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 B : reinforcements of the Tunisian transmission system grid following the commissioning of the ELMED production cluster and the HVDC interconnection Tunisia-Italy

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GLOSSARY

AC : Alternate Current

ATR : Auto-transformer

AVR : Automatic Voltage Regulator

BIL: Basic Insulation Level

CCGT : Combined Cycle Gas Turbine

CCT : Critical Clearing Time

DC : Direct Current

ENTSO-E/SCR: European Network of Transmission System Operators of Electricity/Synchronous Continental Region (European interconnected system, previously called UCTE)

ESCR: Effective Short Circuit Ratio

HVDC : High Voltage Direct Current

PSS : Power System Stabiliser

RES : Renewable Energy Source

1 SCOPE OF THE ANALYSIS

According to the work plan the first set of analyses addresses the impact on the Tunisian transmission system due to the commissioning of the new ELMED power plant (or "ELMED Production Cluster"). These analyses refer to Task B of the overall study (see [1]).
More specifically, the analyses will highlight the reinforcements needed on the Tunisian grid in terms of new lines and interconnection transformers in order to fulfil the static and dynamic criteria recalled in [1]. To this aim, two extreme operating conditions will be examined referred to the peak and minimum load forecasted at the year 2016.

2 SUMMARY OF THE STUDY PROCESS FOR TASK B

The study process follows the methodology illustrated in [1] (see par. 3.1) and is here summarised with some additional details.

The study is basically split in two phases:

a) *screening phase* (see "Step 3" of the methodology) where we examine the needed reinforcements following the commissioning of the new ELMED Production Cluster. Four different alternatives for the location of this new power plant are examined:

- El Hawaria with a CCGT rated 3x400 MW ;
- Bizerte with coal fuelled units rated 2x660 MW ;
- Skhira with coal fuelled units rated 2x660 MW ;
- Enfidha with coal fuelled units rated 2x660 MW.

At this stage, static analyses only are carried out.
Two generation levels of the ELMED power plant are examined:

- 400 MW to supply the *internal demand in Tunisia*. The possible reinforcements necessary for the evacuation of this power generation are dictated by the expected load growth in Tunisia;
- 1200 MW to supply the *internal demand in Tunisia* and to *export the surplus to Sicily*. The additional reinforcements with respect to the previous case are closely linked to the commissioning of the HVDC interconnection towards Sicily. These additional reinforcements shall warrant a power exchange with Sicily up to 1000 MW, which is the target rating of the submarine interconnection in bipolar configuration.

The possible reinforcement possibilities for the four ELMED power plant location have been supplied by STEG trough ELMED Etudes and are depicted in the following table (Tab. 2-2). As far as possible, priority is given to the reinforcements at the 400 kV level, representing the new power corridor across Tunisia.
As for the new lines, the following transmission capacities and electrical parameters are adopted (Tab. 2-1).

Tab. 2-1– Transmission capacity and electrical characteristics of the new lines (source STEG)

Voltage and mechanical characteristics	R (Ω/km)	X (Ω/km)	C (nF/km)	In (A)	S (MVA)
400 kV Almelec 2x570 mm^2	**0,0292**	**0,3311**	**12,19**	**1540,8**	**1067**
220 kV -411 mm^2 Alu-Ac	**0,088**	**0,417**	**8,28**	**620**	**242**
150 kV -411 mm^2 Alu-Ac	**0,088**	**0,417**	**8,28**	**620**	**161**

Whenever two or more reinforcement alternatives fulfil the security constraints, the adopted ranking criterion is the following (elements in order of priority):

a) length of additional lines;
b) number of additional interconnecting transformers;
c) losses at peak conditions;
d) other issues such as: environmental impact (referred to the number of right-of-ways for new lines), ESCR at El Hawaria converter station.

At the end of this screening phase the more binding solution will be chosen according to the previous ranking criterion. The selected location of the new ELMED power plant and related network structure with reinforcements will be used for the dynamic analyses.

b) *Detailed analysis phase* (see “Step 4” of the methodology) where we examine the performance of the Tunisian production and transmission system in dynamic conditions. This set of analyses will highlight the minimum conditions to comply with the dynamic constraints of the Tunisian system interconnected with the rest of Maghreb and in presence of the HVDC interconnection to Sicily.
The expected results are relevant both to the maximum size of the ELMED generating units acceptable by the Tunisian system and / or to possible operation restrictions namely on the power interchange (see [1] for more details) in order to cope with possible tripping of the ELMED generating units.

Tab. 2-2 – List of candidate reinforcements for the power evacuation from the ELMED power plant

Site ELMED	Lines	Transformer substations
Hawaria	- Ligne Hawaria – Mornaguia 400 kV - 150 km - Ligne Hawaria – Oueslatia 400 kV - 280 km	- 3ème ATR 400/225 kV – 400 MVA à Mornaguia - 2ème et 3ème ATR 400/225 kV - 400 MVA à Oueslatia
Bizerte	- Ligne Bizerte – Mornaguia 400 kV – 110 km - Ligne Bizerte –Mateur 400 kV - 60 km - Ligne Bizerte –Jendouba 400 kV - 120 km - Ligne Bizerte – Mnihla 400 kV – 110 km - Ligne Bizerte – Hawaria 400 kV – 250 km	- 3ème ATR 400/225 kV – 400 MVA à Mornaguia - 2ème et 3ème ATR 400/225 kV - 400 MVA à Jendouba - 2ème et 3ème ATR 400/225 kV - 400 MVA à Mateur - 3ème ATR 400/225 kV – 400 MVA à Mnihla
Skhira	- Ligne Skhira – Oueslatia 400 kV – 230 km - Ligne Skhira – Bouchemma 400 kV - 70 km - Ligne Skhira – Mornaguia 400 kV - 350 km - Ligne Oueslatia – Bouchemma 400 kV - 280 km - Ligne Skhira – Hawaria 400 kV - 410 km - E/S ligne Bouchemma – Sidi Mansour 225 kV – 20 km - E/S ligne Bouchemma – Oueslatia 400 kV au poste de Skhira – 25 km et ligne de ce poste à la centrale de Skhira : Oueslatia-Shkira 245 km et Bouchemma-Skhira 85 km - Ligne Skhira – Maknassy 400 kV - 70 km - Ligne Oueslatia – Maknassy 400 kV – 180 km - Ligne Maknassy – Bouchemma 400 kV - 120km	- 2ème et 3ème ATR 400/225 kV - 400 MVA à Bouchemma - 2ème et 3ème ATR 400/225 kV - 400 MVA à Oueslatia - 3ème ATR 400/225 kV – 400 MVA à Mornaguia - 3ème ATR 225/150 kV – 100 MVA à Sidi Mansour - Poste 400/225 kV à Oueslatia (à priori, aucune contrainte de travée et d'ATR)
Enfidha	- Ligne Enfidha – Mornaguia 400 kV – 100 km - Ligne Enfidha – Oueslatia 400 kV - 110 km - Ligne Mornaguia –Oueslatia 400 kV - 130 km - Ligne Enfidha – Hawaria 400 kV - 150 km	- 3ème ATR 400/225 kV – 400 MVA à Mornaguia - 2ème et 3ème ATR 400/225 kV - 400 MVA à Oueslatia

3 SETTING UP AND VALIDATION OF THE BASIC CONFIGURATIONS

The first part of the activity consisted of the setting up of the production-transmission model for the two basic configurations (minimum and maximum load at the year 2016) and for the overall Maghrebian interconnected system up to the border with ENTSO-E system, which is also taken into account, though in an equivalent form (see "Steps 1 and 2" of the methodology).
Starting from the model of the Tunisian system in isolated configuration, the following actions have been undertaken:

- joining of the production-transmission model of Tunisia to the rest of Maghreb (Algeria and Morocco) and the ENTSO-E system, this latter represented by and equivalent unit and load. Slack bus is represented by the ENTSO-E equivalent that has a much predominant size with respect to Maghreb. Two different models are used for the equivalent of the rest of Maghreb and ENTSO-E: equivalent models in peak condition and in minimum load condition.
  The coherency checks of the overall interconnected system with respect to the model of Tunisia stand-alone addressed:
    - voltage profile;
    - active power flows and losses;
    - total cross-border power exchanges, which turn out to be negligible (conditions of null power exchanges).
- Introduction of the AC/DC converter station at El Hawaria:
    - HVDC converter station and connection modelled according to what illustrated in [1];
    - Connection from the converter station to the Tunisian system:
        - One 400 kV line El Hawaria-Mornaguia;
        - A second 400 kV outcoming from El Hawaria and having its second end depending on the location of the ELMED power plant.

  Note: the HVDC link is connected to the rest of the Tunisian system always with two 400 kV lines to comply with the N-1 security criterion.

