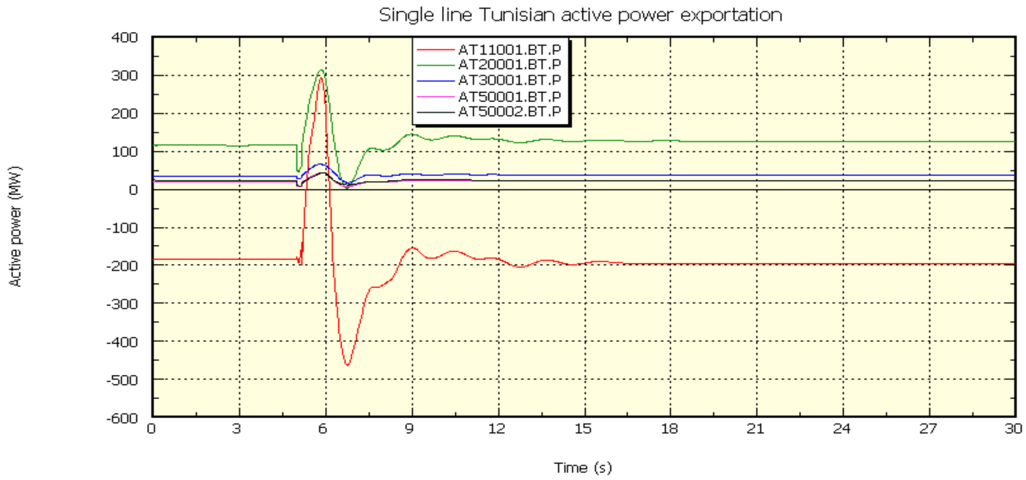

Fig. 6.102 – Peak load condition, fault analysis, single line active power exchanges.

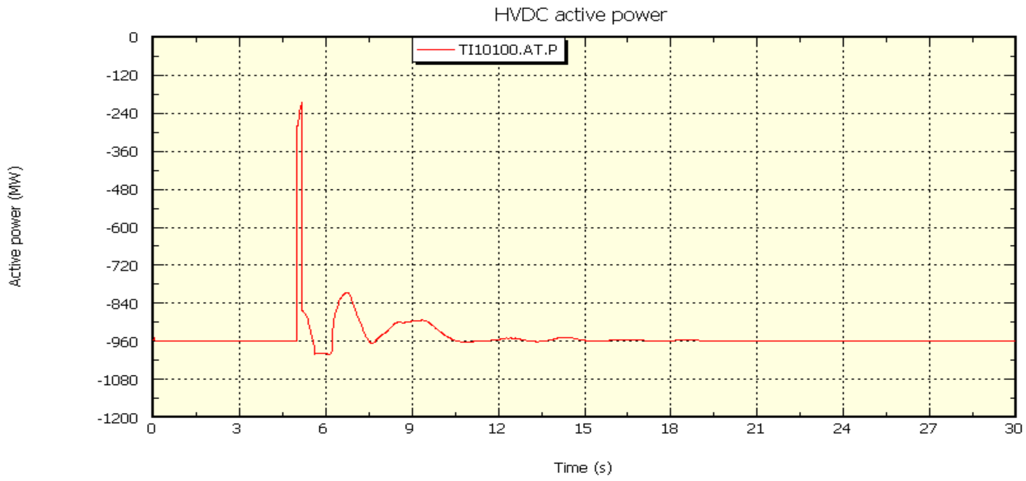

Fig. 6.103 – Peak load condition, fault analysis, HVDC active power flow.

6.5.1.5 Short circuit on Menzel Jemil–Bizerte 90 kV line ***with frequency derivative protections***

Even if this fault happened on 90 kV voltage level, frequency derivative protections of RES power plants confirm even for this fault their effect: all RES generators are disconnect from the grid. The most important effects of these protection, in addition to the loss of 530 MW generations, are the deep voltage falls (particularly in 90 kV nodes) and low steady state frequency after the fault (49.96 Hz). The generation loss is divided among the HVDC system (lower exportation to Italy), tie-lines with Algeria (higher importation) and, for a lower percentage, with internal traditional generation. Moreover, the maximum power import (during transient) reaches about 500 MW on the 400 kV interconnection line.

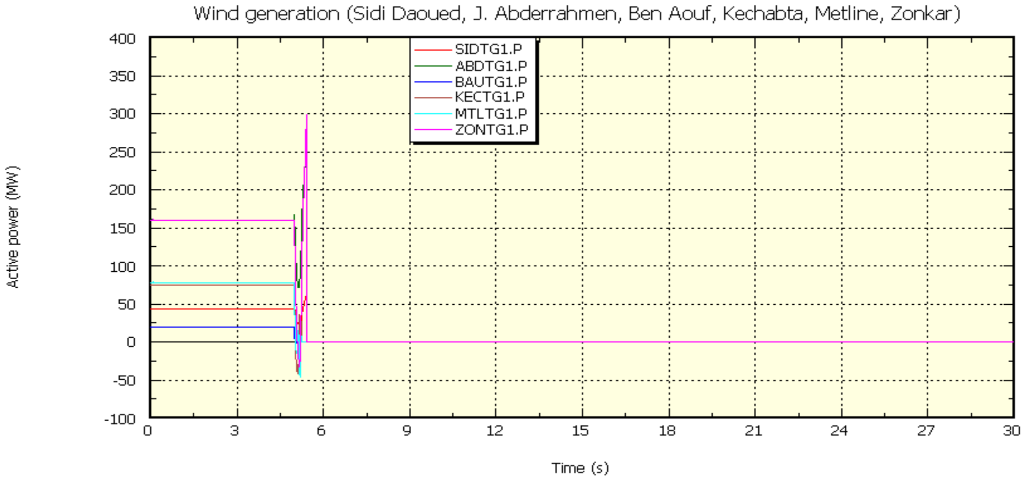

Fig. 6.104 – Peak load condition, fault analysis, RES power production.

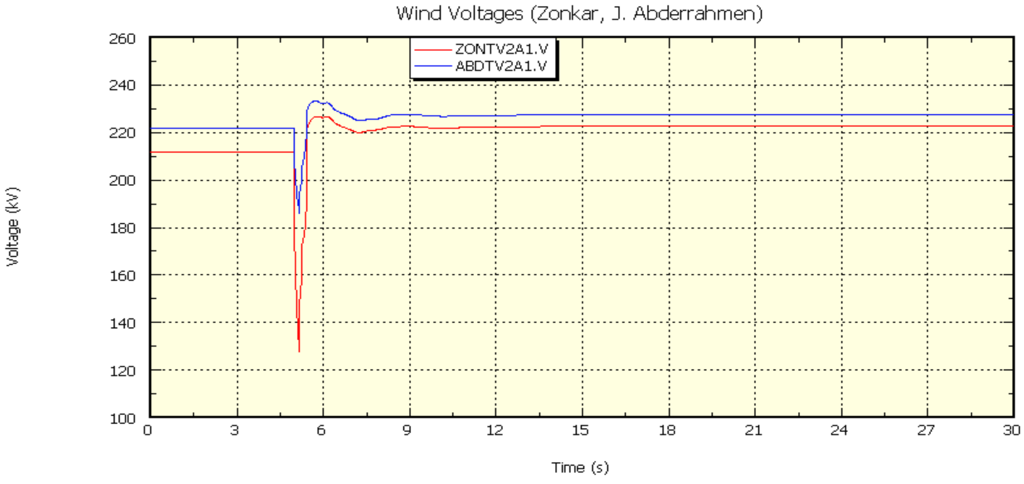

Fig. 6.105 – Peak load condition, fault analysis, RES power plants' voltages (225 kV).

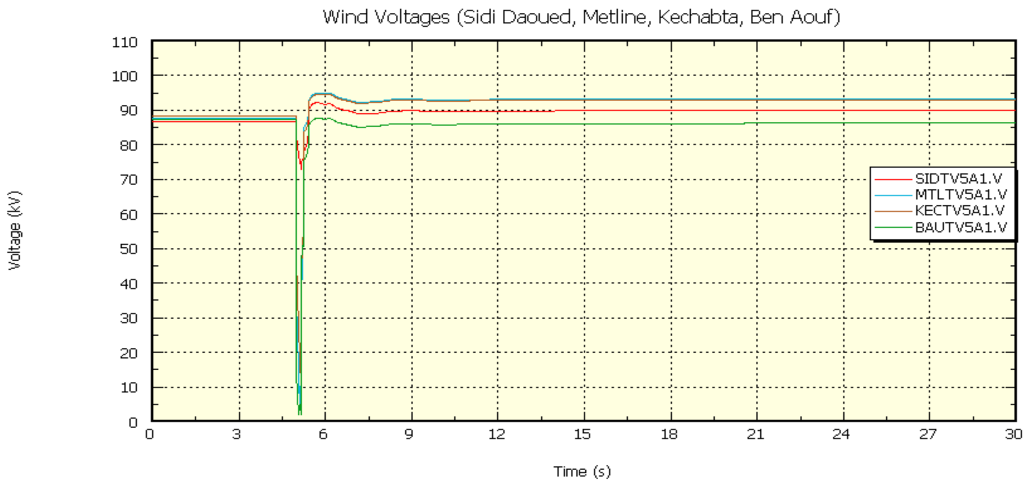

Fig. 6.106 – Peak load condition, fault analysis, RES power plants' voltages (90 kV).

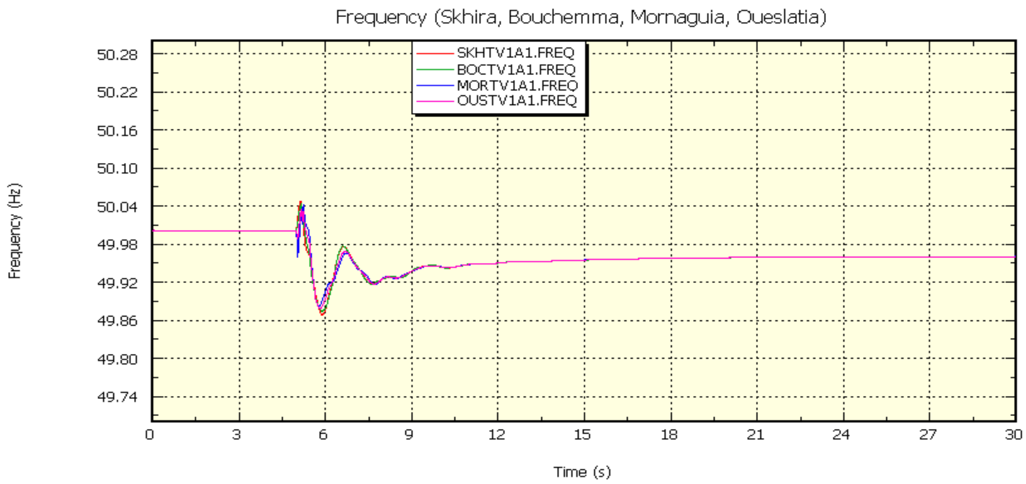

Fig. 6.107 – Peak load condition, fault analysis, system nodes' frequency.

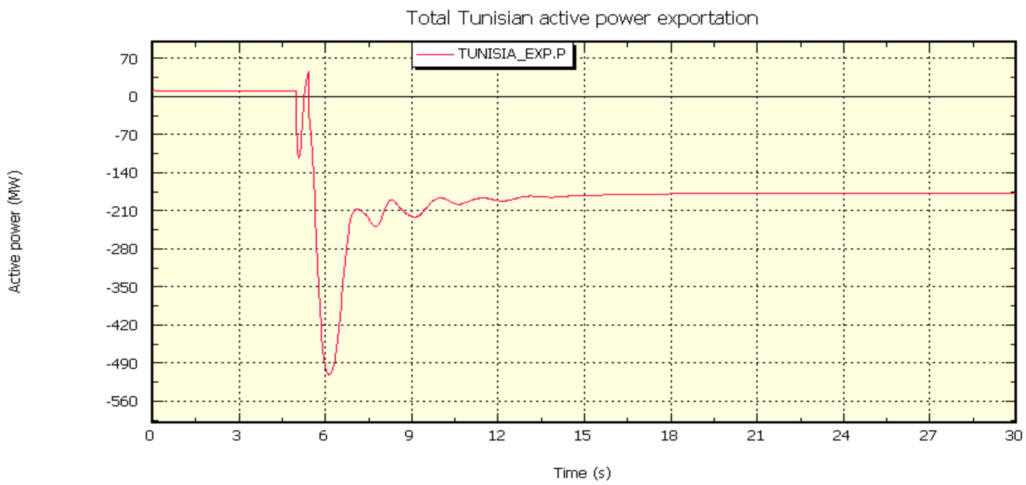

Fig. 6.108 – Peak load condition, fault analysis, total active power exchange with Algeria only.

Fig. 6.109 – Peak load condition, fault analysis, single line active power exchanges.

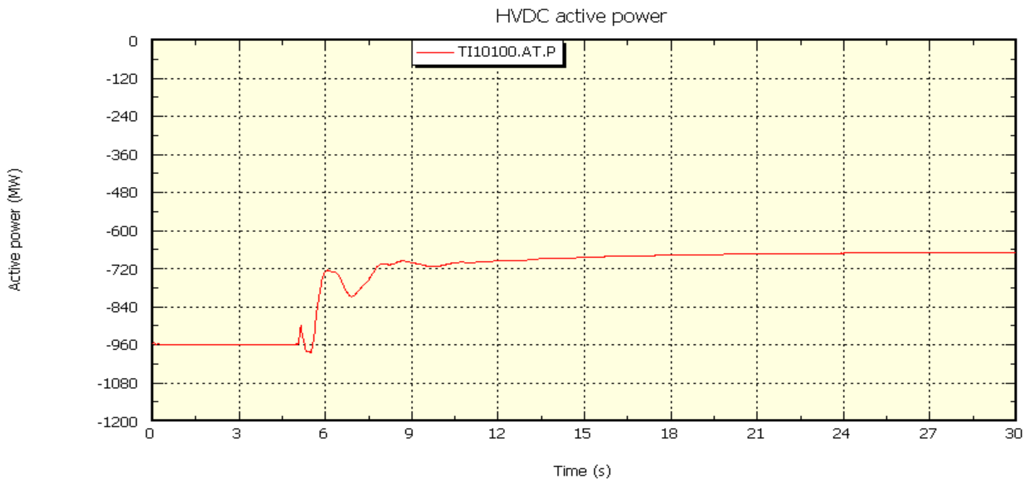

Fig. 6.110 – Peak load condition, fault analysis, HVDC active power flow.

*6.5.1.6 <u>Short circuit on Menzel Jemil–Bizerte 90 kV line **without frequency derivative protections**</u>*

The absence of frequency derivative protections improves the behaviours of the system variables after the fault on this 90 kV line, i.e. close to connection points of RES power plants:

- Disconnection of only one (Ben Auof) out of the two RES power plants connected to a 90 kV node, caused by the exceeding of the underfrequency threshold (47 Hz, see annexe 2): this doesn't represent an undervoltage problem, because the fulfilment of the "fault-ride-through" characteristics (Fig. 6-3) avoids, also in this case, this intervention;
- Voltages and frequency remains within an acceptable range during the transient, and after the fault recover the initial values;
- Exchange power on the 400 kV interconnection line below 300 MW even during the transient.

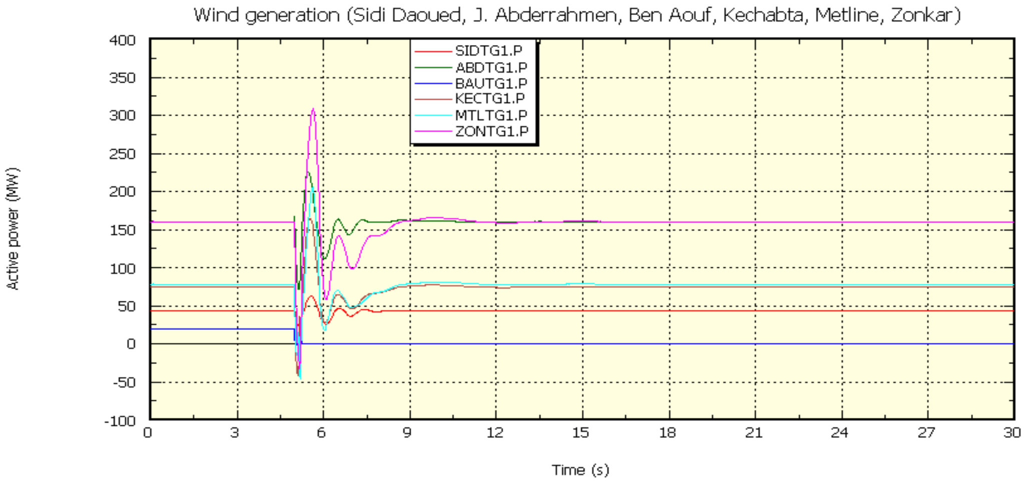

Fig. 6.111 – Peak load condition, fault analysis, RES power production.