As for the static analyses, the load flow analysis has been carried out both in peak load and in off-peak load conditions with the generation dispatch described in paragraph 5.2 of [1] referred to the horizon year 2016.
Static security analysis with the deterministic criterion of N-1 has been applied: in particular outages of 400, 220 and 150 kV lines or autotransformers have been considered. These contingencies have indeed the higher influence to evaluate the impact of the new ELMED power plant and HVDC link on the network. In the static analysis, the outage of generating units and their step-up transformers aren't considered; the same holds true also for loads in radial configuration that is loads fed along one path only. These contingencies in fact will be analysed better during the dynamic study.
Here below, results and remarks are mainly referred to the 400/220/150 kV network. N and N-1 constraints are checked against the operating criteria indicated by STEG; particularly, in static conditions the following constraints are considered:

- sound network conditions (N security)
    - no overloads of lines and transformer
    - voltage has to be within the range ±7%, that is:
        - 372 ÷ 428 kV on the 400 kV level
        - 205 ÷ 235 kV on the 220 kV level

        - 140 ÷ 161 kV on the 150 kV system
    - Reactive power production of the generators within the limits of capability.
- N-1 operating conditions:
    - Overload limits:
        - Lower than 20 % of the current limits of lines;
        - Lower than 20 % of the rated power of transformers;
    - Voltage deviation limits within ±10%, that is:
        - 360 ÷ 440 kV for the 400 kV nodes;
        - 198 ÷ 242 kV for the 220 kV nodes;
        - 135 ÷ 165 kV for the 150 kV nodes;
    - Reactive power production of the generators within the limits of capability.

Computations have been carried out with SPIRA package.

3.1 Coherency checks in basic conditions (static analyses)

3.1.1 Peak load condition

In the base case of peak load condition, total demand is 3960 MW while total losses are 48 MW, as Fig. 3.1 shows; total Tunisian generation is therefore slightly higher than 4000 MW.
This and all next schemes show a reactive import or export from Tunisia. As a matter of fact, when Tunisian grid is interconnected with Algeria, a small active and reactive loop flow id present. The reactive power, in particular, is linked to the very low loading level the cross-border lines.

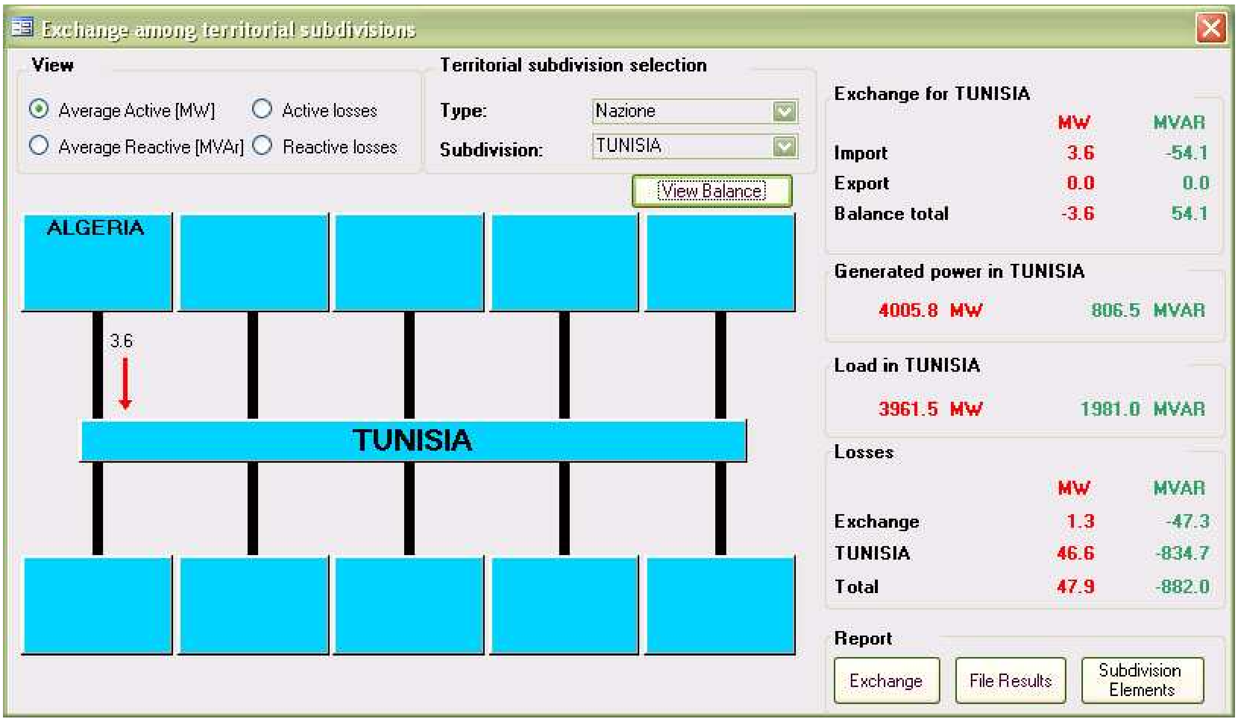

Fig. 3.1 - Peak condition, base case - International exchanges and power balances for the Tunisian grid.

In sound network condition, no voltage violation or overloads are present on the Tunisian network.
Constraints are also met in the N-1 condition. In this situation, we recall that the voltages in Tajerouine and Kasserine Nord 150 kV are at the maximum acceptable limit in case of loss of the 150 kV line

Kasserine Nord – Kasserine: in this case the above mentioned substations are supplied by the 220/150kV transformer of Tajerouine. Also in Rades 150 kV the voltage is slightly high at the occurrence of the tripping of the 150 kV line Hammamet – Rades. Slight voltage limit violations and a light overload has been detected at the 90 kV level in the area of Grombalia when applying a double contingency consisting of the tripping of the two 90 kV circuits Grombalia-Korba[1]. Anyway, this double contingency exceeds the basic security criterion adopted by STEG and furthermore these limited violations can be easily solved with local measures.

3.1.2 Minimum load condition

The minimum load condition in the base case is characterized by a total demand of 1400 MW supplied by the Tunisian generation, as shown in Fig. 3.2; no DC link is present in this scenario so the power exchange with Italy is null.

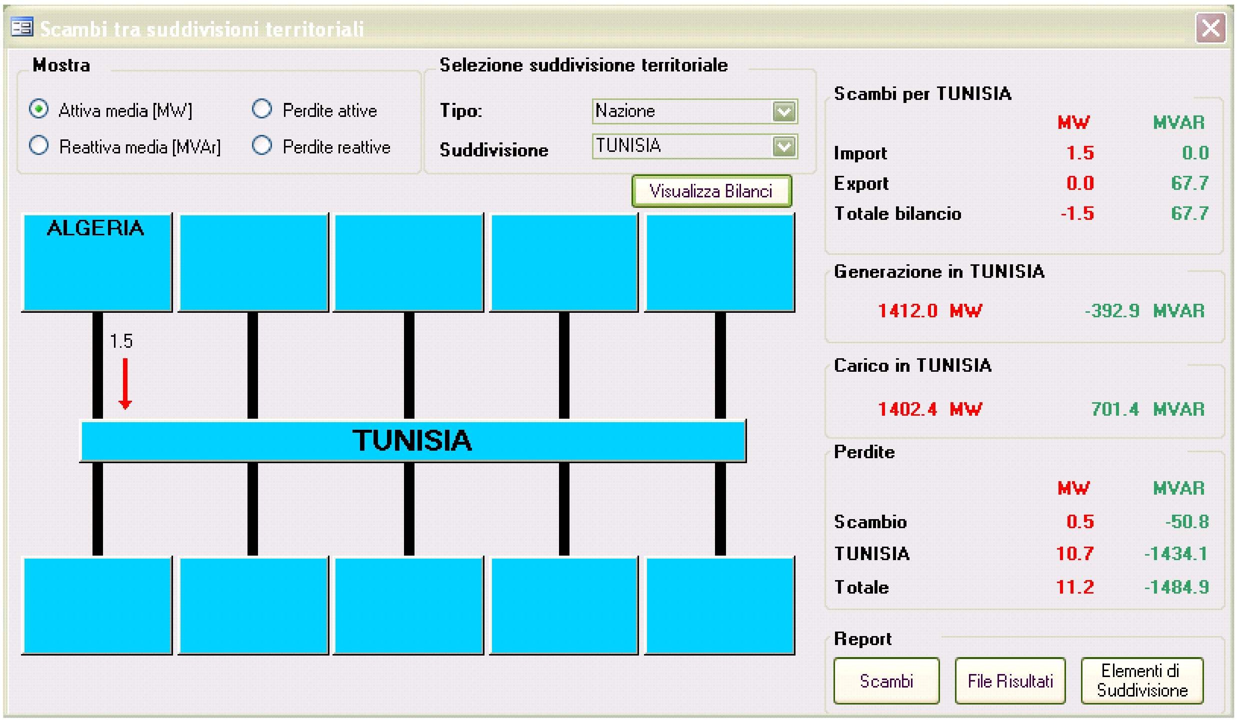

Fig. 3.2 - Off peak condition, base case - International exchanges and power balances for the Tunisian grid.

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. The analysis in N-1 condition shows an overvoltage in Bouchemma 400 kV in case of out-of-service of the 400/220 kV transformer of the station. However the voltage in the node is quite high (424 kV) also in N condition. It is interesting to observe that on the 220 kV level a 20 Mvar reactor is present: thus, the loss of the interconnecting transformer increases the voltage level on 400 kV level.