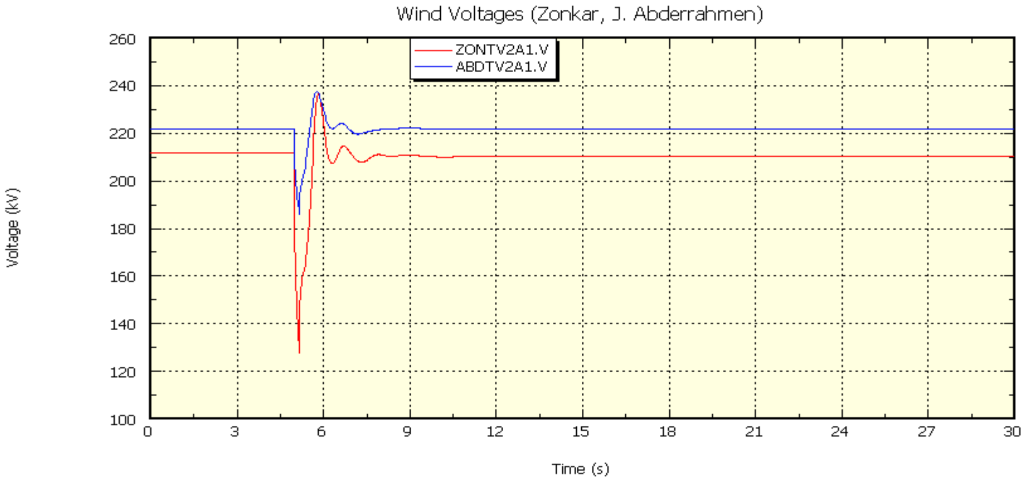

Fig. 6.112 – Peak load condition, fault analysis, RES power plants' voltages (225 kV).

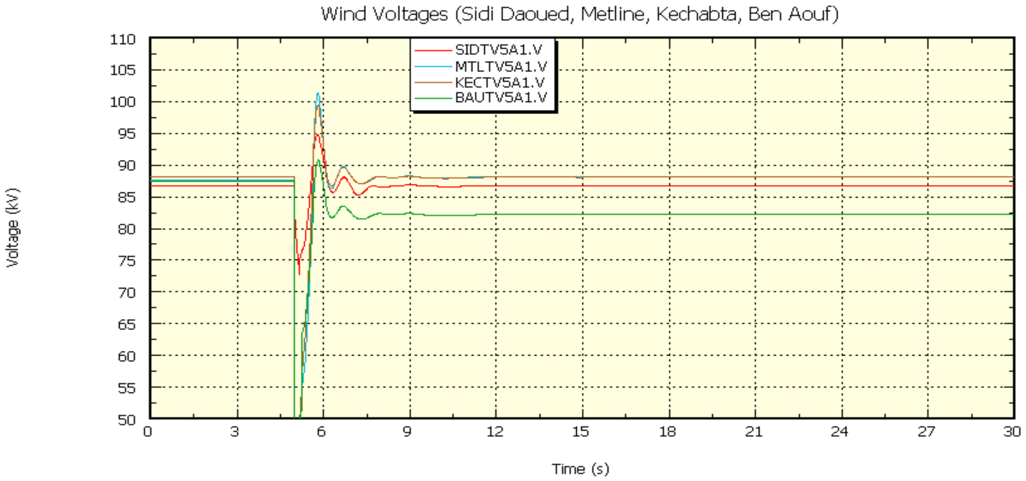

Fig. 6.113 – Peak load condition, fault analysis, RES power plants' voltages (90 kV).

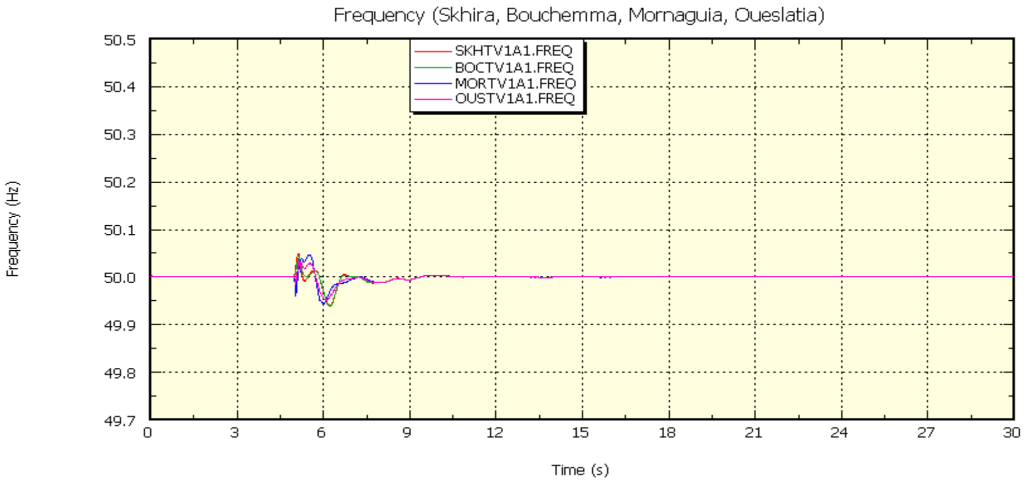

Fig. 6.114 – Peak load condition, fault analysis, system nodes' frequency.

Fig. 6.115 – Peak load condition, fault analysis, total active power exchange with Algeria only.

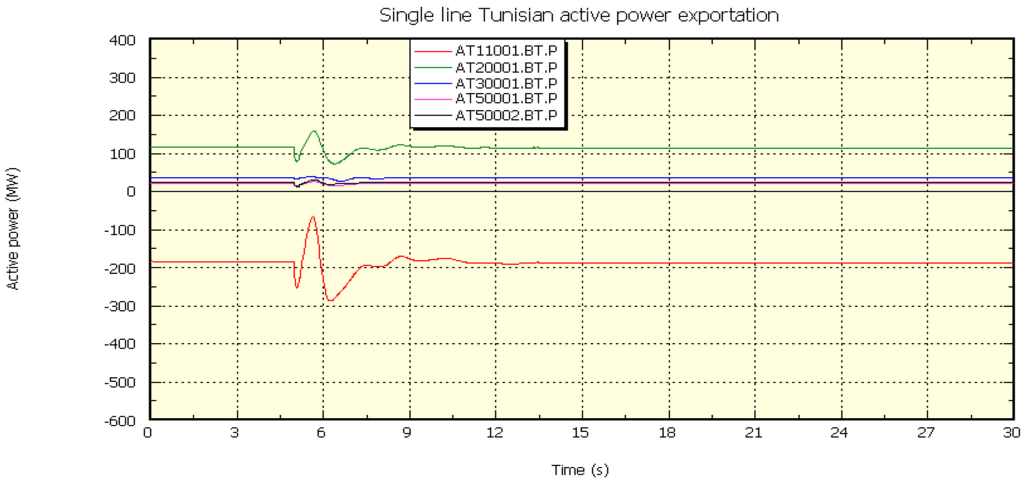

Fig. 6.116 – Peak load condition, fault analysis, single line active power exchanges.

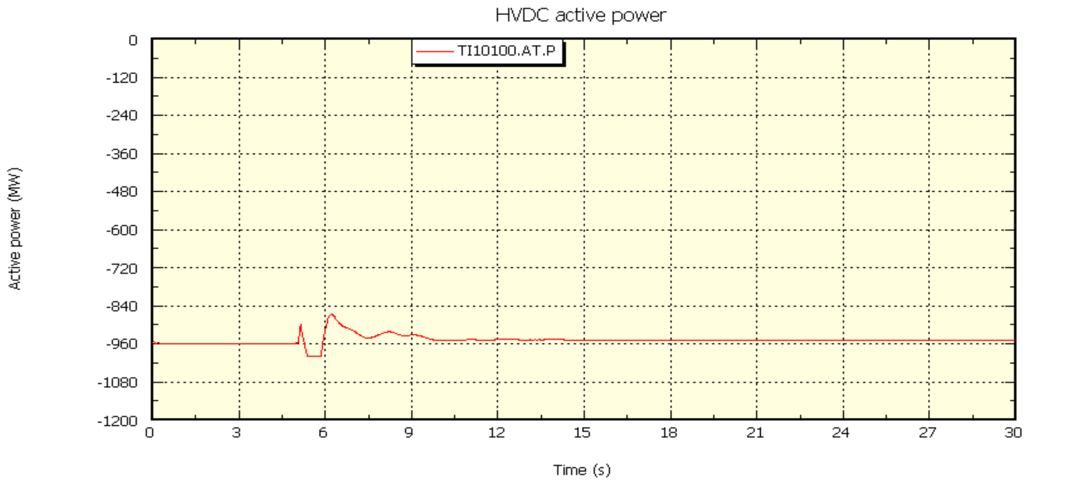

Fig. 6.117 – Peak load condition, fault analysis, HVDC active power flow.

6.5.2 Minimum load scenario

6.5.2.1 Short circuit on Skhira – Maknassy 400 kV line ***with frequency derivative protections***

The effect of frequency derivative protection for RES generation plants are very similar to those described for peak load scenario.

During this fault frequency derivative protections cause the disconnection of all RES power plants.

While voltages and frequency behaviours are pretty similar to those in peak load condition, the generation loss is covered almost entirely by the HVDC system and the interconnection lines do not present any particular active power transient in comparison to those of peak load scenario.

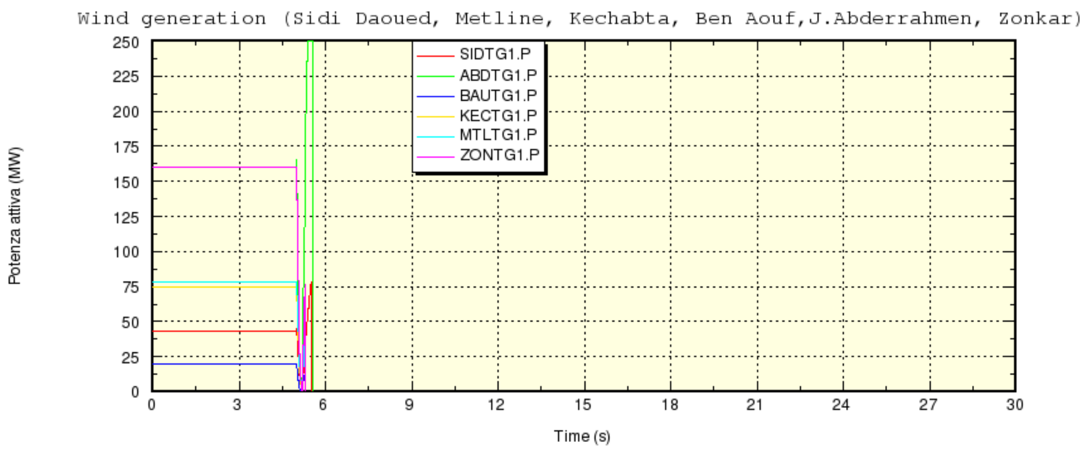

Fig. 6.118 –Minimum load condition, fault analysis, RES power production.

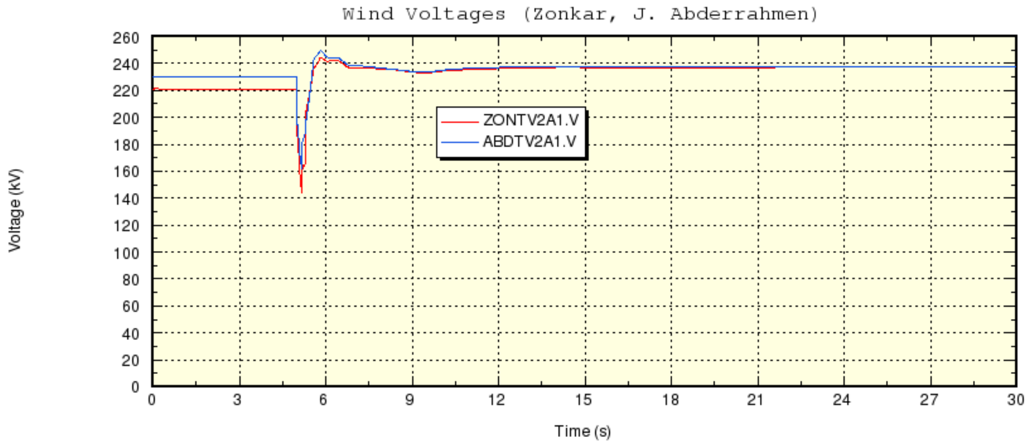

Fig. 6.119 – Minimum load condition, fault analysis, RES power plants' voltages (225 kV).

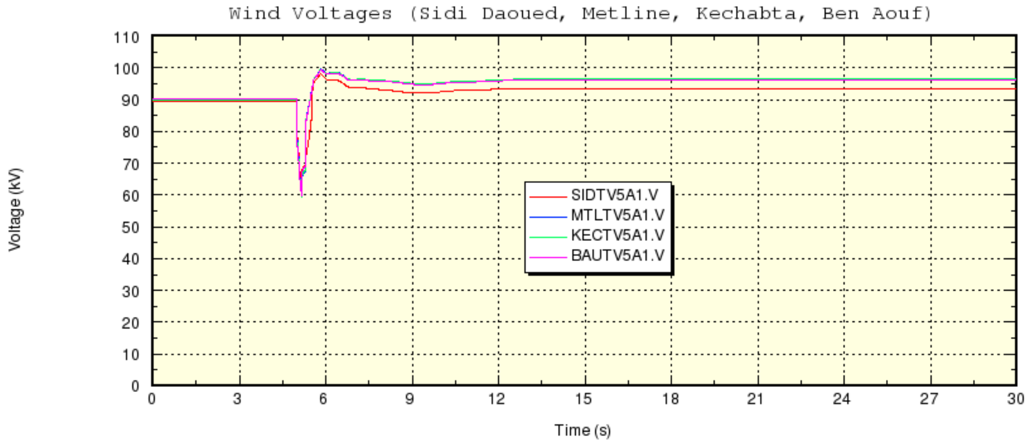

Fig. 6.120 – Minimum load condition, fault analysis, RES power plants' voltages (90 kV).

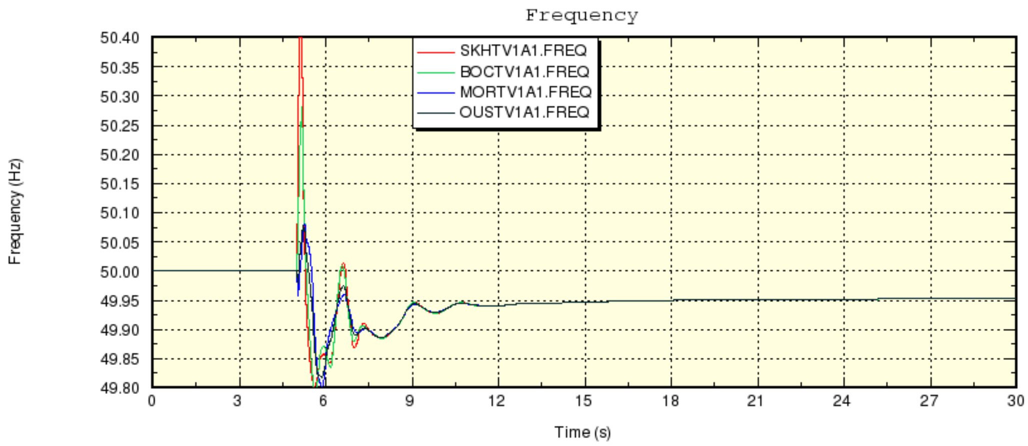

Fig. 6.121 – Minimum load condition, fault analysis, system nodes' frequency.

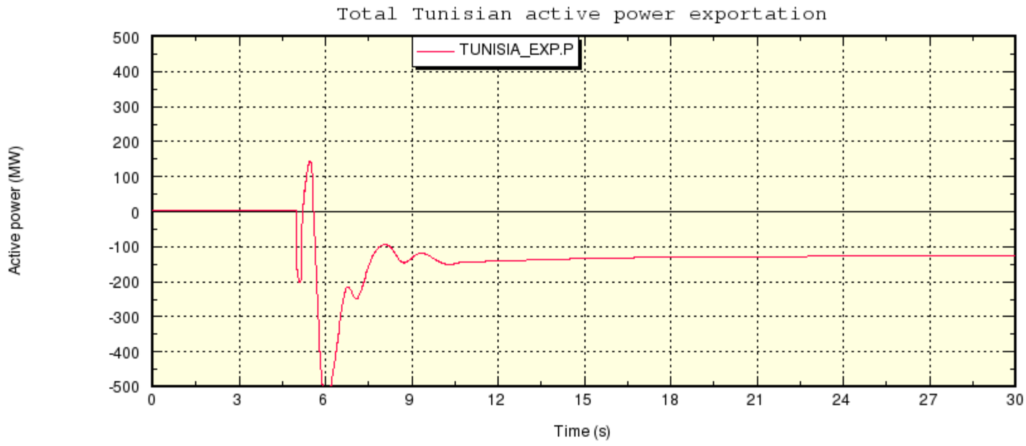

Fig. 6.122 – Minimum load condition, fault analysis, total active power exchange with Algeria only.