[1] Like in previous studies on Tunisian network, we considered the double circuit lines as single elements, so this represents a N-1 condition assuming the tripping of one circuit may cause the simultaneous tripping also of the remaining circuit on the same electric tower.

Tab. 3-1 - "N-1" security analysis results: voltage violations

Contingency		**Vn (kV)**	**Violation**	**Vn (kV)**	**V_N (kV)**	**V_{N-1} (kV)**	**ΔV (%)**
BOUCHEMMA	BOUCHEMMA	400/220	BOUCHEMMA	400	423.8	453.8	13%

The first remark is on the voltage profile in Bouchemma: it is quite high also in sound network condition and it is possible therefore to tune the reactor on the 220 kV level.
Then, when the 400/220kV transformer is lost, Bouchemma 400 kV is connected in radial configuration on Oueslatia; if also the line is opened, no critical conditions are present on the network.

4 IMPACT OF THE ELMED PRODUCTION CLUSTER ON THE TUNISIAN TRANSMISSION SYSTEM: SCREENING ANALYSIS

This chapter presents the results of the screening analysis applied to the four possible sites of the ELMED power plants. Static analyses consist of load flow calculations to identify the minimum network reinforcements as well as ESCR[2] computations in some network configurations, which might present a too weak short circuit power at the El Hawaria converter station. This parameter is not bounded to harmonic analysis but only to voltage control capacity and it is not directly used to the choice of ELEMD power plant but it is influenced by this choice: higher is its value and stronger is the capacity of voltage control in the station.

For all the alternatives, the analyses are carried out distinguishing the two cases:

- 400 MW ELMED power plant production to satisfy the internal Tunisian needs (only one generating unit in service);
- 1200 MW ELMED power plant production, including the 800 MW power export through the HVDC connection with Italy.

To comply with the N-1 security criterion, all the proposed solutions will be characterised by at least two connections between the ELMED power plant and the Tunisian transmission system. As mentioned above, the same criterion is adopted for the connection of the AC/DC converter station in El Hawaria to the rest of the Tunisian grid. Whenever possible, the new lines will be proposed at 400 kV level.

Note 1: in the peak load conditions, the fictitious CCGT in Aousdja included in the input data base provided by STEG through ELMED Etudes was eliminated and replaced by the new units of the ELMED

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[2] The “strength” of the AC network in correspondence with the converter station can be evaluated by means of the ESCR parameter (Effective Short Circuit Ratio), which is defined as:

$$ESCR = \frac{S_{CC} - Q_C}{Pn_{DC}}$$

where:

S_{CC}	short circuit power in MVA in the node of the converter station;
Q_C	the reactive power of the filters/capacitors;
Pn_{DC}	the rated power of the HVDC link.

This parameter, unlike SCR (Short Circuit Ratio) = S_{CC}/Pn_{DC}, considers the filters connected to the AC node of the converter station, which cause a reduction of the short circuit level.

A low ESCR level indicates a stronger interaction between the HVDC station and the AC network, and usually reveals the need for special control strategies such as the Static Var Compensator (SVC), or a non-standard project of the converter station, e.g. the need for an increase of reactive power produced by filters/capacitors and their division into small size banks. The availability of a high ESCR (“strong” network) limits voltage oscillations due to the AC network or the variations of DC power. In particular:

- ESCR > 3 means a “strong” system
- ESCR < 2 “weak” system means

ESCR values lower than 2 normally require special means of reactive compensation (e.g. SVC), while for intermediate ESCR values, between 2 and 3, the need for flexible compensation devices must be verified with dedicated studies.

ESCR evaluation is normally performed considering minimum short circuit power situations. The maximum short circuit level, on the contrary, considering the capacity of the modern thyristor valves does not cause worries.

power plant. Hence, in peak conditions two operating situations have been examined:

a) the ELMED power plant generating 400 MW only for supplying the internal load in Tunisia;
b) the ELMED power plant generating 1200 MW, out of which 800 MW are dedicated to the export to Sicily.

Note 2: in the minimum load conditions, we assume a full load of the HVDC link (1000 MW) for power export to Sicily, which allowed testing the system behaviour in the weakest configuration of the Tunisian system. The corresponding generation is produced by the ELMED power plant. The unit commitment inside Tunisia and related power dispatch has not been changed.

4.1 ELMED power plant in Bizerte

In this alternative the ELMED power plant is situated in the area of Bizerte and it's composed of two coal generating units, each of them with a rated power of 750 MVA.
Since different solutions to evacuate the power from this power plant are proposed, each of those is tested distinguishing the two cases above mentioned (400 MW for internal needs in Tunisia and 1200 MW including also the power export).
With reference to the possible connection alternatives (see Tab. 2-2), the following three solutions are examined for the connection of the ELMED power plant in Bizerte.
To fulfil the N-1 security criterion, solutions "A" and "B" are characterised by two 400 kV lines connecting El Hawaria to Mornaguia, while in solution "C" one 400 kV line connects El Hawaria to Mornaguia and the second one connects directly Bizerte to El Hawaria.
In the analyses, when the power export is zero, the relevant lines connecting El Hawaria to the Tunisian system are kept out of service whenever possible.

Tab. 4-1 – ELMED power plant in Bizerte : connection alternatives

SOLUTION "A"	line from Bizerte to Mateur
	line from Bizerte to Mornaguia
SOLUTION "B"	line from Bizerte to Mateur
	line from Bizerte to Mnihla
SOLUTION "C"	line from Bizerte to Mateur
	line from Bizerte to El Hawaria

4.1.1 Bizerte: peak load conditions

4.1.1.1 Power generation to supply the internal load in Tunisia (400 MW)

SOLUTION "A"

In *Fig.4.1* the international exchanges and the internal power balances are represented. The total exchange with Algeria is close to zero, and as the HVDC connection is disconnected, there's no power export to Italy.
Fig.4.2 shows the active power flows on the new lines and their average loading[3]. The reactive power flows are not reported because they are not the focus of the analysis and they depend by many variables

[3] It is calculated as the ratio between the actual and the maximum current of the line.

such as the voltage set points of generators and the reactive compensations that have not been optimized. The effect of current increase is obviously considered in the calculation of average loading.

The power produced by ELMED power plant distributes itself pretty equally on those two connections, causing about 20% loading. Even if this value appears to be too low, both the lines are necessary in order to avoid the disconnection from the grid of the power plant, in case of fault on one of them.

A “N-1” security analysis has been carried out as well, but no violations or overloads have showed up. Therefore, this solution is technically feasible from the static point of view.

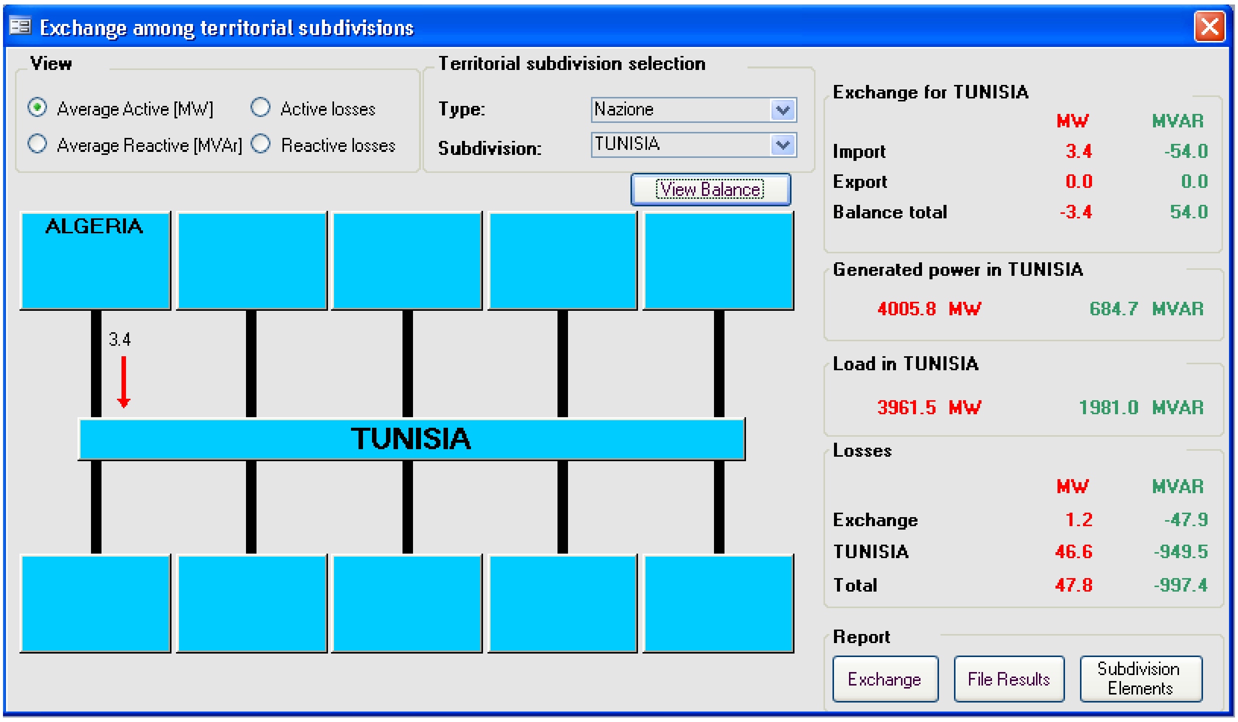


Fig.4.1 - 400MW case - International exchanges and power balances for the Tunisian grid.

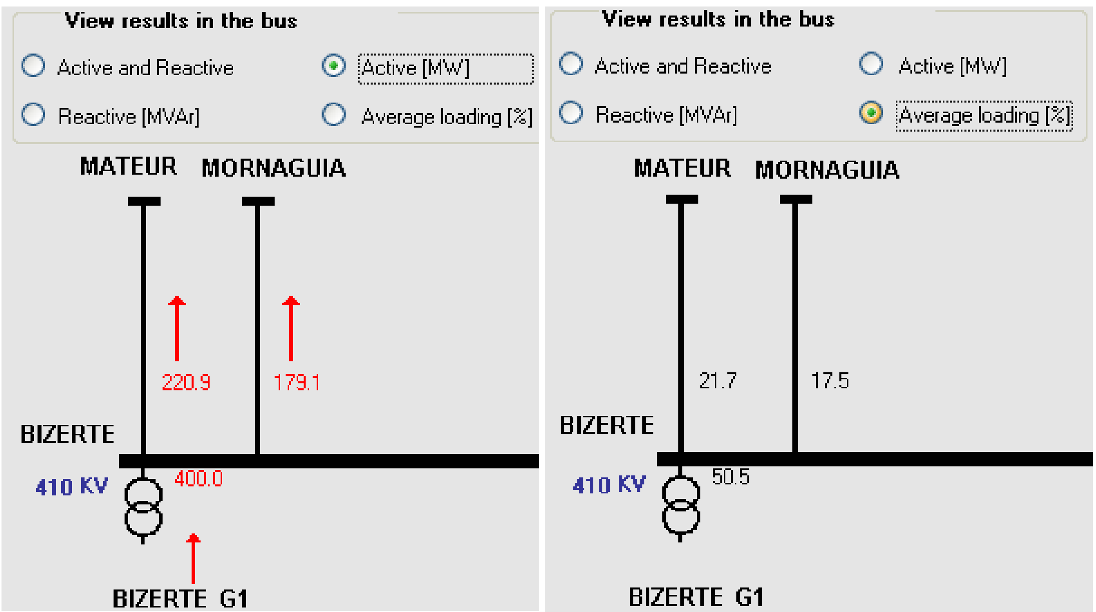


Fig.4.2 - 400MW case - Power flows and average loading on the two new 400kV connections.

SOLUTION "B"

As already described in solution "A", the balance between import and export is close to zero and almost no additional loss of power in comparison to the first solution occurs (*Fig.4.3*).

The power flows on the new lines (*Fig.4.4*) are similar to those of solution "A", and no remarkable difference has been noticed.

Also with the "N-1" security analysis the same results have been obtained.

Therefore, this solution is technically feasible from the static point of view.

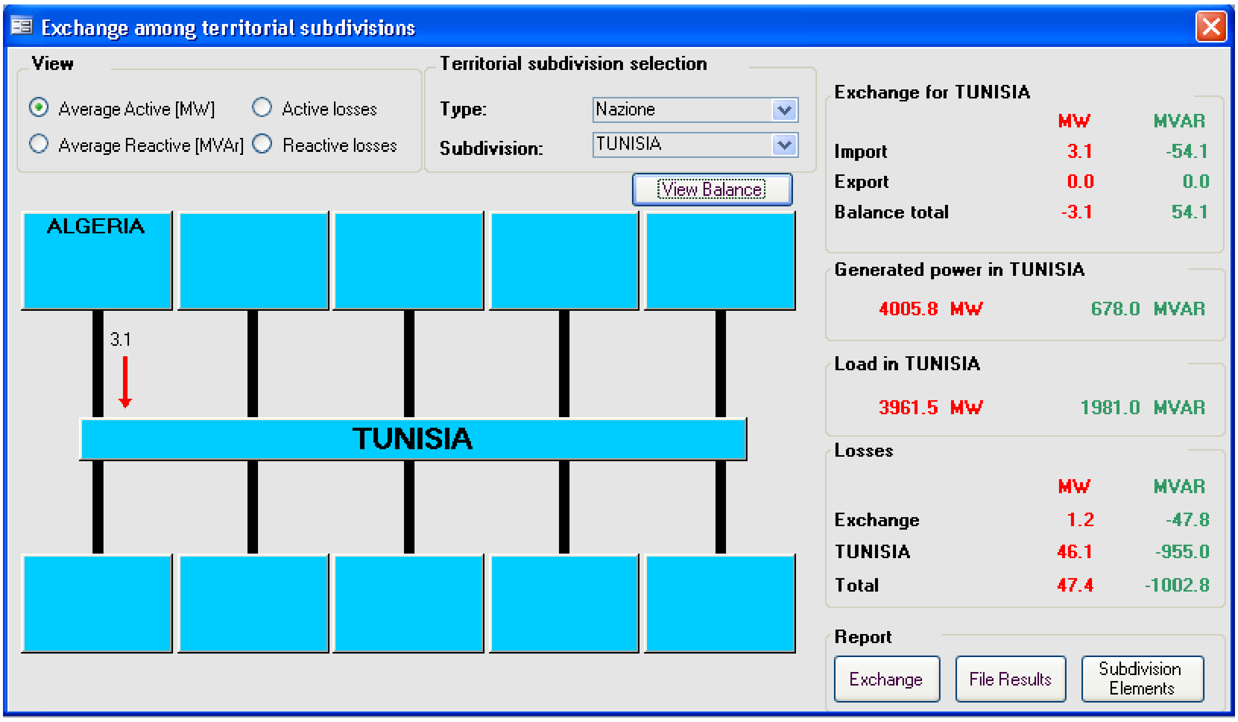


Fig.4.3 - 400MW case - International exchanges and power balances for the Tunisian grid.

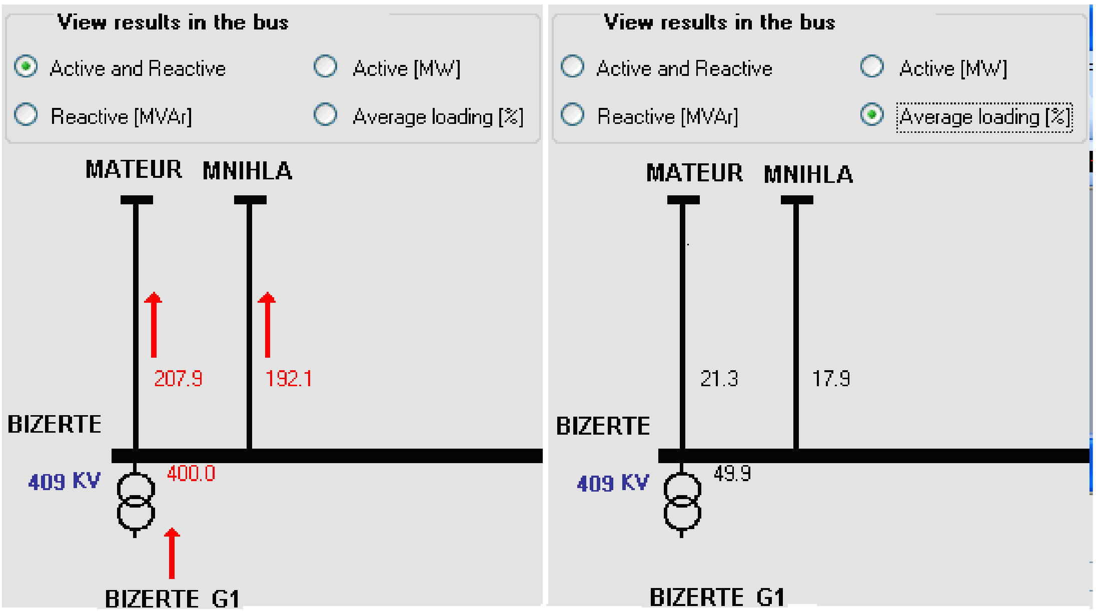


Fig.4.4 - 400MW case - Power flows and average loading on the two new 400kV connections[4].

SOLUTION "C"

As this solution provides a direct connection from Bizerte to El Hawaria, only one 400kV connection between El Hawaria and Mornaguia has been added.

Whilst the power balances (*Fig.4.5*) remains quite similar to those already discussed (the active power losses increase slightly), the power flows on the new lines is differently distributed (*Fig.4.6*). The Bizerte-Mateur connection is more loaded than before (30%), while the one to El Hawaria has an average loading lower than 15% due to its higher impedance.

The "N-1" security analysis hasn't provided any remarkable result.

This solution is also technically feasible, though with slightly higher losses and an uneven distribution of the power outgoing from the ELMED power plant in Bizerte.

[4] Note: reactive power flows are implicitly considered in the evaluation of the average loading of the line, displayed in the various schemes; they are closely related to the local conditions and are not optimised in our study targeting the transfer capacity of active power.