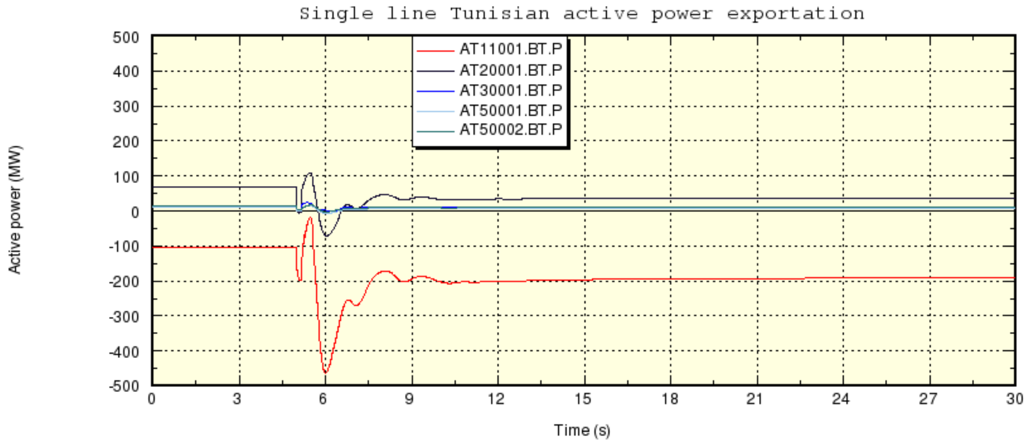

Fig. 6.123 – Minimum load condition, fault analysis, single line active power exchanges.

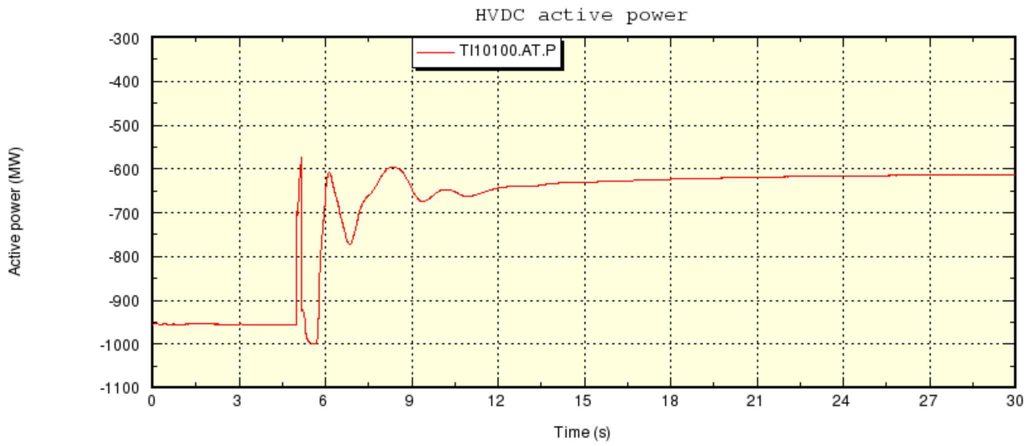

Fig. 6.124 – Minimum load condition, fault analysis, HVDC active power flow.

*6.5.2.2 Short circuit on Skhira – Maknassy 400 kV line **without frequency derivative protections***

The improvements coming from the absence of frequency derivative protections are evident in this case. No RES power plant disconnects from grid, and voltages and frequency after the fault regain the same values they had before the fault. In addition there's a further benefit, this time deriving from the minimum load condition, that is a pretty low peak of active power exchange on tie-lines during the transient.

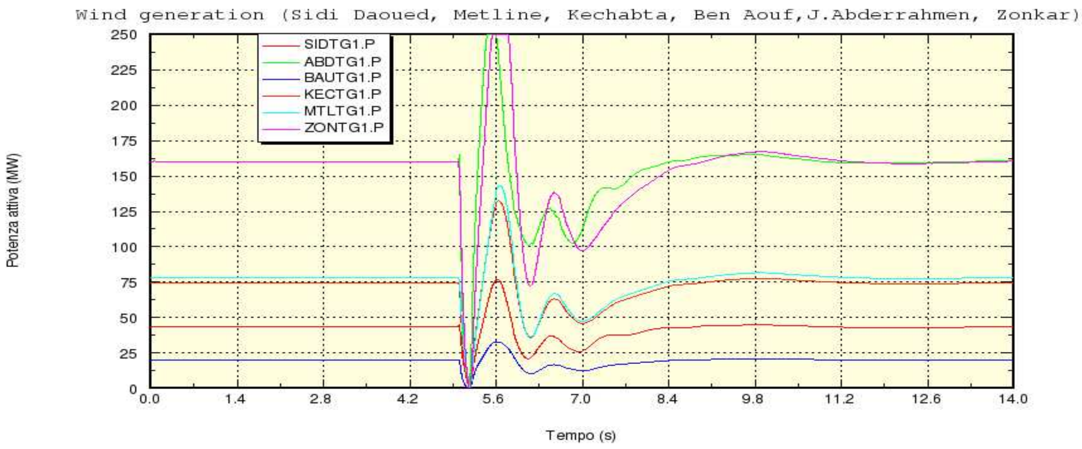

Fig. 6.125 –Minimum load condition, fault analysis, RES power production.

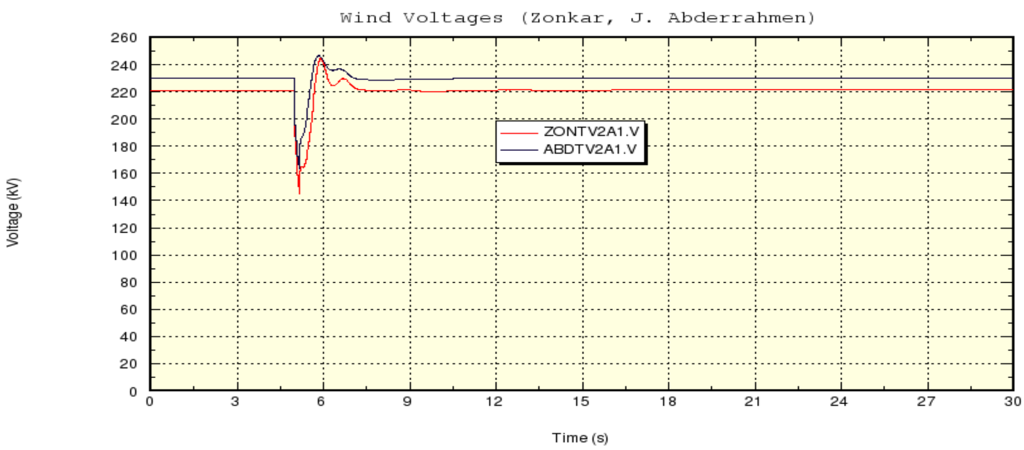

Fig. 6.126 – Minimum load condition, fault analysis, RES power plants' voltages (225 kV).

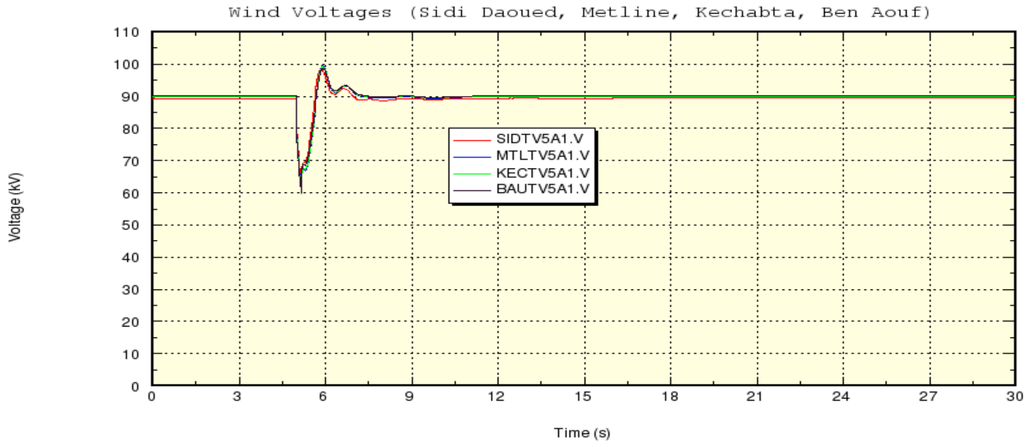

Fig. 6.127 – Minimum load condition, fault analysis, RES power plants' voltages (90 kV).

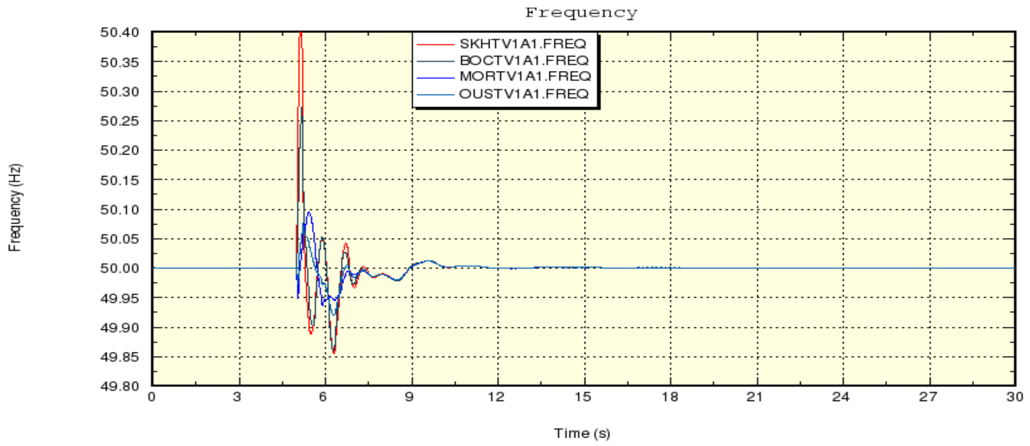

Fig. 6.128 – Minimum load condition, fault analysis, system nodes' frequency.

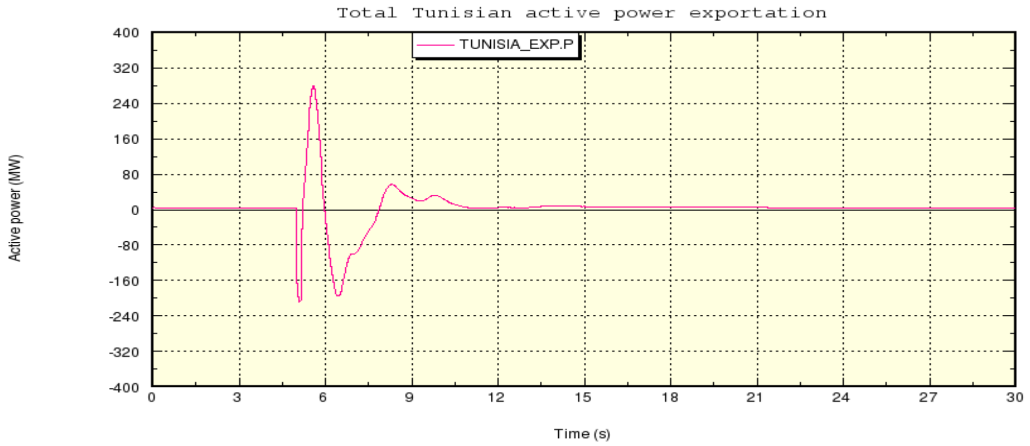

Fig. 6.129 – Minimum load condition, fault analysis, total active power exchange with Algeria only.

Fig. 6.130 – Minimum load condition, fault analysis, single line active power exchanges.

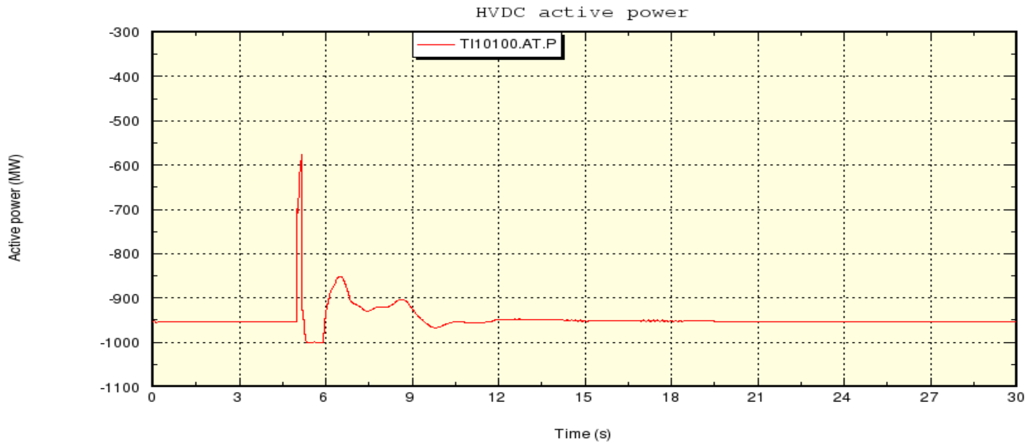

Fig. 6.131 – Minimum load condition, fault analysis, HVDC active power flow.

6.5.2.3 <u>Short circuit on Oueslatia – Mornaguia 400 kV line</u> ***<u>with frequency derivative protections</u>***

Frequency derivative protections cause the disconnection of all the RES power plants, and the generation loss is covered mainly by an export reduction of the HVDC system. The interconnection lines with Algeria do not present particularly high transients (below 500 MW).

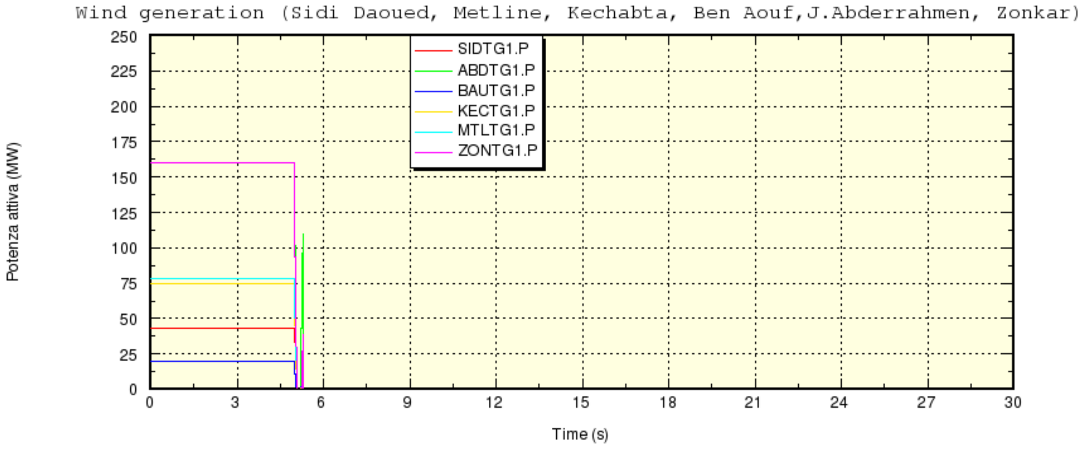

Fig. 6.132 – Minimum load condition, fault analysis, RES power production.

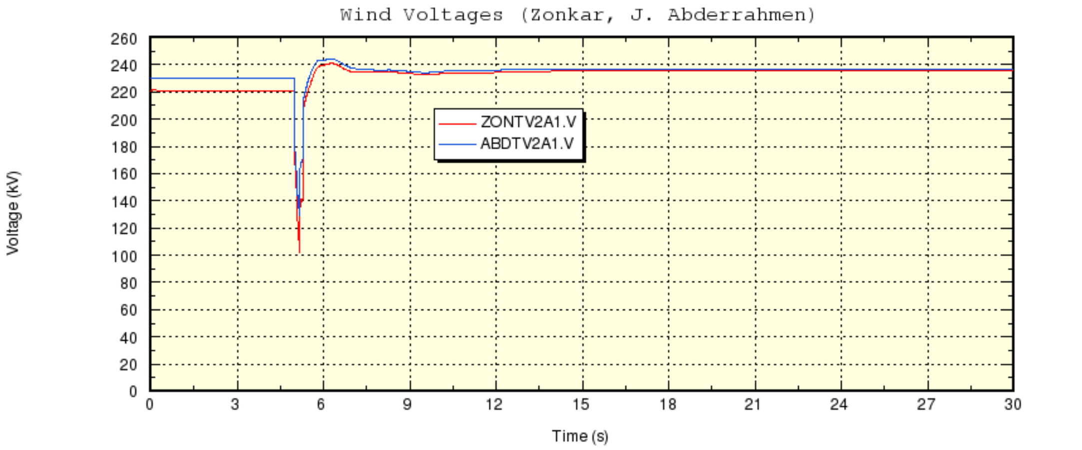

Fig. 6.133 – Minimum load condition, fault analysis, RES power plants' voltages (225 kV).

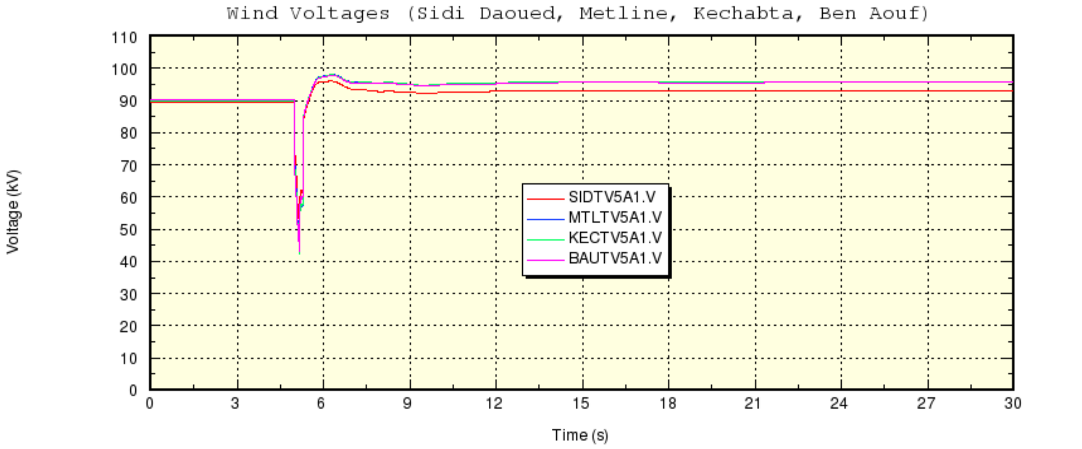

Fig. 6.134 – Minimum load condition, fault analysis, RES power plants' voltages (90 kV).

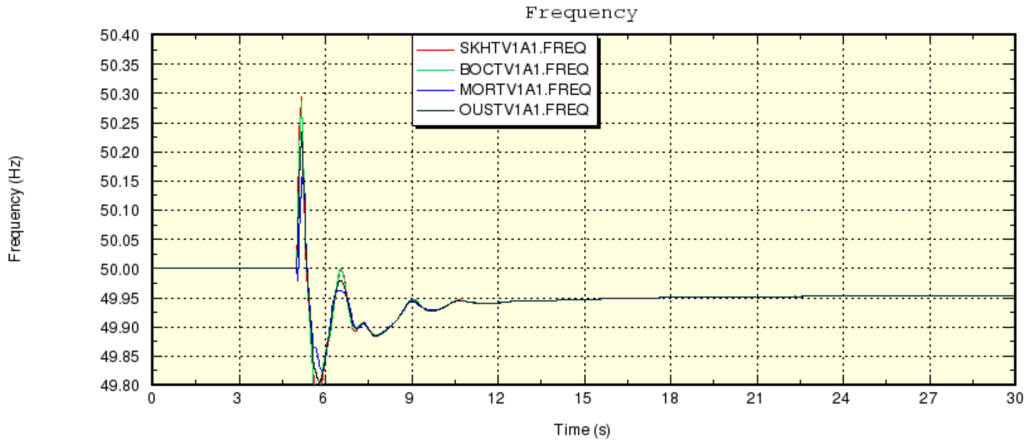

Fig. 6.135 – Minimum load condition, fault analysis, system nodes' frequency.

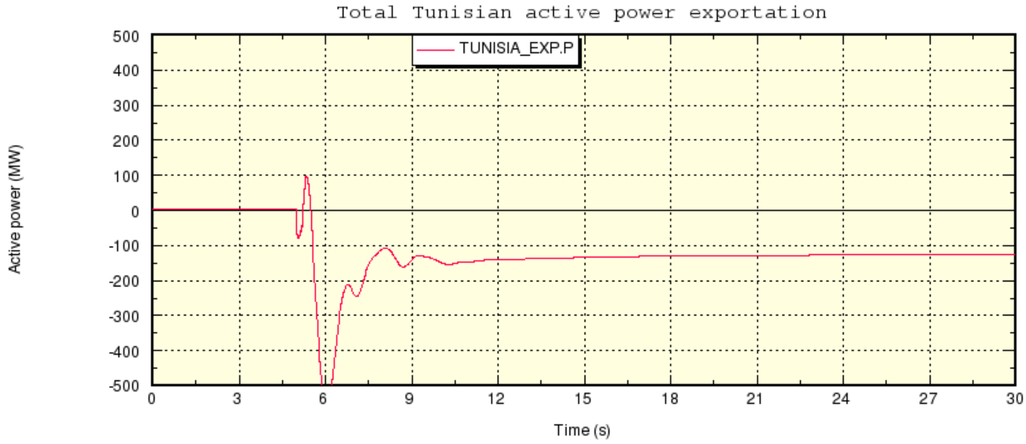

Fig. 6.136 – Minimum load condition, fault analysis, total active power exchange with Algeria only.

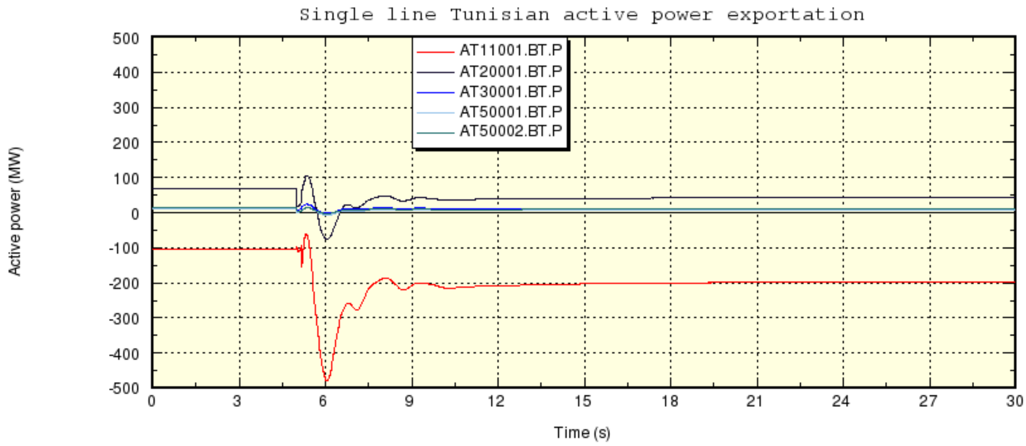

Fig. 6.137 – Minimum load condition, fault analysis, single line active power exchanges.

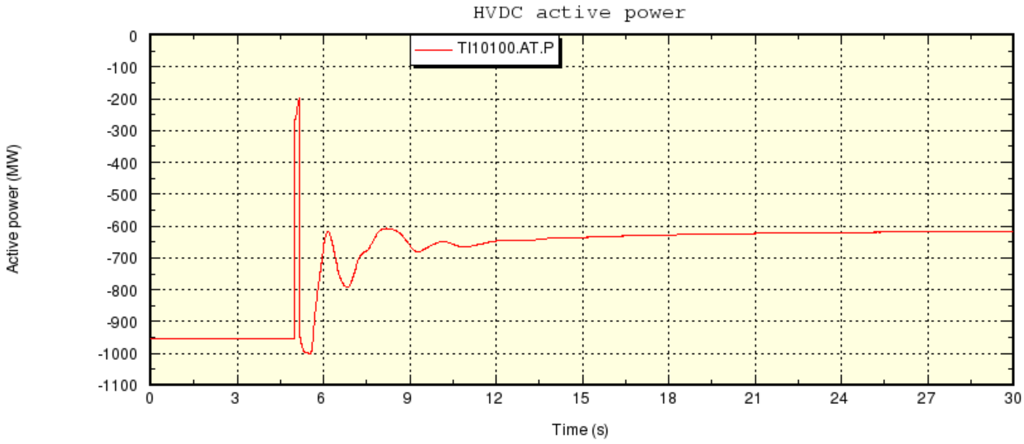

Fig. 6.138 – Minimum load condition, fault analysis, HVDC active power flow.

*6.5.2.4 <u>Short circuit on Oueslatia – Mornaguia 400 kV line</u> <u>**without frequency derivative protections**</u>*

The absence of frequency derivative protections improves the system behaviour after the fault and no relevant problems have been noticed, as frequency and voltages final values are similar to those before the fault, and the power exchange on the interconnection lines does not vary excessively.

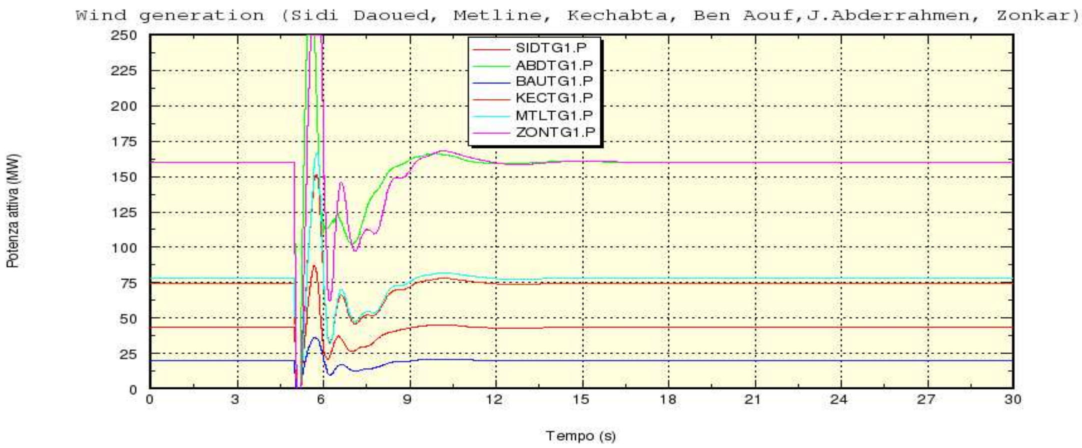

Fig. 6.139 – Minimum load condition, fault analysis, RES power production.

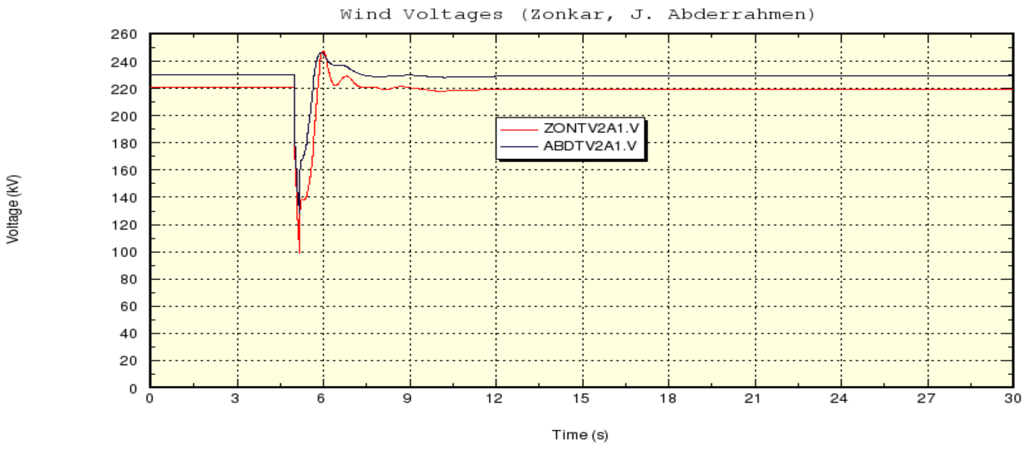

Fig. 6.140 – Minimum load condition, fault analysis, RES power plants' voltages (225 kV).

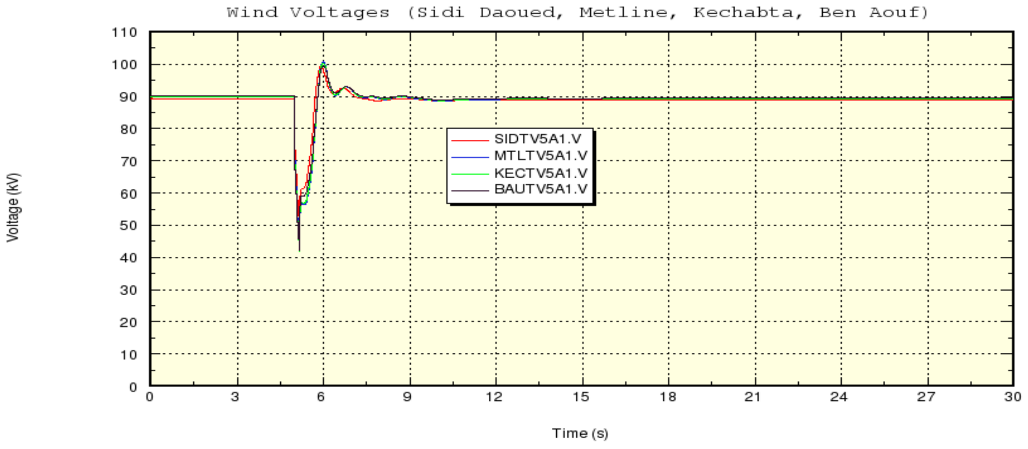

Fig. 6.141 – Minimum load condition, fault analysis, RES power plants' voltages (90 kV).

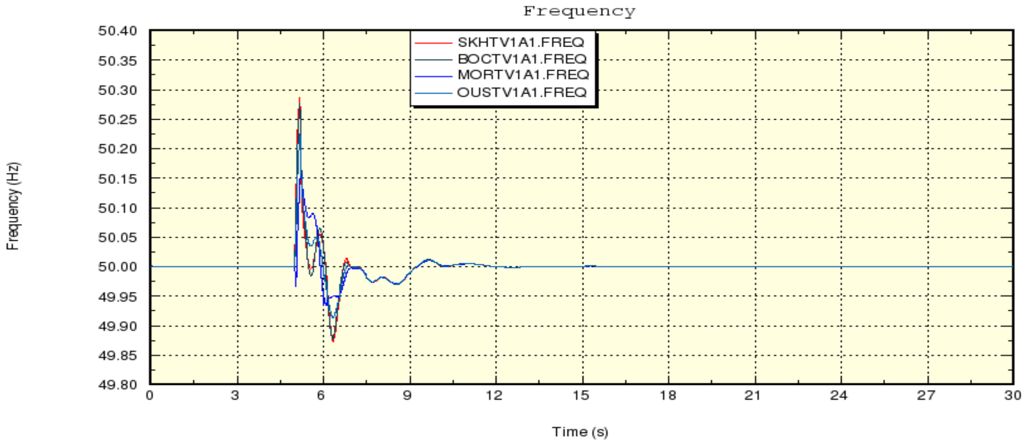

Fig. 6.142 – Minimum load condition, fault analysis, system nodes' frequency.

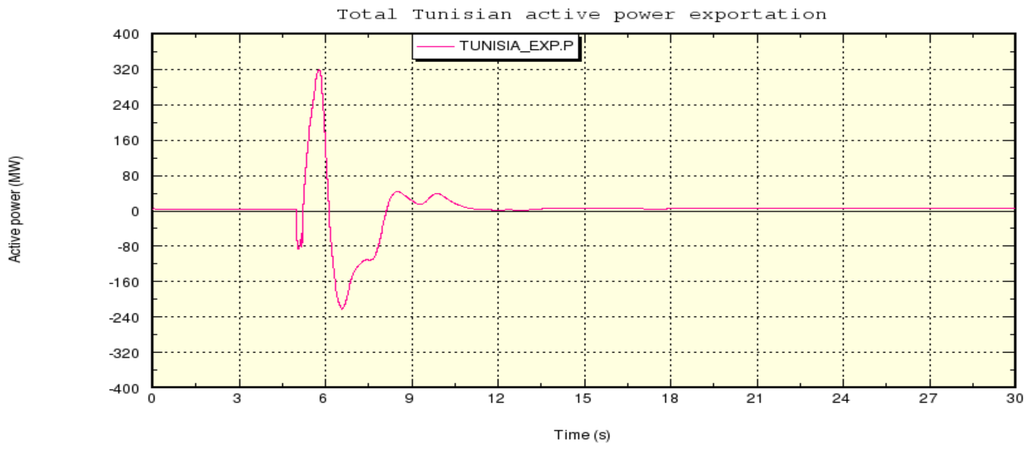

Fig. 6.143 – Minimum load condition, fault analysis, total active power exchange with Algeria only.

Fig. 6.144 – Minimum load condition, fault analysis, single line active power exchanges.

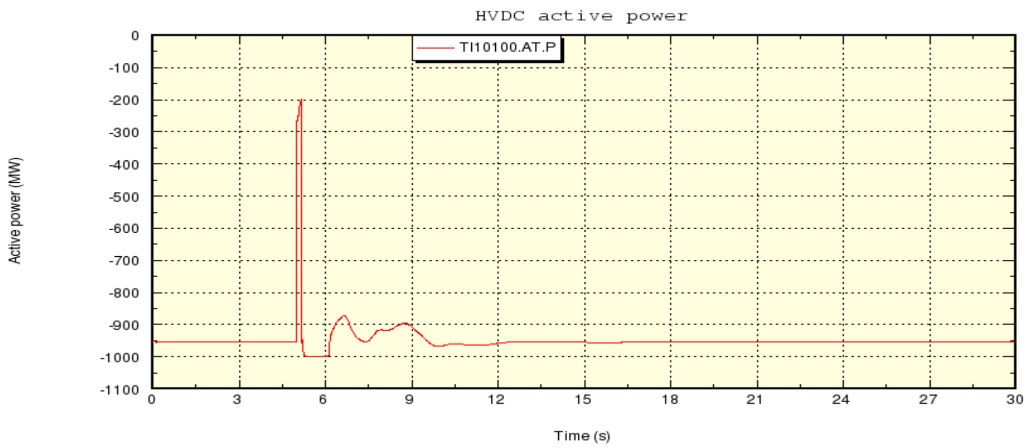

Fig. 6.145 – Minimum load condition, fault analysis, HVDC active power flow.

*6.5.2.5 Short circuit on Menzel Jemil–Bizerte 90 kV line **with frequency derivative protections***

Frequency derivative protections affect the system behaviour, as shown in every simulation till now, causing the disconnection of all the RES power plants. Nevertheless, the system doesn't undergo any particular problems thanks to the HVDC connection to Italy, which is essential to regulate the frequency after such a heavy generation reduction.