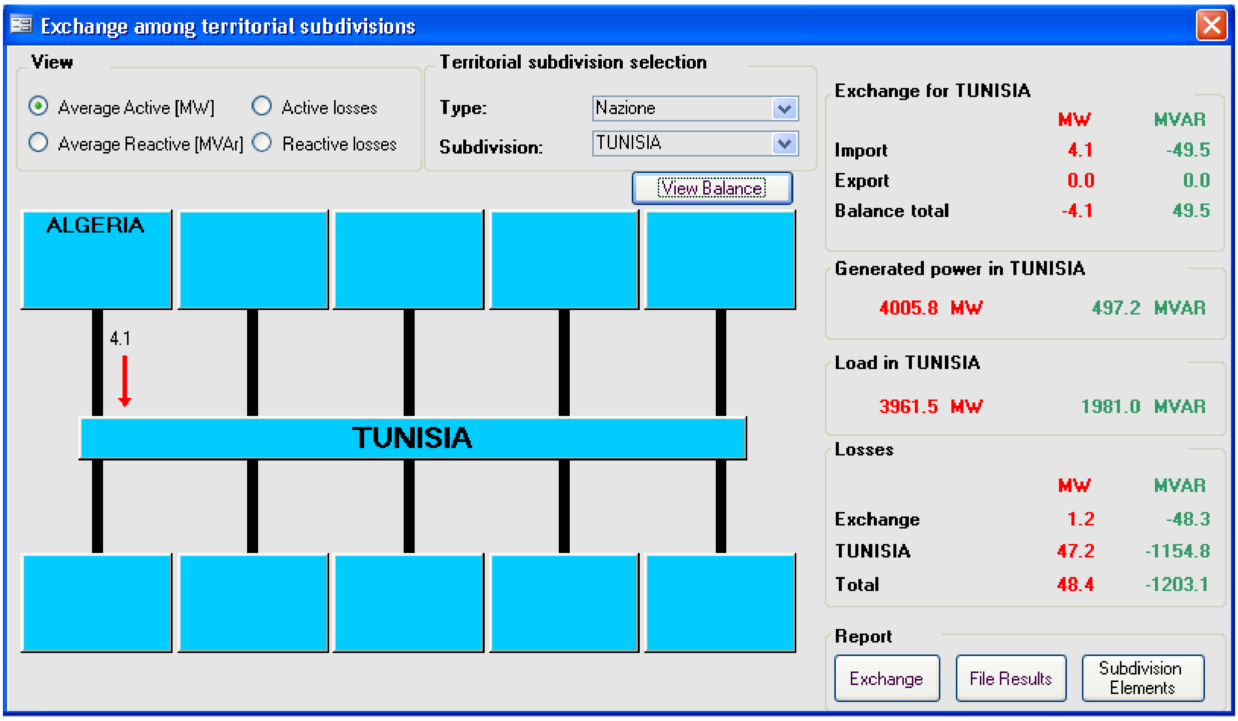


Fig.4.5 - 400MW case - International exchanges and power balances for the Tunisian grid.

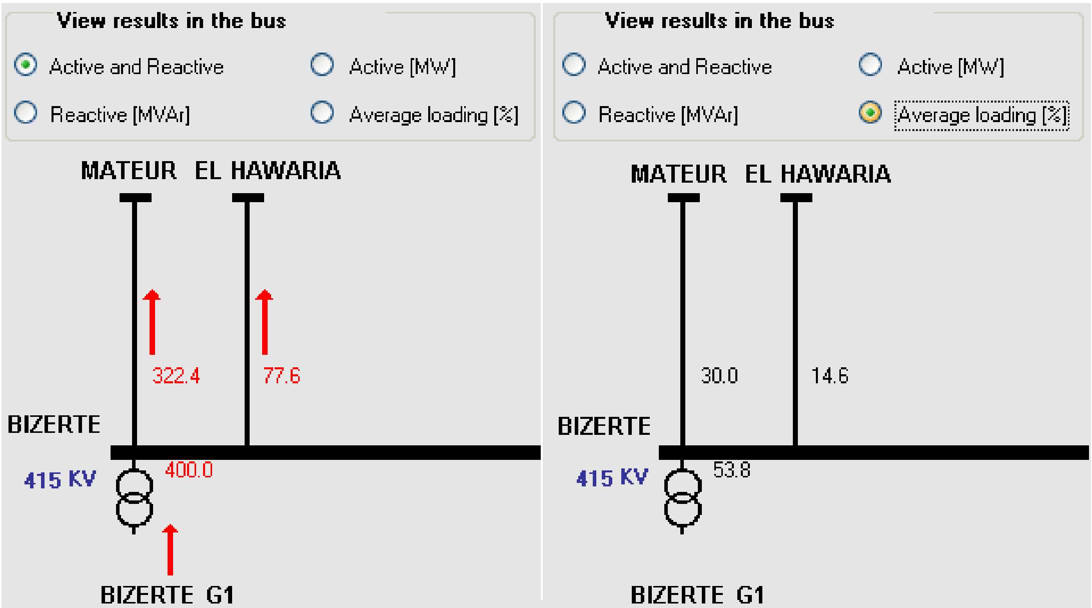


Fig.4.6 - 400 MW case - Power flows and average loading on the two new 400kV connections.

4.1.1.2 Power generation to supply the internal load in Tunisia and for power export (1200 MW)

<u>SOLUTION "A"</u>

The first effects of the export through the HVDC system are showed in Fig.4.7: the export to Italy has grown to 800 MW, all of them produced by ELMED power plant, and the active power losses have increased.

The power flows and the average loadings (Fig.4.8) have obviously increased too; however the power

distribution between the two lines has remained quite the same of the previous case (Fig.4.2).
The "N-1" security analysis (Tab.4-2) has shown a too high voltage drop in El Hawaria node in case of out-of-service of one of the two lines connecting that node to Mornaguia. That can be easily avoided compensating the reactive power absorption of the HVDC connection till 400 MVar (instead of 293 MVar[5]). In this way the bus-voltage (V = 406 kV) in the "N" condition does not exceed the limits previously described (par. 3.1) and in fault condition such a voltage drop is avoided. Moreover, no voltage control problem is expected as the ESCR remains greater than "3".
<u>This solution is technically feasible from the point of view of performances in static conditions.</u>

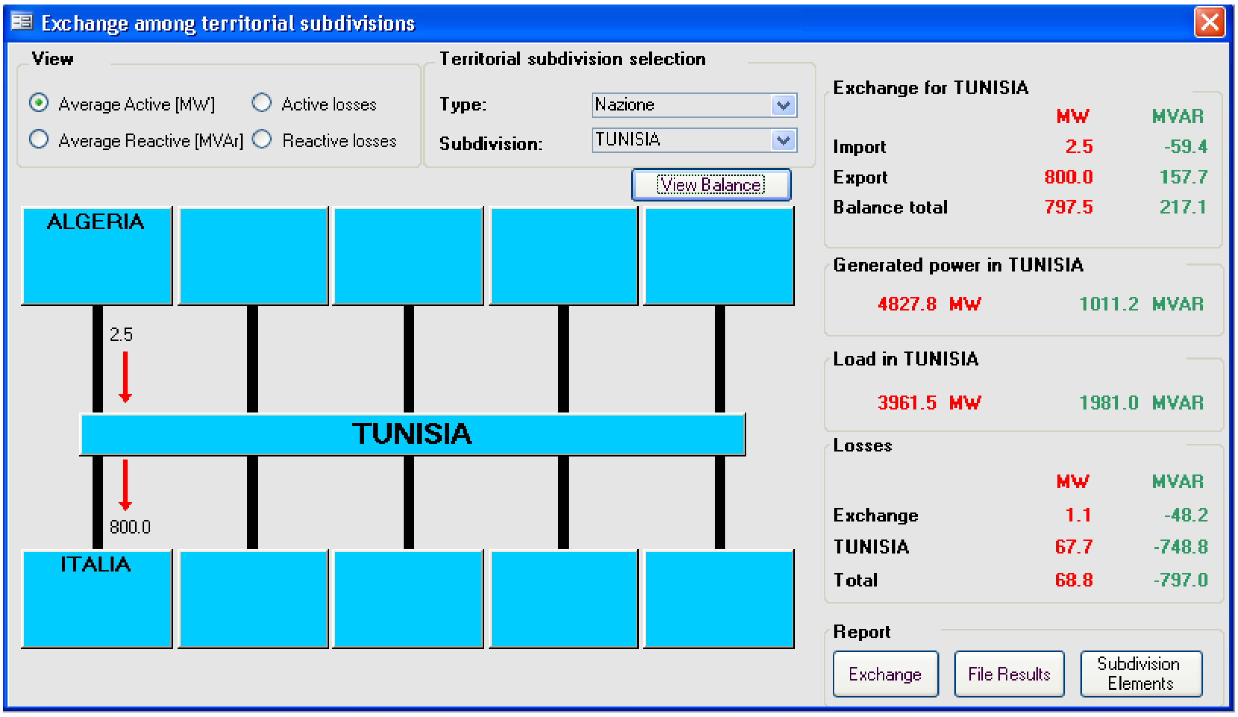


Fig.4.7 - 1200 MW case - International exchanges and power balances for the Tunisian grid.