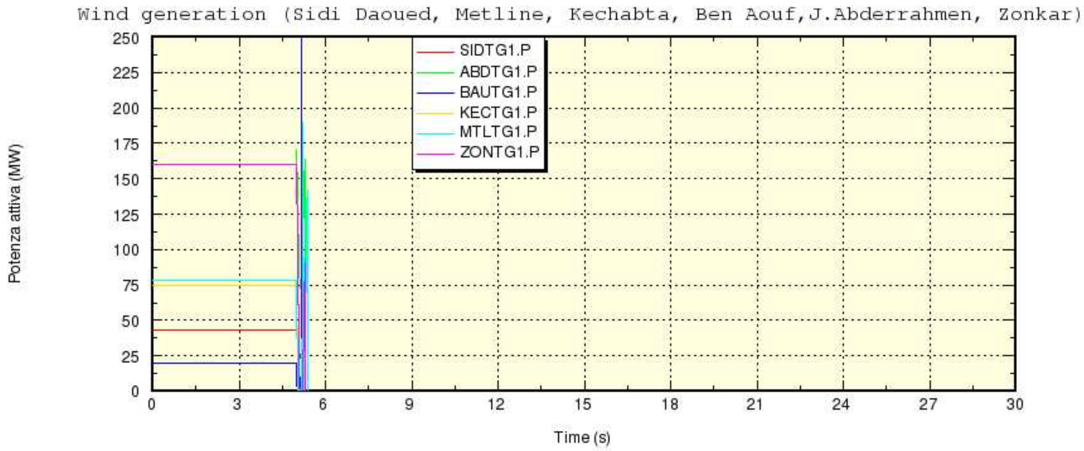

Fig. 6.146 –Minimum load condition, fault analysis, RES power production.

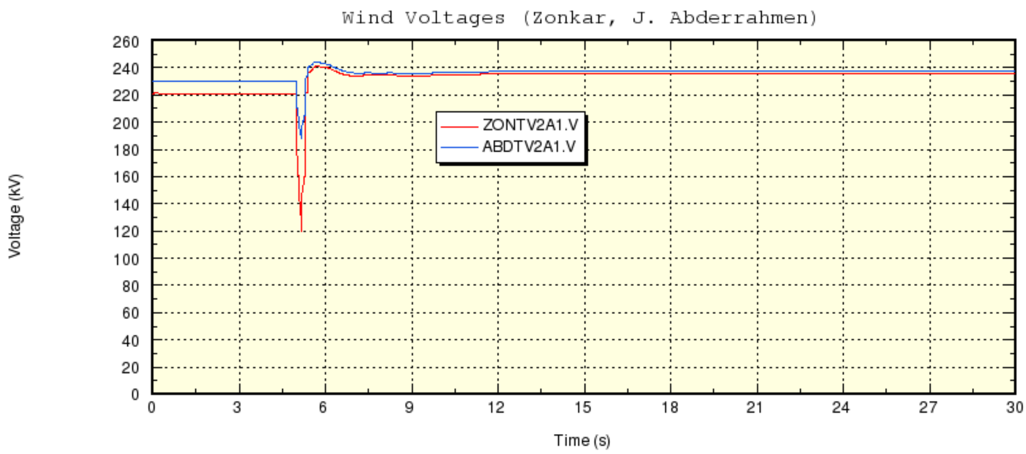

Fig. 6.147 – Minimum load condition, fault analysis, RES power plants' voltages (225 kV).

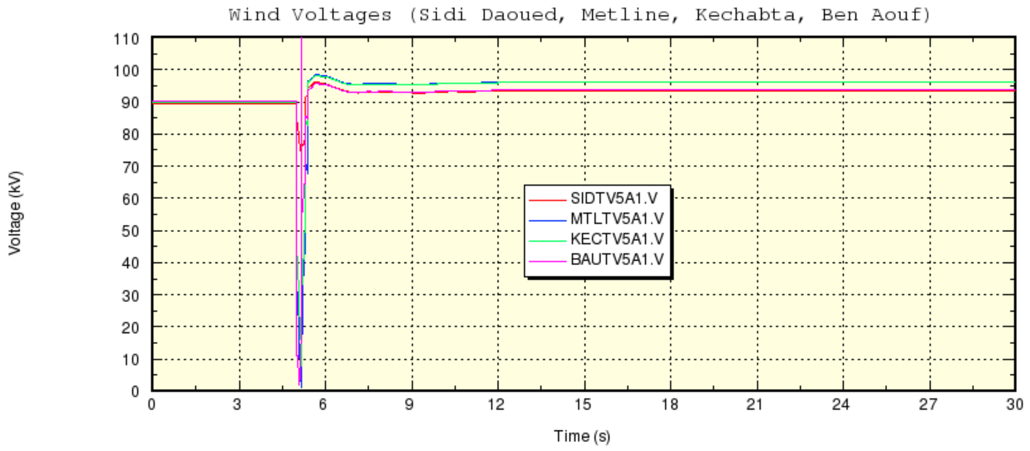

Fig. 6.148 – Minimum load condition, fault analysis, RES power plants' voltages (90 kV).

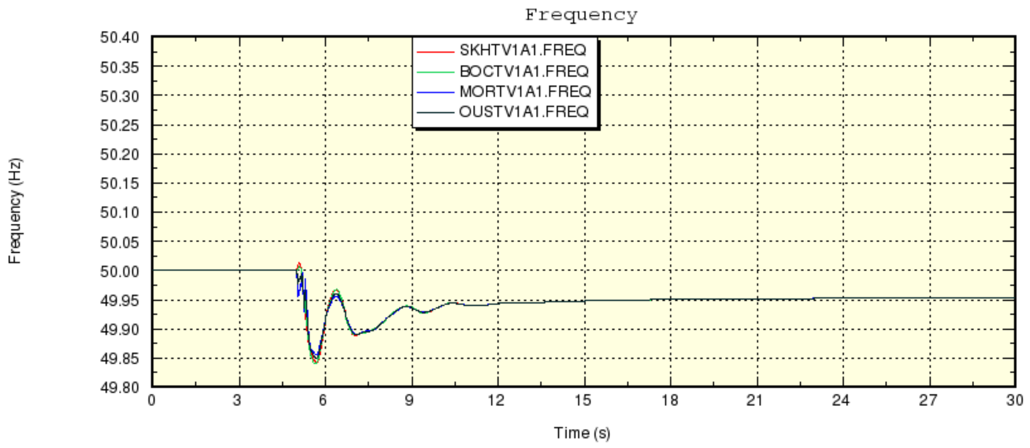

Fig. 6.149 – Minimum load condition, fault analysis, system nodes' frequency.

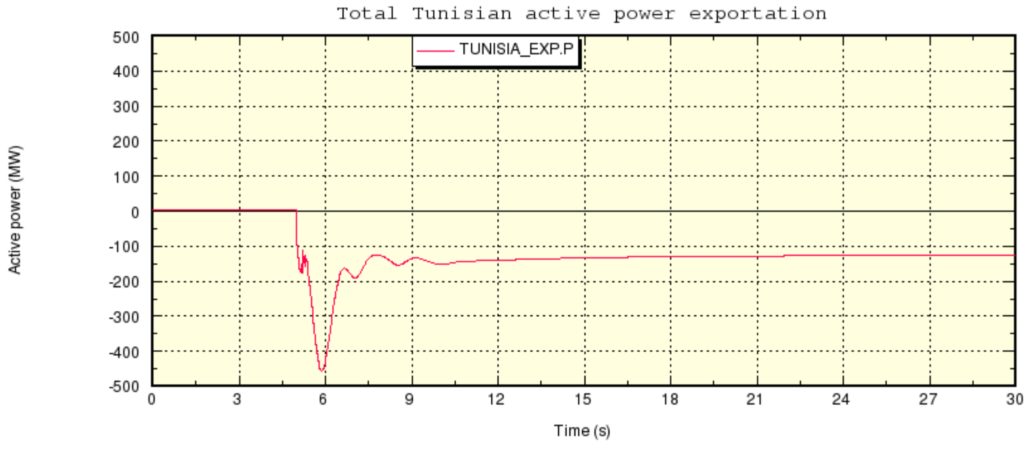

Fig. 6.150 – Minimum load condition, fault analysis, total active power exchange with Algeria only.

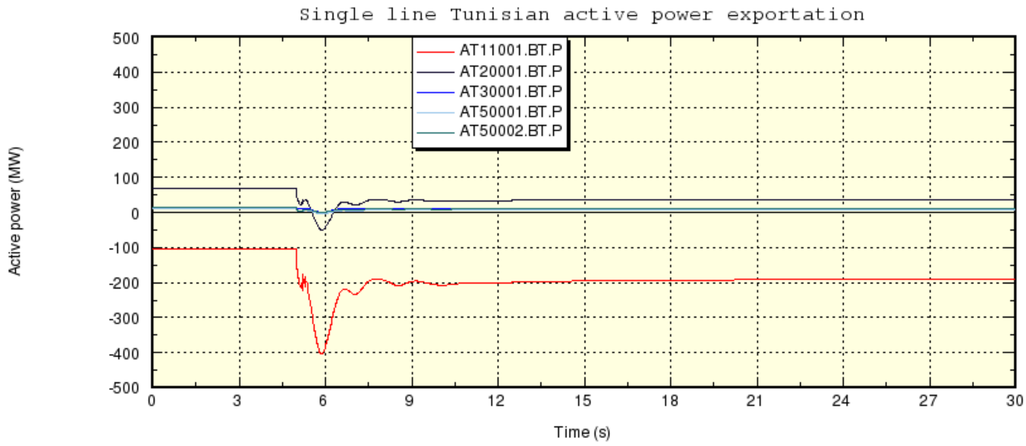

Fig. 6.151 – Minimum load condition, fault analysis, single line active power exchanges.

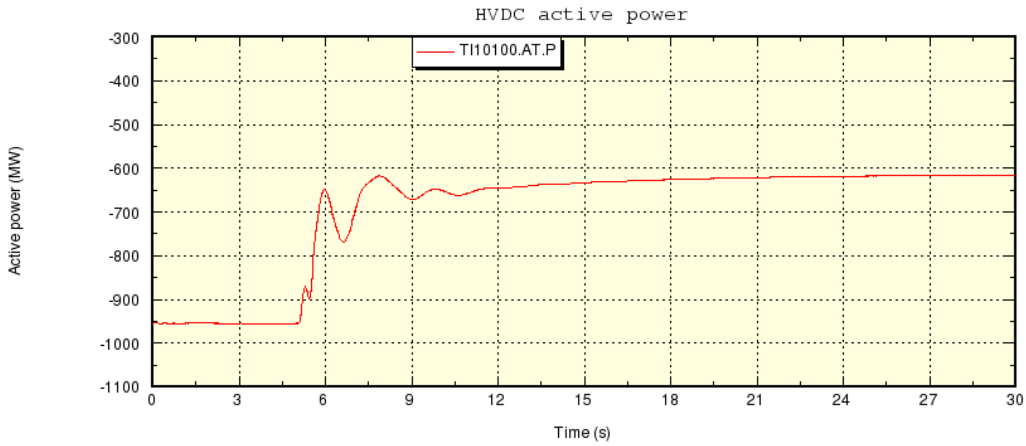

Fig. 6.152 – Minimum load condition, fault analysis, HVDC active power flow.

6.5.2.6 *Short circuit on Menzel Jemil–Bizerte 90 kV line* ***without frequency derivative protections***

While in peak load condition this fault caused the disconnection of one RES power plant, in minimum load scenario all the RES generation plants remain connected to the grid, thus avoiding the problems that a loss of generation could cause (frequency decreasing and importation increasing). The power oscillations on the interconnection lines appear to be acceptable, as those of frequency and voltages in the observed nodes.

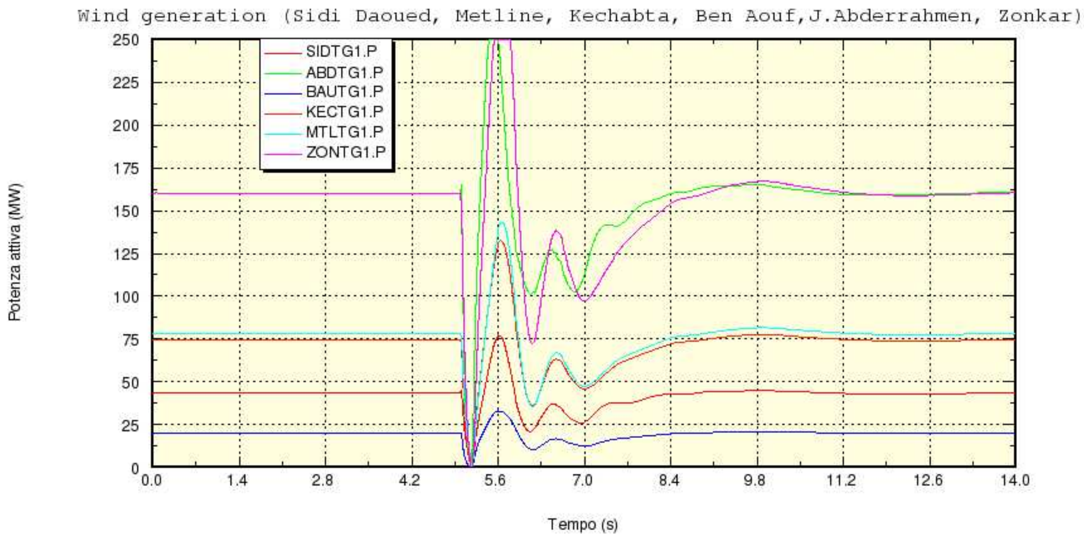

Fig. 6.153 – Minimum load condition, fault analysis, RES power production.

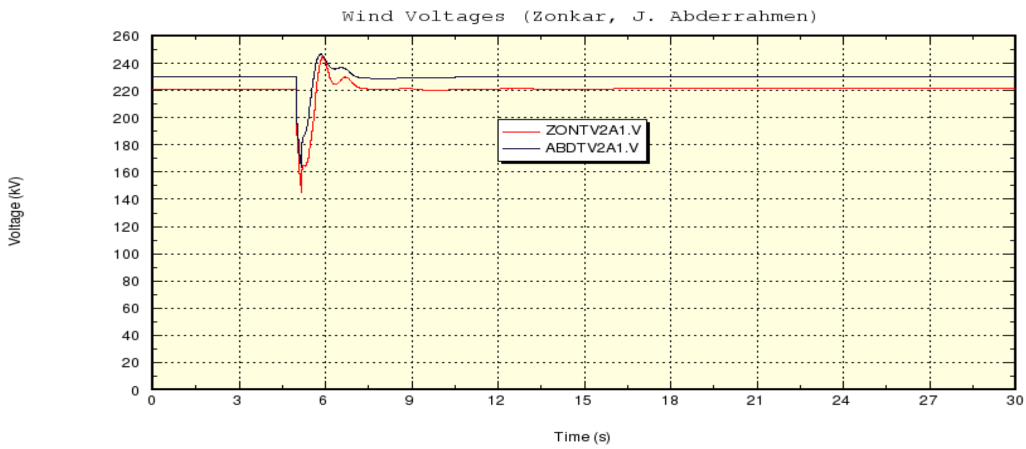

Fig. 6.154 – Minimum load condition, fault analysis, RES power plants' voltages (225 kV).

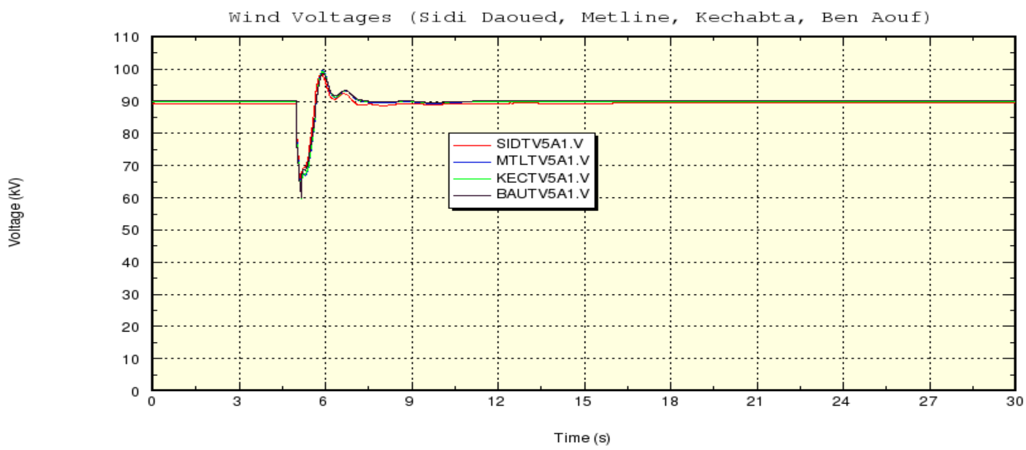

Fig. 6.155 – Minimum load condition, fault analysis, RES power plants' voltages (90 kV).

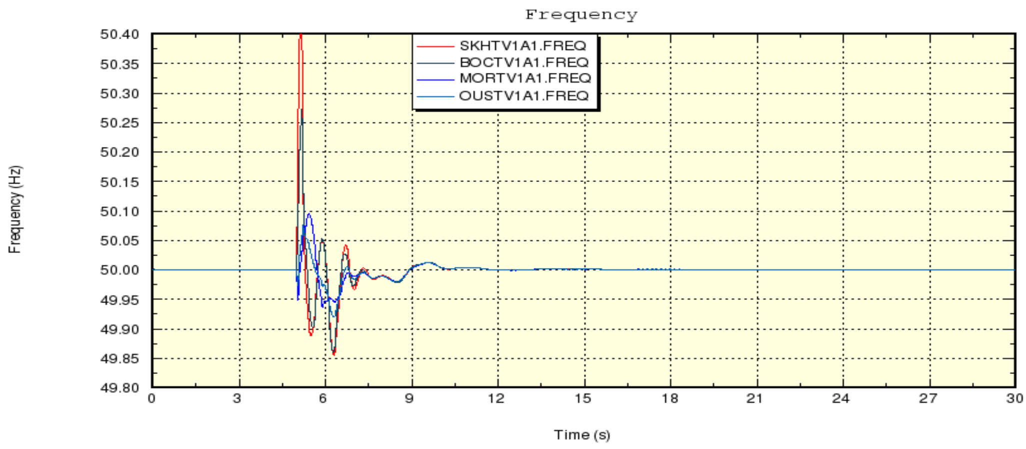

Fig. 6.156 – Minimum load condition, fault analysis, system nodes' frequency.

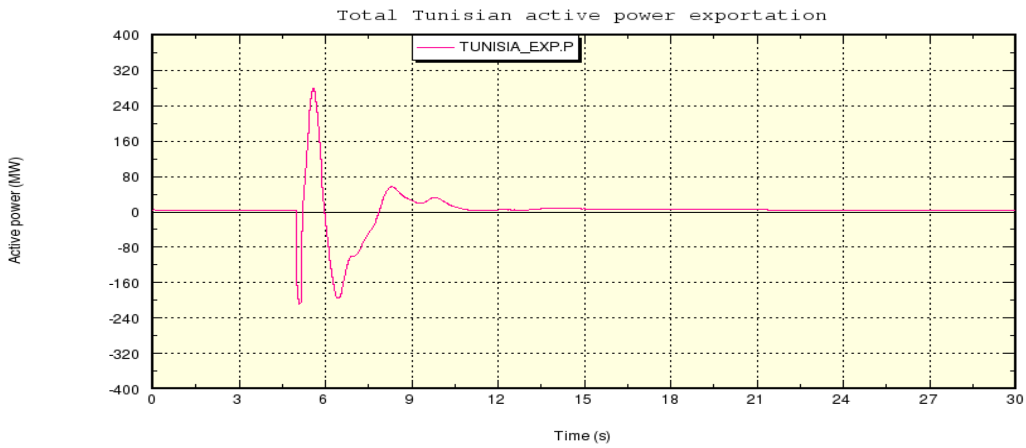

Fig. 6.157 – Minimum load condition, fault analysis, total active power exchange with Algeria only.

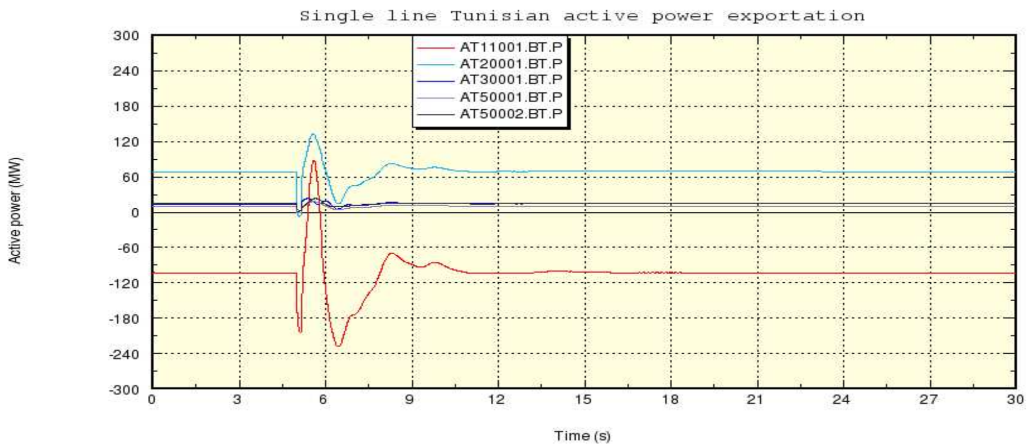

Fig. 6.158 – Minimum load condition, fault analysis, single line active power exchanges.

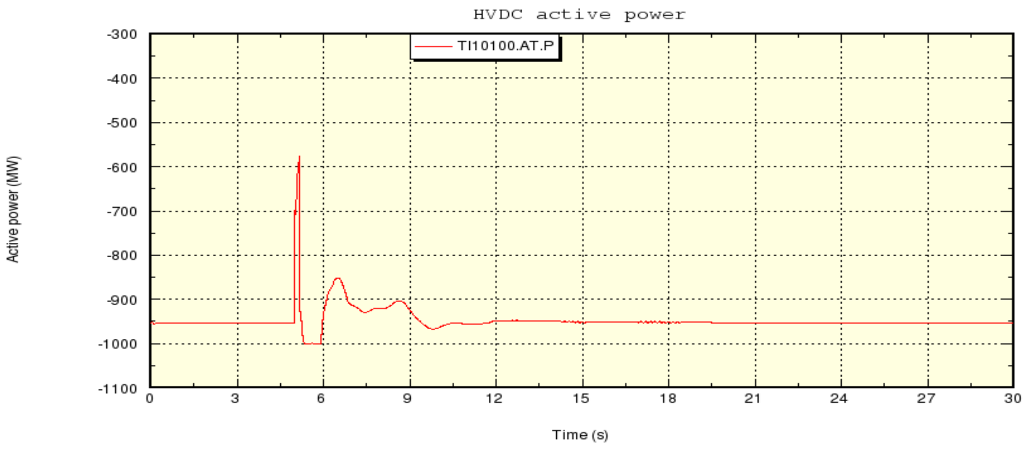

Fig. 6.159 – Minimum load condition, fault analysis, HVDC active power flow.

7 CONCLUSIONS

The scope of this phase of the study is the assessment of the maximum non-dispatchable generation connectable to the Tunisian system.

The study has been split in three phases that can be summarised as follow:

a) "*single bus bar*" *analysis*, the scope of which was to determine the maximum non-dispatchable RES power generation considering only the generating unit constraints (i.e. frequency regulation reserve).

   This analysis has been carried out according to the hypotheses reported in paragraph 3.1: the validity of the results reported in this document is not warranted, if all these hypotheses are not fulfilled.

   Secondary/tertiary reserve and additional reserve due to non-dispatchable RES power connection have been calculated according to what reported in [1].

   The analysis has concerned both minimum and peak load scenarios, in order to assess a value acceptable by the grid in every load condition.

b) *static analysis*, where a new grid configuration is determined with the grid integrations required for the RES power plants connection. Thereafter, the static performances of the Tunisian system have been tested in order to verify the occurrence of possible voltage violations and overloads, both in peak and minimum load scenarios, and in "N" and "N-1" conditions.

c) *dynamic analysis*, addressing two sets of analyses:
   - sensitivity analysis, where the effects of renewable generation fluctuations have been investigated in terms of voltage and frequency oscillations;
   - fault analysis, where the stability of the system in case of main grid contingences (i.e. three phase short circuit) has been tested to verify the behaviour of RES power plants in case of fault.

All the analyses have been carried out considering the horizon year 2016. Two operating conditions have been considered:

- yearly peak load;
- yearly minimum load.

All analyses have been executed starting from the grid configuration determined in Task B [2] with the ELMED power plant located in Skhira (solution "A1") without any additional network reinforcement except those strictly requested for the RES power plants connection.

<u>Results of the "single bus bar" analysis</u>

First of all, the peak load scenario has been investigated. The starting condition derives from Task B of this study, i.e.:

- total internal load equal to 3960 MW;
- 950 MW is the power export to Sicily through the HVDC link (a 5% regulation bandwidth referred to the rating of the cable has been considered);

- tertiary frequency regulation reserve calculated as the 8% of the total load, according to the rules of ENTSO-E[12] (the export through the HVDC link is not included in this calculation because the system has its frequency regulation capability).

This scenario doesn't show any particular restrictive conditions, as the only constraint is the downward reserve increased by the additional reserve (due to renewable generation), which should be lower than conventional generated power. Thus, the decreasing margin for conventional units (i.e. connectable wind generation) is sufficiently high.

The restrictive scenario is, indeed, the minimum load one, where the difference between conventional generated power and the technical minimum of the units appears quite low, always keeping the hypothesis not to change the unit commitment.
The starting condition is:

- total internal load equal to 1400 MW;
- 950 MW is the exportation to Sicily through the HVDC link (a 5% regulation bandwidth has been considered);
- tertiary frequency regulation reserve calculated as the 8% of the total load (the export through the HVDC link is not included in this calculation because the system has its frequency regulation capability).

The maximum power of non-dispatchable RES generation is about 530 MW, with an additional reserve of about 80 MW, which corresponds to an installed power of about 660 MW, considering a generating rate for RES equal to 80%.
The previous result is valid under the assumption of thermal production at the ELMED power plant equal to 400 MW in low load conditions. However, if the level of thermal generation at the ELMED power plant exceeds 400 MW, the non-dispachable RES generation shall be reduced according to the following table.

Tab. 7-1 – Maximum non-dispatchable RES generation and installation in function of thermal ELMED production

Production of ELMED power plant [MW]	Maximum RES power generation [MW]	Installed RES power (*) [MW]
400 *(limit condition)*	530	660
500	450	560
600	370	460
700	285	355
800	205	255

(*) generation rate equal to 80%

In conclusion, from the above values it is possible to point out that if the production of ELMED power plant increases of 100 MW, the non-dispatchable RES power generation must decrease of about 80 MW in linear way.

[12] ENTSO-E: European Network of Transmission System Operators of Electricity.

The most problematic situation for the Tunisian system is that one characterised by the highest amount of renewable generation (reference scenario). For this reason, all static and dynamic analyses have been carried out considering a RES power generation equal to 530 MW.

Results of the static analysis

The static analysis has the objective to define the best solution to connect the new RES power plants to Tunisian grid in compliance with the "N-1" security criterion both in peak and minimum load conditions. In the same time, in the new scenarios a redispatching of traditional production has been done according to the "merit order" criterion without changing the unit commitment.
To assure a non-dispatchable RES power production equal to 530 MW obtained after the "single bus bar" analysis, the following RES generation plants have been connected to the network in the two scenarios.

Name of site	Region	Connection stations	Exploitable RES power (MW)
Sidi Daoued	Cap Bon	Menzel Temime **90 kV: 29 km**	54
Metline	Bizerte	Menzel Jemil **90 kV: 11 km**	97
Kechabta	Bizerte	E/S on existing line **90 kV** Menzel Jemil-Menzel Bourguiba: **6 km**	93
Ben Aouf	Bizerte	Bizerte **90 kV: 12 km**	25
Jebel Abderrahmen	Cap Bon	Grombalia **225 kV: 43 km**	200
Zonkar	Bizerte	Menzel Bourguiba **225 kV: 30 km**	200

The redispatching, carried out considering the merit order of the units, is different in the two scenarios considered because the configuration of the generating units in service is different.
For both scenarios the exportation to Sicily through the HVDC interconnection is always considered equal to 950 MW.
The merit order criterion followed in this study is based on the data provided by STEG and reported in detail in [1]. In presence of the new ELMED power plant, these data should be re-examined, since the redispatching based on the merit order criterion can be different with respect to the one followed in this study also depending on the adopted technology and fuel for the new ELMED power plant (i.e. gas, coal).

Moreover, in minimum load conditions and with a generation level of renewable power RES equal to 530 MW, it is inevitable to change the dispatching of the ELMED power plant down to 400 MW increased by its regulation bandwidth equal to 5% of its nominal power. The downward redispatching of the ELMED power plant is necessary, since all other plants in operation are already at their technical minimums. The decrease of ELMED generation to a value close to its technical minimum with the aim to give priority to RES generation can have negative effects in term of the unit efficiency.

Redispatching in Peak load conditions

Considering that:

- 530 MW is the production of new non-dispatchable RES power plants;
- HVDC exportation to Sicily increases from 800 MW to 950 MW;

the redispatch carried out for this scenario is the following:

Tab. 7-2 – generating redispatching in peak load scenario.

Power plant	Unit	C S M [Tep/GWh]	Initial production [MW]	Final Production [MW]	Variation [MW]	Pmin [MW]
EL BIBENE	TG1	400	24.0	12.0	-12.0	12
BIR MCHERGUA	TG1	300	107.0	82.3	-23.7	40
BIR MCHERGUA	TG2	300	107.0	82.3	-23.7	40
BOUCHEMMA	TG1	300	107.0	82.3	-23.7	40
FERIANA	TG1	300	97.0	76.5	-19.5	40
FERIANA	TG2	300	97.0	76.5	-19.5	40
THYNA	TG1	300	105.0	80.8	-23.2	40
THYNA	TG2	300	107.0	81.9	-24.1	40
THYNA	TG3	300	107.0	81.9	-24.1	40
TOTAL			**858.0**	**656.5**	**-201.5**	

Redispatching in minimum load conditions

Considering that:

- 530 MW is the production of new non-dispatchable RES power plants;
- HVDC export to Sicily is fixed at 950 MW;

the redispatch carried out for this scenario involves also the ELMED power plant production that is decreased to its minimum value plus its regulating bandwidth, since all the other units in operation are already at their technical minimum.

On the other hand, this very binding operating mode refers to the worst possible condition for the Tunisian system, i.e. maximum non-dispatchable RES generation at the minimum loading conditions.

Numerical results

Static analyses carried out considering these two new scenarios show that:

- In sound network condition in peak and in minimum load scenarios, no voltage violations or overloads are present.
- In N-1 conditions the security criteria are fulfilled. However, two additional violations with respect to the base case are detected in peak load condition:
    - after the tripping of the double circuit 90 kV line Grombalia-Korba: the voltage at Sidi Daoued station decreases to 79.7 kV (-11.4 %);

- o the line Rades 2 – Kram 225 kV has a load factor equal to 121% after the tripping of the double circuit Goulette – Rades 2 225 kV.

However, these latter situations occur after a fault involving a double-circuit, so, strictly speaking, they refer to N-2 security operation modes.

<u>Results of the dynamic analysis</u>

The scope of this analysis is to test the dynamic behaviour of the system, starting from the scenarios (peak and minimum load conditions) deriving from static analysis.

Since from the very first simulations the voltage levels appear to be too high if the RES power plants are operated at a null reactive power exchange with the grid (power factor equal to 1), an absorption of reactive power equal to 20% of rated power has been fixed for each RES generator. It means that the power factor would be about 0.97 (lagging reactive generation).

Sensitivity analysis

This analysis consisted of the simulation of RES generation power fluctuations, due to unpredictability and variability of generation, in order to assess their influence on grid voltages and frequency.

The cases presented in Tab. 7-3 have been tested both in peak and minimum load scenarios:

Tab. 7-3 – Tested cases in dynamic analysis.

	HVDC frequency regulation	***Interconnection with Algeria***
CASE 1	NO	NO
CASE 2	YES	NO
CASE 3	NO	YES
CASE 4	YES	YES

Considering that, to evaluate the system performances, we made reference to the parameters deeply described in 6.1 and in [1]. The most important results obtained in this analysis are:

a) power fluctuations do not affect excessively the system performance, as the frequency and voltages variations remains within acceptable ranges thanks to HVDC system frequency regulation and the interconnection to Algeria.
b) lacking one of these two conditions, the situation worsen; when both the above conditions are not met, the situation becomes unacceptable as the frequency goes beyond acceptable limits .
c) If Tunisia is interconnected with the rest of Maghreb, no particular differences between peak and minimum load scenarios have been noticed (just a slight worsening, but leaving the main results unchanged), even if the penetration of non-dispatchable RES generation is pretty higher in minimum load condition (22.4% instead of 11%).
d) The effect of HVDC frequency regulation is important in both scenarios, particularly if the Tunisian grid is isolated from the rest of Maghreb (also in this case the fluctuations are generally contained in the acceptable limits).

Fault analysis

This analysis consisted in the simulation of three contingences, i.e. three-phase short circuits without fault impedance each of them having a particular scope:

- Skhira – Maknassy 400 kV : contingency near the biggest power plant of the Tunisian system: the proximity of the fault to the ELMED power plant causes important oscillations for the whole system.
- Oueslatia – Mornaguia 400 kV : contingency on the backbone of Tunisian system.
- Menzil Jemine – Bizerte 90 kV : contingence in proximity of RES power plants' connection to Tunisian system.

In order to evaluate the dynamic behaviour of RES power plants during grid faults, the inserted protections have been those described in [1], and referring to: voltage, frequency and derivative frequency.

As the frequency derivative protection from the very first simulations appeared to be a too restrictive condition and being its presence not mentioned neither in Italian Grid Code [4] nor in Spanish Grid Code [5], the same simulations have been run both with and without this protection.