[5] This value is obtained considering the following standard base hypothesis:

$$Q_{abs} = 0.55\ P_{HVDC}$$
$$Q_{cap} = 2/3\ Q_{abs}$$

Where:

Q_{abs} is the reactive power absorbed by converters;
Q_{cap} is the size of compensator installed
P_{HVDC} is the power flowing on HVDC connection.

In this case P_{HVDC} = 800 MW and Q_{cap} = 293 Mvar. This is a conservative hypothesis because it is possible also to compensate all reactive power absorbed by converters, but it is used to show the network response in standard conditions.

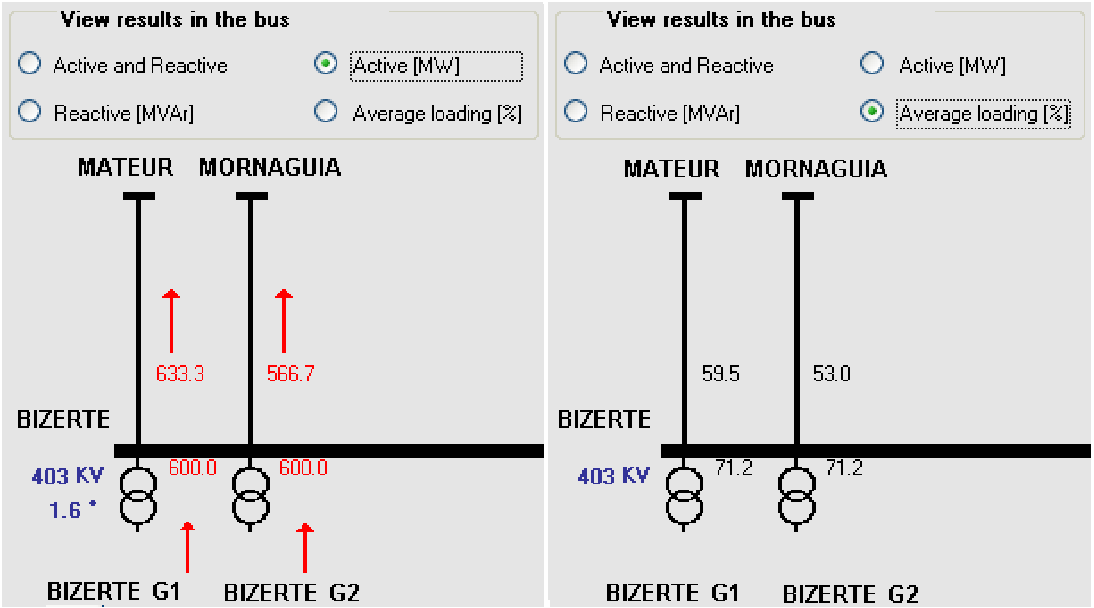


Fig.4.8 - 1200 MW case - Power flows and average loading on the two new 400kV connections.

Tab.4-2 - "N-1" security analysis results without compensation in El Hawaria

Contingency		Vn (kV)	Violation	Vn (kV)	V_N (kV)	V_{N-1} (kV)	ΔV (%)
MORNAGUIA	**HAWARIA**	**400**	**HAWARIA**	**400**	**392.6**	**337.7**	**-15.5**

<u>SOLUTION "B"</u>

Solution "B" provides quite the same results of solution "A" in terms of power balances and power flows (Fig.4.9 and Fig.4.10).

Even the same violation in El Hawaria bus-voltage in the "N-1" security analysis (Tab.4-3) has been reported and the same countermeasure could be used (increased compensation of HVDC reactive power absorption).

<u>This solution is technically feasible from the point of view of performances in static conditions.</u>

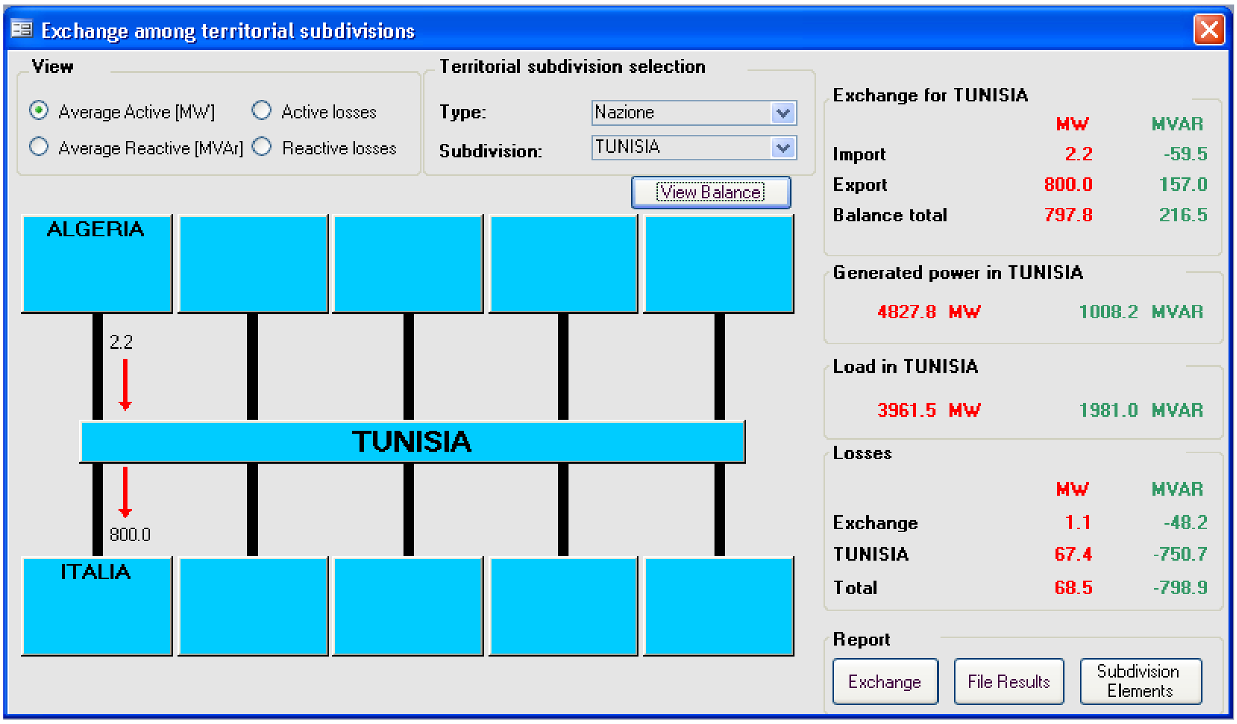


Fig.4.9 - 1200 MW case - International exchanges and power balances for the Tunisian grid.

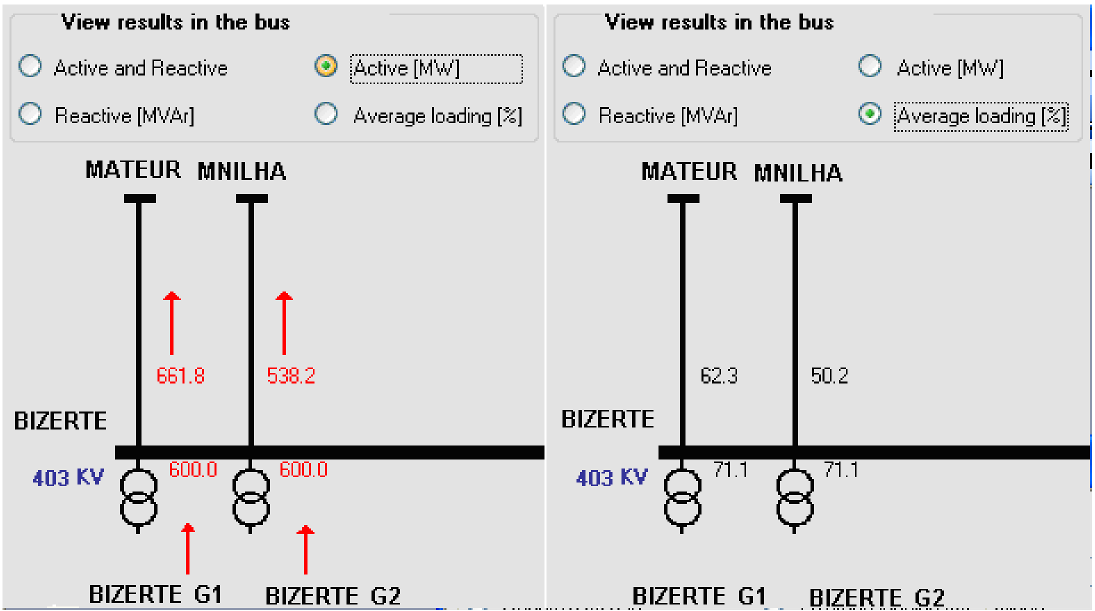


Fig.4.10 - 1200 MW case - Power flows and average loading on the two new 400kV connections.

Tab.4-3 - “N-1” security analysis results

Contingency		Vn (kV)	Violation	Vn (kV)	V_N (kV)	V_{N-1} (kV)	ΔV (%)
MORNAGUIA	**HAWARIA**	**400**	**HAWARIA**	**400**	**392.6**	**337.7**	**-15.5**

SOLUTION “C”

The power balances and the international exchanges showed in Fig.4.11 are still similar to those of the previous solutions.

On the contrary, different power flows and average loadings are shown in Fig.4.12. The whole power needed to satisfy the internal Tunisian needs (400 MW) is injected in Bizerte-Mateur line, while the one

(800 MW) headed to the HVDC connection flows in both lines. Each generator of Bizerte in this scenario absorbs 56,8 Mvar of reactive power.

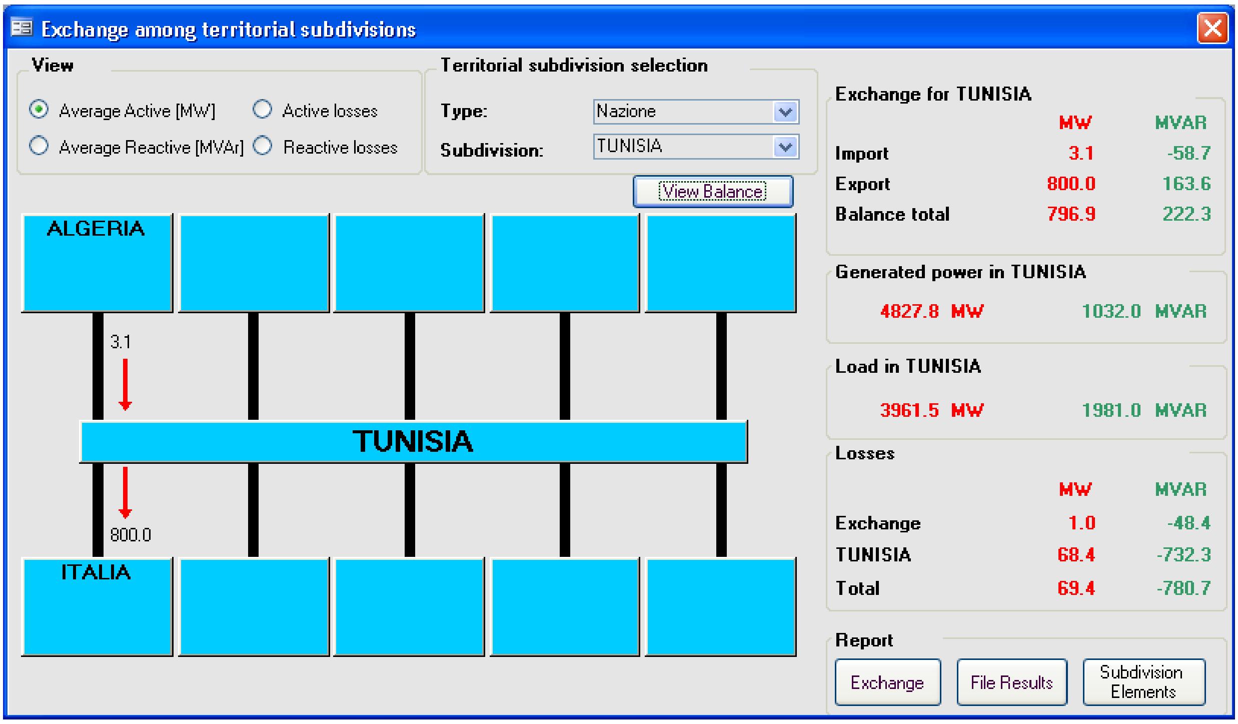


Fig.4.11 - 1200 MW case - International exchanges and power balances for the Tunisian grid.

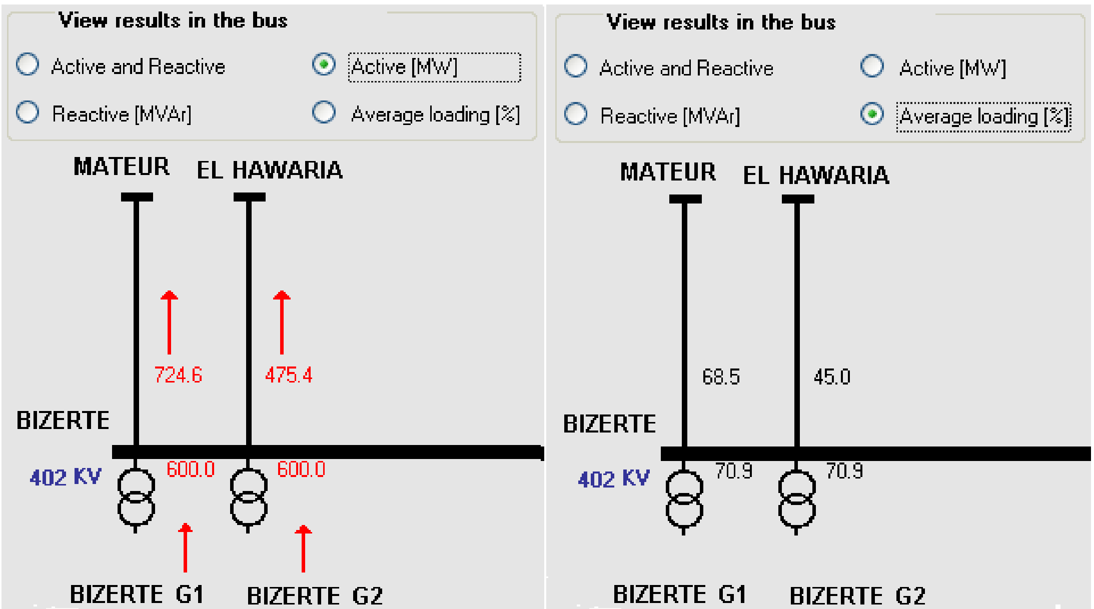


Fig.4.12 - 1200 MW case - Power flows and average loading on the two new 400kV connections.

The "N-1" security analysis demonstrates how problematic this solution could be. In addition to bad voltage violations (-30%) in El Hawaria node that could be eventually prevented increasing the reactive power compensation in case of fault on Bizerte-Mateur line the whole power produced by ELMED power plant (1200 MW) flows in the Bizerte-El Hawaria connection causing an overload higher than 130%.

Hence, this solution shows a poor technical performance and voltage control problems in El Hawaria, especially when tripping the Bizerte-Mateur line.

Tab.4-4 - "N-1" security analysis results (violations and overloads).

Contingency		Vn (kV)	Violation	Vn (kV)	V_N (kV)	V_{N-1} (kV)	ΔV (%)
BIZERTE	**MATEUR**	**400**	**HAWARIA**	**400**	**388.5**	**303.1**	**-24.2**
BIZERTE	**HAWARIA**	**400**	**HAWARIA**	**400**	**388.5**	**325.4**	**-18.6**
MORNAGUI	**HAWARIA**	**400**	**HAWARIA**	**400**	**388.5**	**269.7**	**-32.6**

Contingency		Vn (kV)	Overload		Vn (kV)	I_{N-1} (kA)	I_{N-1} (p.u.)
BIZERTE	**MATEUR**	**400**	**BIZERTE**	**HAWARIA**	**400**	**2.068**	**1.34**

4.1.2 Bizerte: minimum load conditions

4.1.2.1 Power generation (1000 MW) to supply the internal load in Tunisia and for power export[6]

SOLUTION "A"

The power balance of Tunisian network and power exchanges with Algeria and Italy of this scenario are in Fig. 4.13, while the power flows outgoing from the 400 kV station of Bizerte are in Fig. 4.14

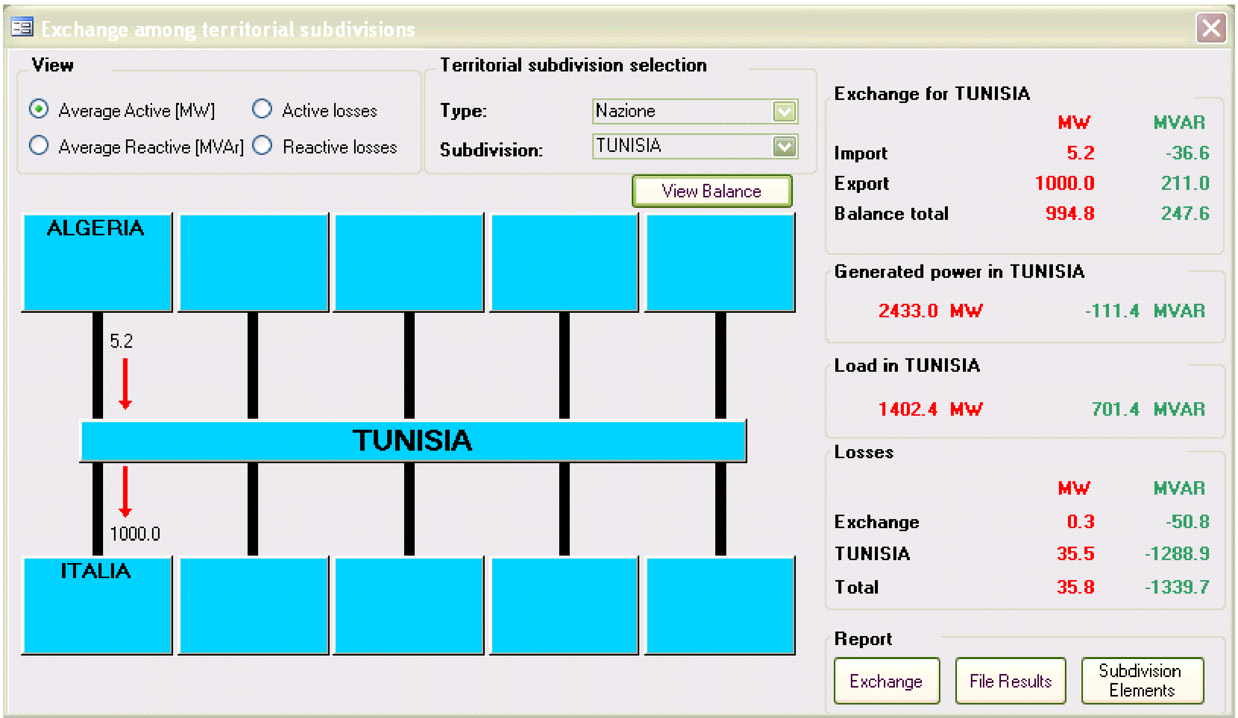


Fig. 4.13 - 1000MW case A - International exchanges and power balances for the Tunisian grid, off peak condition