The most important results obtained from the analyses are reported below:

a) The frequency derivative protections cause in every simulation the disconnection of all RES generation plants, leading to the loss of a significant generation amount (530 MW). Therefore, we recommend evaluating the possibility to avoid_the installation of frequency derivative protections[13].
b) Without frequency derivative protection, the RES power plants remain in service for almost all the contingencies. Only the fault on Menzel Jemil–Bizerte causes the disconnection for the intervention of underfrequency protection of one RES power plant: the nearest. This doesn't represent an undervoltage problem, because the fulfilment of the "fault-ride-through" characteristics (Fig. 6-3) avoids, also in this case, the intervention of this type of protection.
   In general, the tree-phase short circuit close to a RES power plant can cause its disconnection.
c) The only difference noticed between peak and minimum load scenarios has been the voltage levels, which are slightly higher in minimum load conditions. However, thanks to the RES power plants' reactive power absorption, they do not exceed the acceptable limits.
d) The HVDC frequency regulation is important for improving the system performances (in terms of frequency regulation) after a grid fault. Its beneficial effect becomes even more evident in the simulations of chapter 8, where an extreme situation has been presented.

In conclusion, considering the analyses carried out in compliance with the assumptions adopted in our study (namely the possibility of downward modulation of the ELMED power plant in low load conditions), a non-dispatchable RES generation equal to 530 MW appears adequate with the thermal

[13] Obviously, to make this choice it is necessary to compare the consequences with and without this type of protection. The installation of frequency derivative protection is aimed to protect the wind generators from all problems coming from the network in case of faults. However, the presence of this type of protection shall not become a problem for the power system operation, causing important losses of generation in case of faults (i.e. short-circuit). A compromise between these two opposite needs is necessary. The same considerations are valid for wind voltage protections: they have to comply with the fault ride through curve to avoid the disconnection of a large number of wind farms for under-voltage problems in case of short circuit.

production of ELMED power plant equal to 400 MW in low load condition. With a generating power rate of 80% of the installed capacity, the total installed renewable power would reach about 660 MW. However, if the ELMED power plant has its production greater than the assumed value equal to 400 MW, the non-dispatchable RES power generation must be reduced according to Tab. 7-1.

8 ANNEXE 1: EXTREME CONTINGENCY

In this chapter the simulation results obtained in case of an extreme contingency occurred on the Tunisian system are examined.
The event simulated consists of the following steps:

- At time t = 5 s a three phase short circuit without fault impedance occurs on Skhira-Maknassy 400 kV line: the duration of this fault is equal to 300 ms, greater than the CCT value for this transmission line;
- To avoid instability phenomena on the network, when the fault is removed, both generators of ELMED power plant are put out of service too;
- The RES power plants are equipped also with frequency derivative protections: this causes the out of service of all RES power plants a few seconds after the fault;
- When the active power flow on 400 kV tie-line with Algeria reaches about 900 – 1000 MW, the Tunisia grid is isolated because of the intervention of the protections: we assume that all tie-lines are put out of service at the same time.

The graphs reported below are referred to three different cases:

- Case 1: HVDC system with frequency regulation: it remains in service after the contingency (no remote tripping-device involves DC link);
- Case 2: HVDC system without frequency regulation: it remains in service after the contingency but it does not change the exportation to Italy;
- Case 3: the HVDC system is equipped with remote tripping-device: because of the loss of both Skhira units, both HVDC poles are put out of service.

The aim of these simulations is to point out the advantages, for the Tunisian power system, due to HVDC interconnection to Italy, considering also the presence of RES power plants.
The contingency simulated in this chapter is an extreme case that involves a cascade of events quite improbable, but it is a significant occasion to demonstrate the HVDC interconnection benefits.

Figures from Fig. 8.1 to Fig. 8.9 show the Tunisian system response after the contingency in "Case 1". In this situation the power shortfall caused by the tripping of both Skhira generators (1000 MW) and RES power plants (530 MW) causes the tripping of all tie-lines with Algeria: only the HVDC interconnection avoids the complete islanding of Tunisian electric system. Fig. 8.6 shows the active power on HVDC link: it is possible to notice that after the contingency the system reverts the power flow to control the frequency: after few seconds Tunisia starts importing from Italy to supply the lack of internal generation. This behaviour has very positive effects on frequency performances, as reported in Fig. 8.7: during the transient its minimum value is equal to about 49 Hz, but in a few seconds it increases rapidly to about 49.80 Hz. These frequency values, even if they don't avoid the first intervention of load shedding defence plan, can be considered high due to the fault cascade happening on the Tunisian system. Also the behaviours of other variables can be considered acceptable.

Figure Fig. 8.10 and Fig. 8.11 report the same fault events but considering the HVDC system without frequency regulation (opposite situation). Comparing these behaviours with those of Case 1 the advantages of HVDC regulation for the Tunisian network are evident: in this case the frequency goes down indefinitely and the collapse of whole system (even with a strong load shedding intervention) is very probable.

Fig. 8.12 and Fig. 8.13 report the same fault events considering an intermediate situation: HVDC system is equipped with a remote tripping-device and a significant lack of internal generation causes the out of service of the DC poles (in this case the tripping of both HVDC poles has been considered due to the lack of a big amount of internal generation). Comparing these results with those referred to Case 1, it is possible to point out that this is not the best solution for the Tunisian system.

In conclusion, from the simulation reported in this section we have pointed out the positive effect of the HVDC link for Tunisian system also in case of extreme contingency, i.e. lack of important internal generating power followed by the islanding of the electric system. Moreover, the simulations highlight that the best solution for the Tunisian system is to provide the DC interconnection with a frequency control avoiding remote tripping-device, which prevents the power flow inversion (and its related beneficial effect) in case of significant loss of generation.

8.1.1.1 Case 1: HVDC with frequency regulation

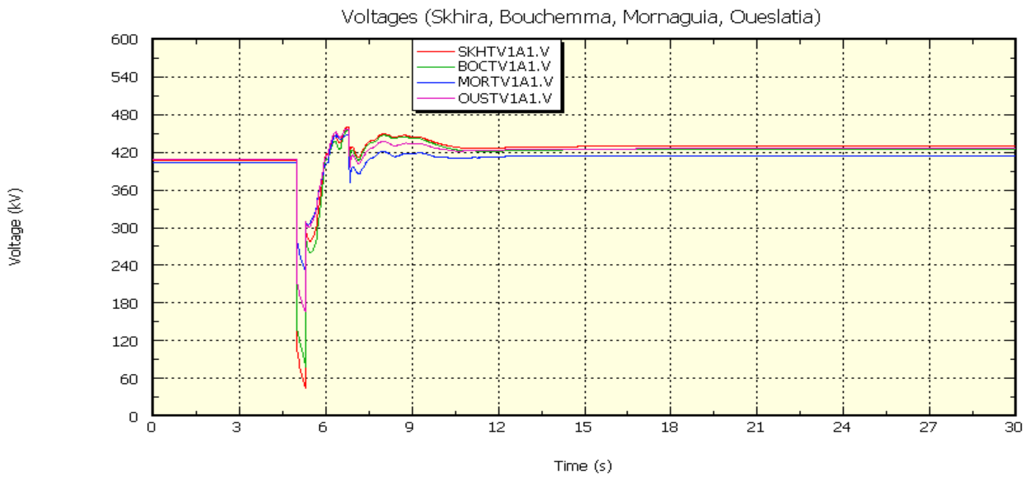

Fig. 8.1 - Peak condition, extreme contingency, 400 kV voltages (Skhira, Bouchemma, Mornaguia, Oueslatia) (Case 1).

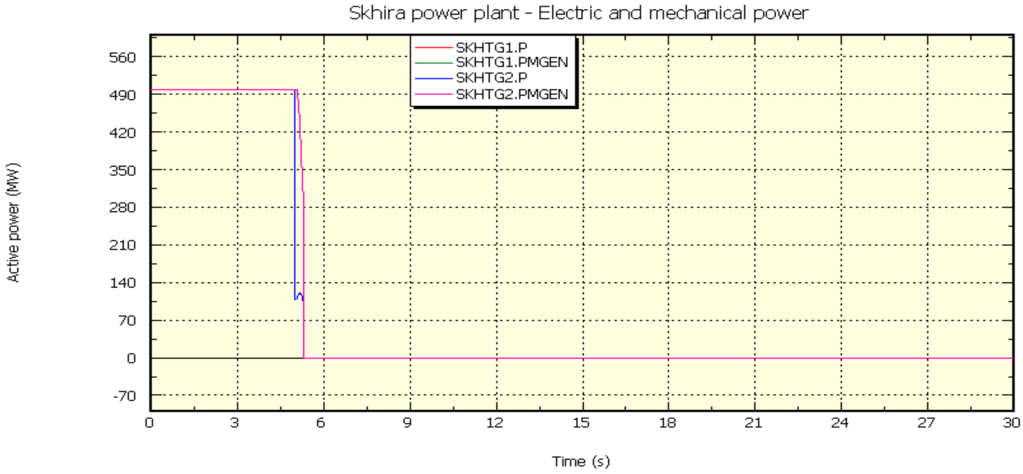

Fig. 8.2 - Peak condition, extreme contingency, electric and mechanical power of Skhira (Case 1).
Legend: P – Electric Power; PMGEN – Mechanical Power

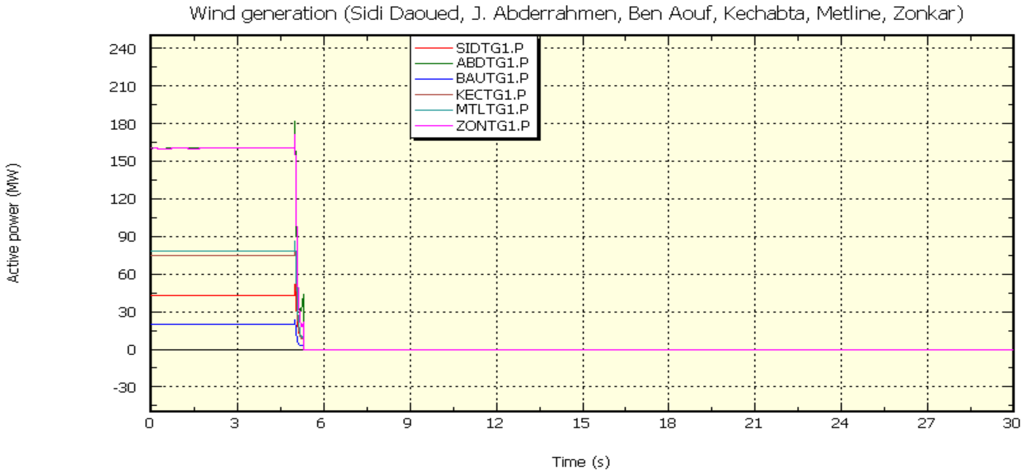

Fig. 8.3 – Peak condition, extreme contingency, RES power production (Case 1).

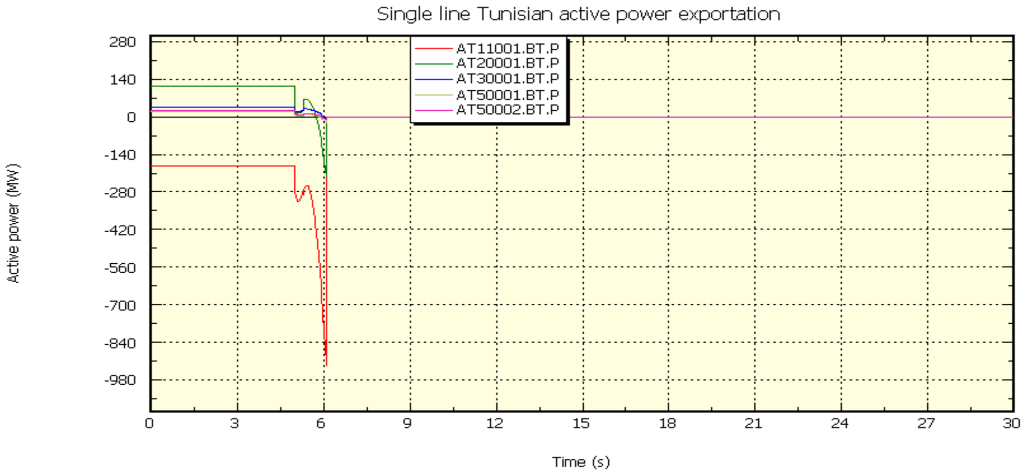

Fig. 8.4 – Peak condition, extreme contingency, single line active power exchanges (Case 1).

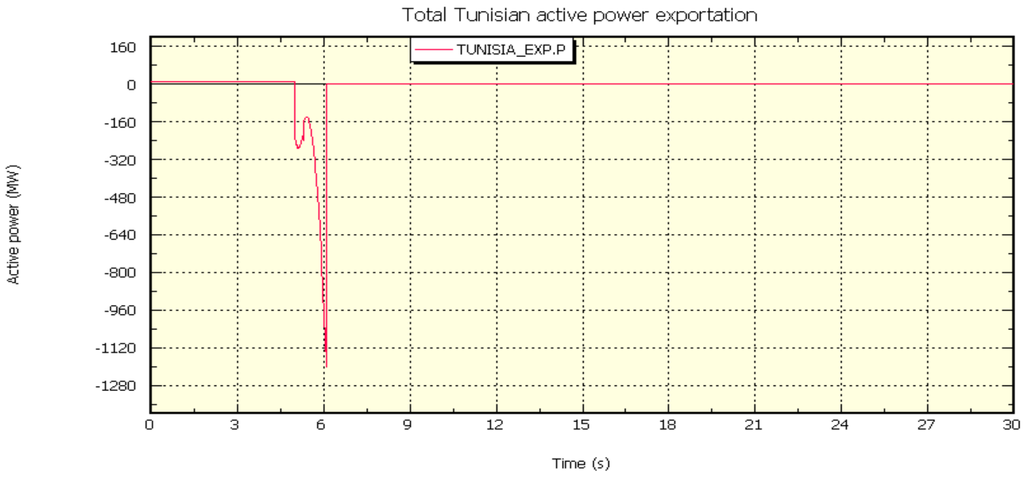

Fig. 8.5 – Peak condition, extreme contingency, total active power exchange with Algeria only (Case 1).

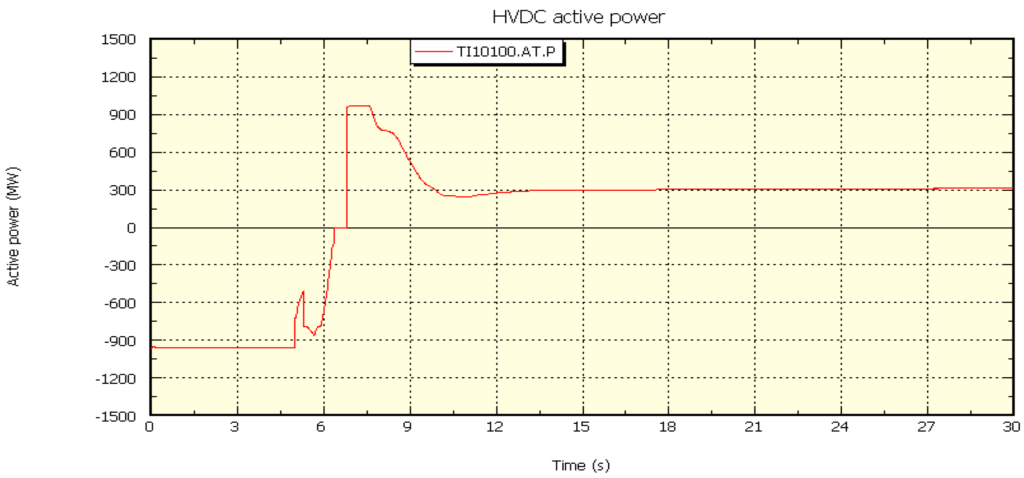

Fig. 8.6 – Peak condition, extreme contingency, HVDC active power flow (Case 1).

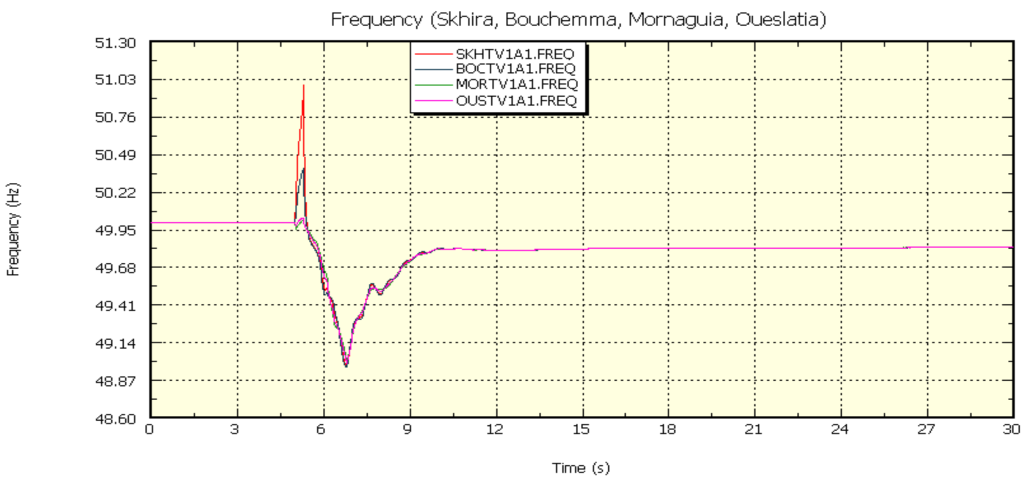

Fig. 8.7 – Peak condition, extreme contingency, system nodes' frequency (Case 1).

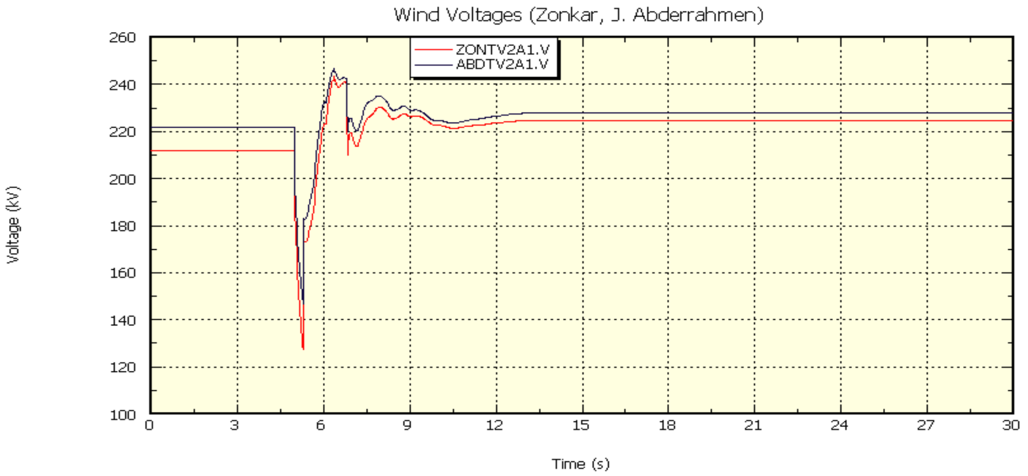

Fig. 8.8 – Peak condition, extreme contingency, RES stations' voltages (225 kV) (Case 1).

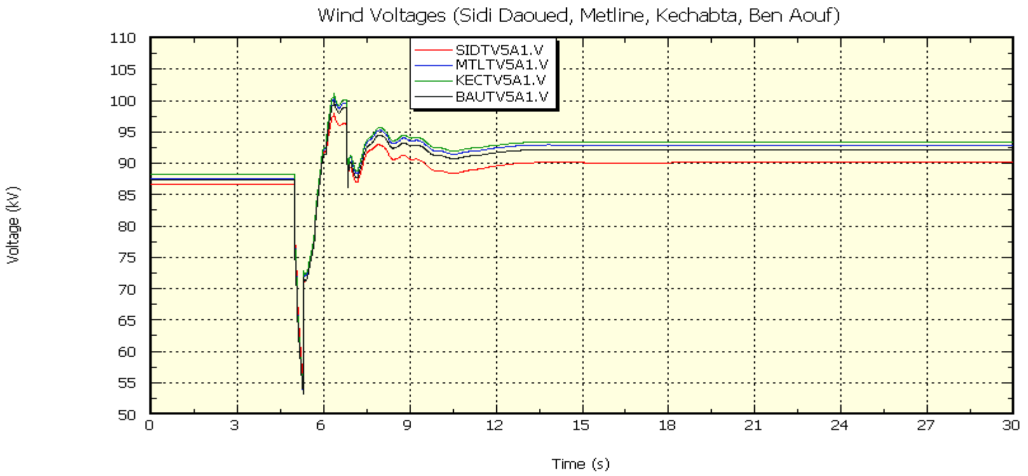

Fig. 8.9 – Peak condition, extreme contingency, RES stations'' voltages (90 kV) (Case 1).

8.1.1.2 Case 2: HVDC without frequency regulation

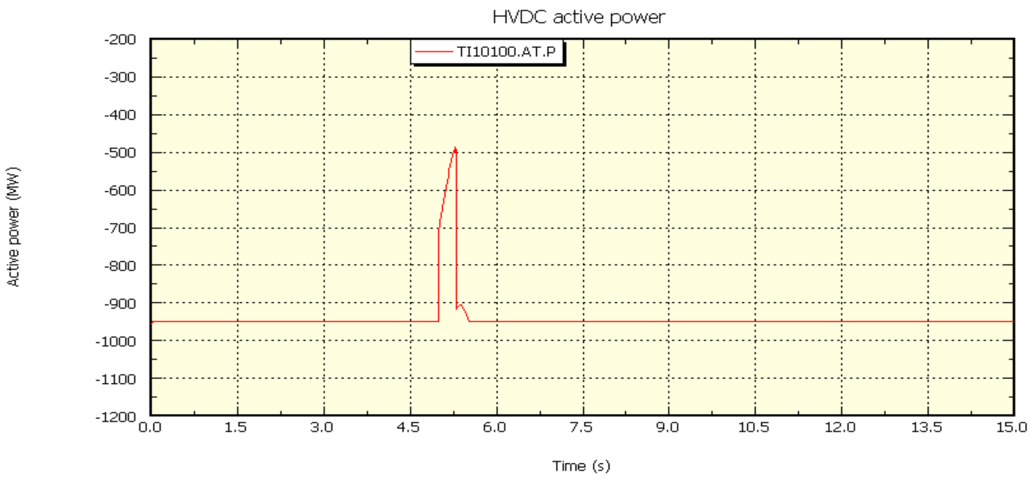

Fig. 8.10 – Peak condition, extreme contingency, HVDC active power flow (Case 2).

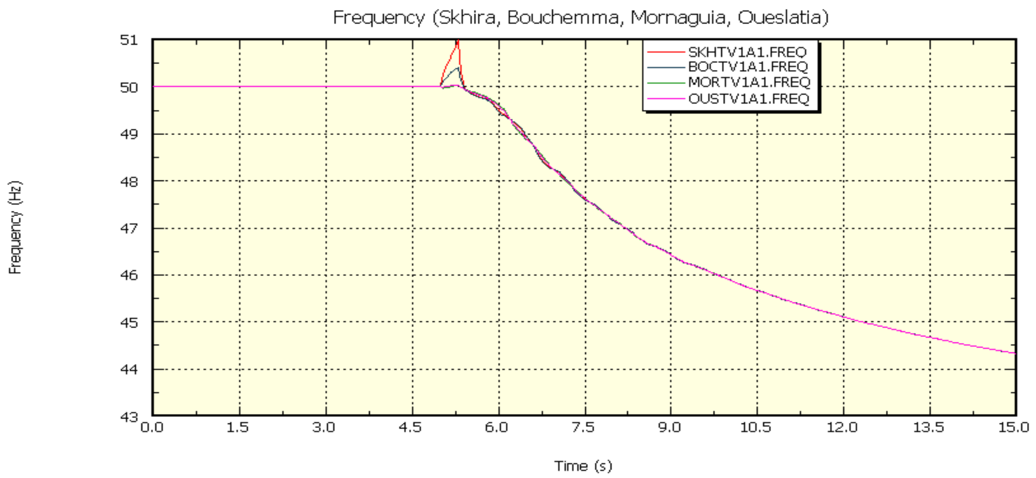

Fig. 8.11 – Peak condition, extreme contingency, system nodes' frequency (Case 2).

8.1.1.3 Case 3: HVDC with remote tripping-device

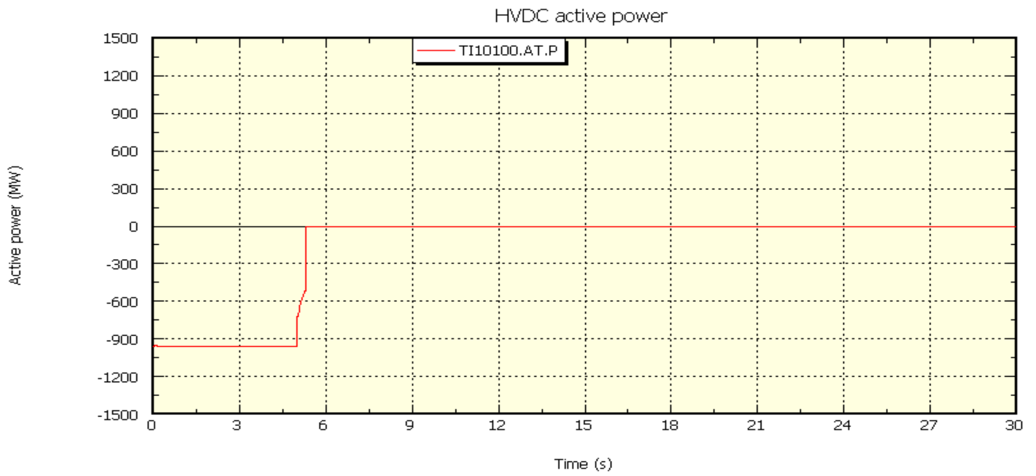

Fig. 8.12 – Peak condition, extreme contingency, HVDC active power flow (Case 3).

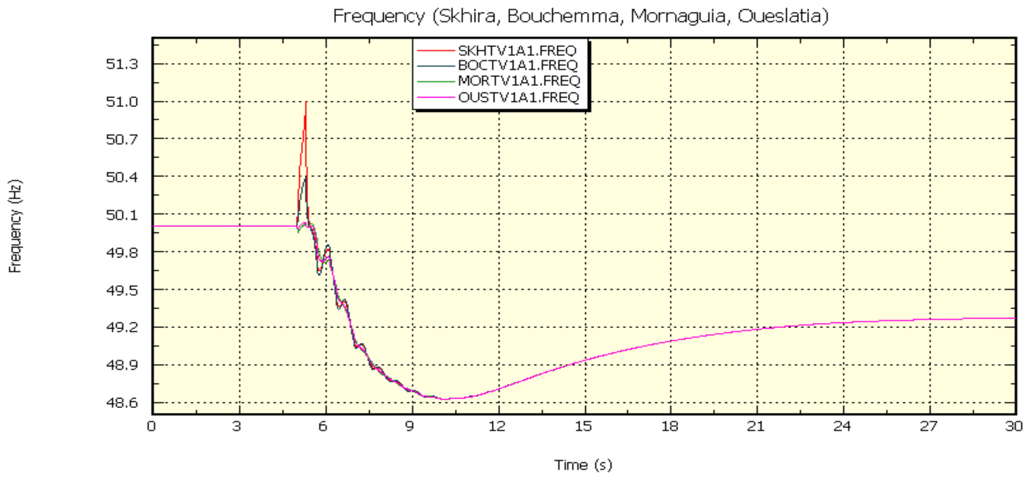

Fig. 8.13 – Peak condition, extreme contingency, system nodes' frequency (Case 3).

9 ANNEXE 2: BEN AOUF WIND FARM

The figure below show how the frequency of Ben Aouf wind farm decreases to a value much lower than the acceptable limit. This is the reason for the intervention of minimal frequency protection.
<u>Note: Fig. 9.3 and Fig. 9.4 show that during the transitory, the frequencies are different for each node of the network; only in state conditions the frequency is the same in all network stations.</u>

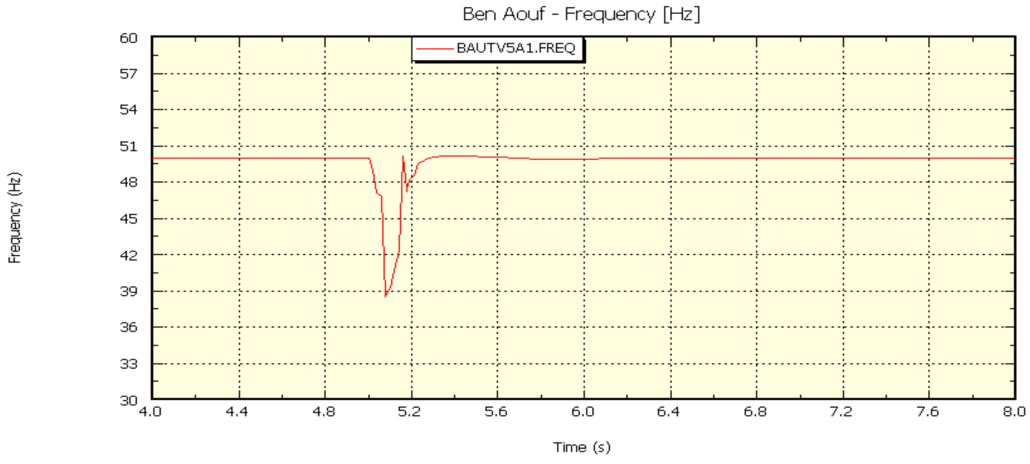

Fig. 9.1 – Peak load conditions, fault analyses, Ben Aouf frequency

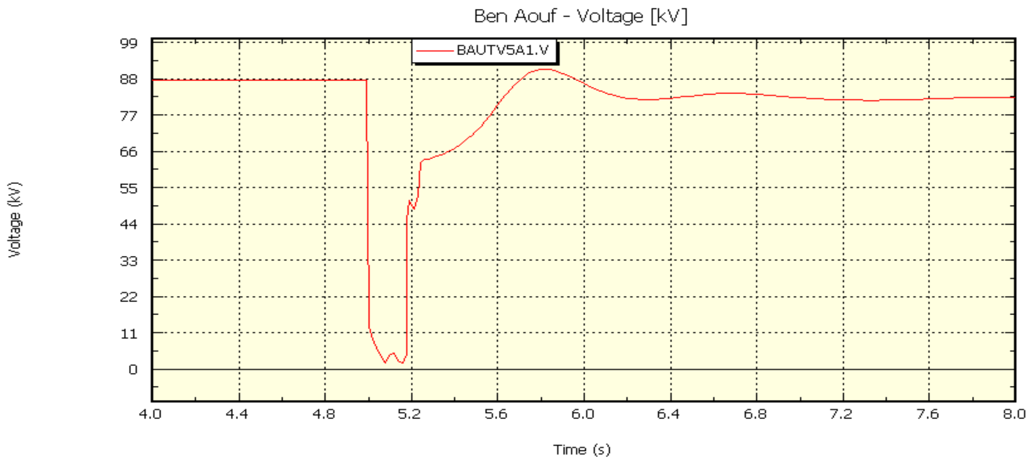

Fig. 9.2 – Peak load conditions, fault analyses, Ben Aouf voltage.

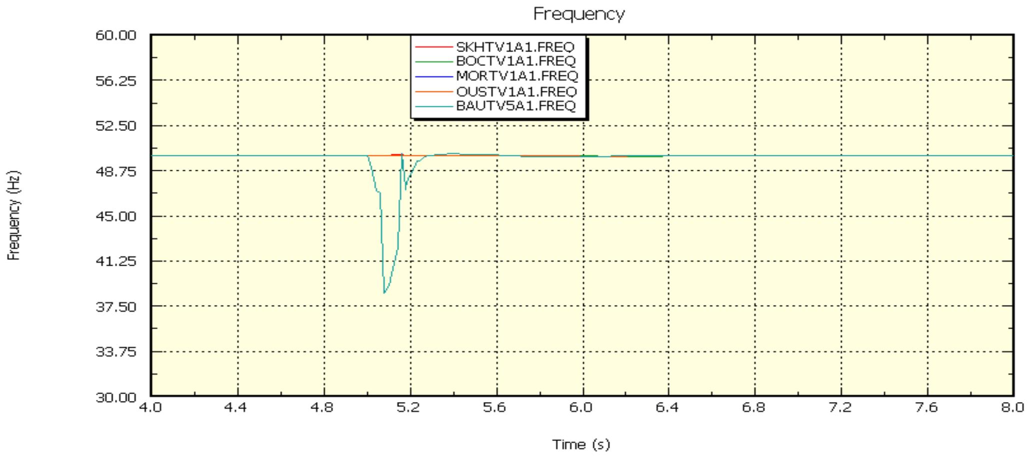

Fig. 9.3 – Peak load conditions, fault analyses, frequencies.

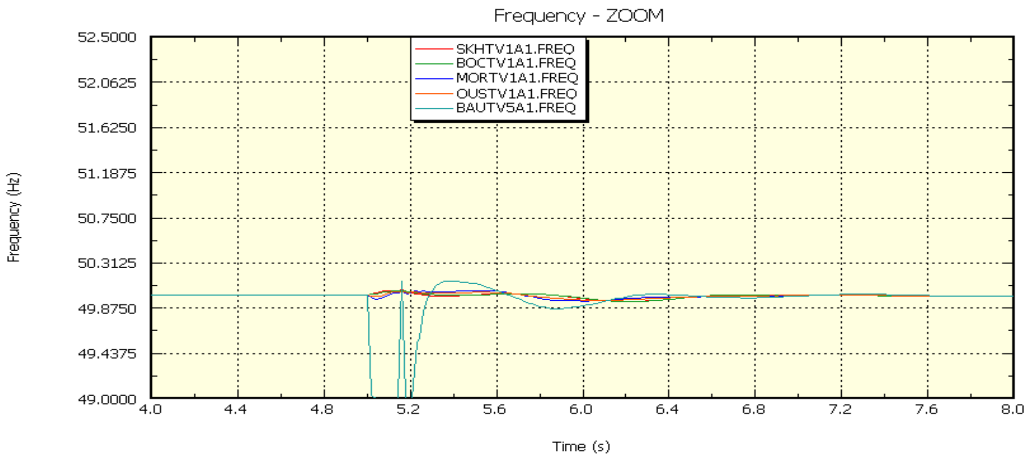

Fig. 9.4 – Peak load conditions, fault analyses, frequencies (ZOOM).

10 REFERENCES

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