[6] Note: in minimum loading conditions we simulate the maximum power export to Sicily irrespective from the units that are generating for power export.

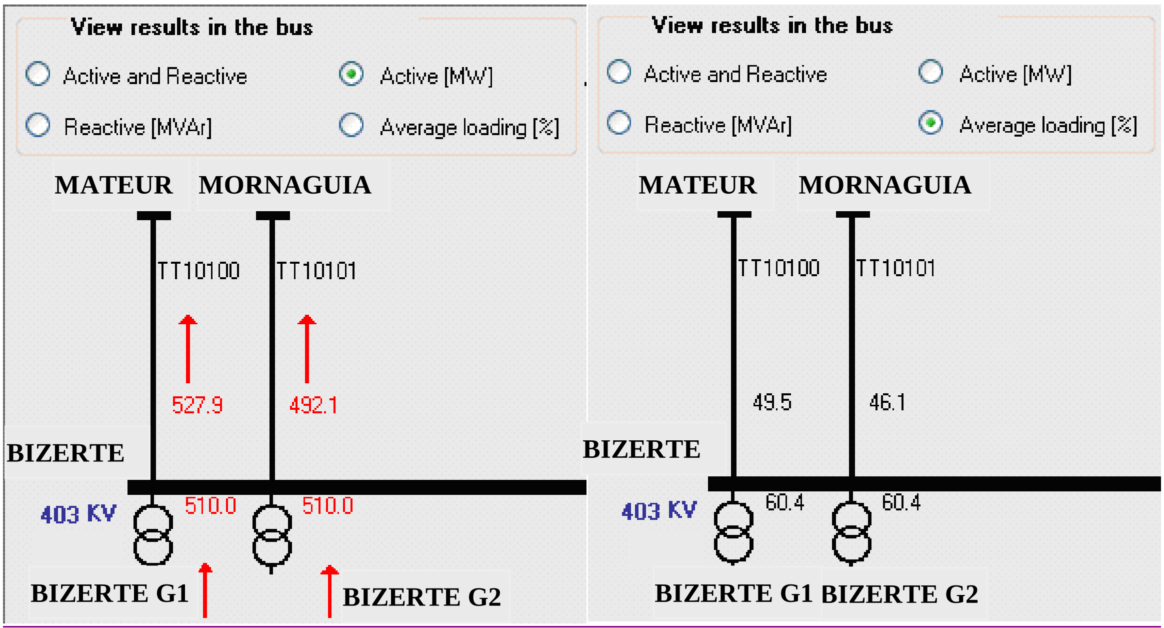


Fig. 4.14 - 1000MW case A - Power flows and average loading on the two new 400kV connections, off peak

The analysis in sound network condition doesn't point out any critical situation, while in N-1 a strong voltage violation is present in El Hawaria (291 kV) in case of loss of one 400 kV line Mornaguia – El Hawaria. The high level of reactive power flow also points out the overloading of the remaining line. The voltage drop can be avoided with a careful design of capacitor filter banks in El Hawaria: with an overcompensation of about 650 Mvar (instead of 370 Mvar at Vn)[7] of reactive compensation in El Hawaria, the voltage in the AC substation during contingency is 378 kV. This higher compensation in El Hawaria increases the overvoltage in Bouchemma when the 400/220 kV transformer of the station is lost, but the effect could be minimized by means of shunt Var compensation or opening the line at the occurrence of the 400/220 transformer disconnection at Bouchemma.

Tab.4-5 - "N-1" security analysis results

Contingency		Vn (kV)	Violation	Vn (kV)	V_N (kV)	V_{N-1} (kV)	ΔV (%)
MORNAGUIA	HAWARIA	400	HAWARIA	400	384.5	290.9	-27.7
BOUCHEMMA		400/220	BOUCHEMMA	400	418.0	441.7	+10.4

Contingency		Vn (kV)	Overload		Vn (kV)	I_{N-1} (kA)	I_{N-1} (p.u.)
MORNAGUIA	HAWARIA	400	MORNAGUIA	HAWARIA	400	1.93	1.25

In off peak condition, the ESCR parameter evaluation is particularly interesting and binding in the AC substation where the converter station is present. With the high level of reactive power compensation, the ESCR values are in the range **1.99** ÷ 3.55 p.u.; the particularly low value of 1.99 p.u. is reached in case of the outage of one 400 kV line El Hawaria – Mornaguia.
<u>The solution is technically feasible but it requires a tuning of the capacitor banks in El Hawaria and specific measure for voltage control could be needed (typically flexible Var compensation).</u>

[7] This value is obtained with the same considerations reported in the comment number 5 with P_{HVDC} = 1000 MW instead 800 MW.

SOLUTION "B"

The case considering the power plant of Bizerte connected with Mateur and Mnihla is characterized by the power balance of Fig. 4.15. The active power flow and loading of the lines outgoing from the station are in Fig. 4.16.

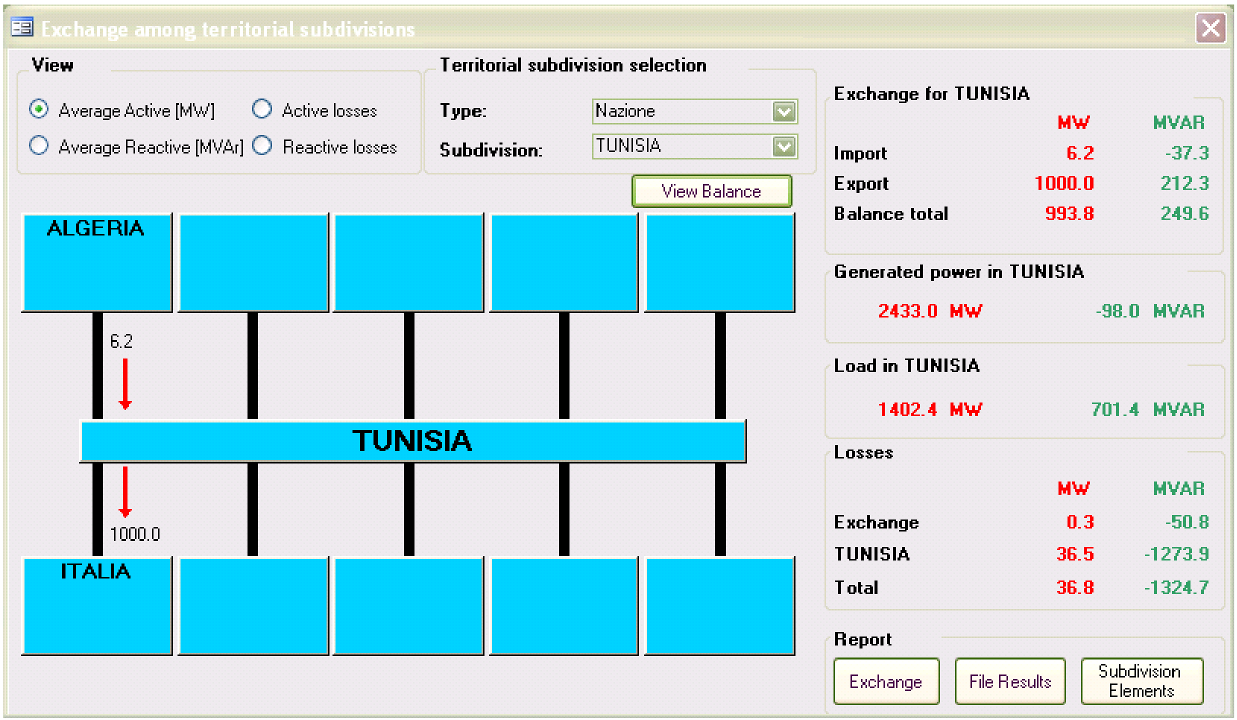


Fig. 4.15 - 1000MW case B - International exchanges and power balances for the Tunisian grid, off peak condition

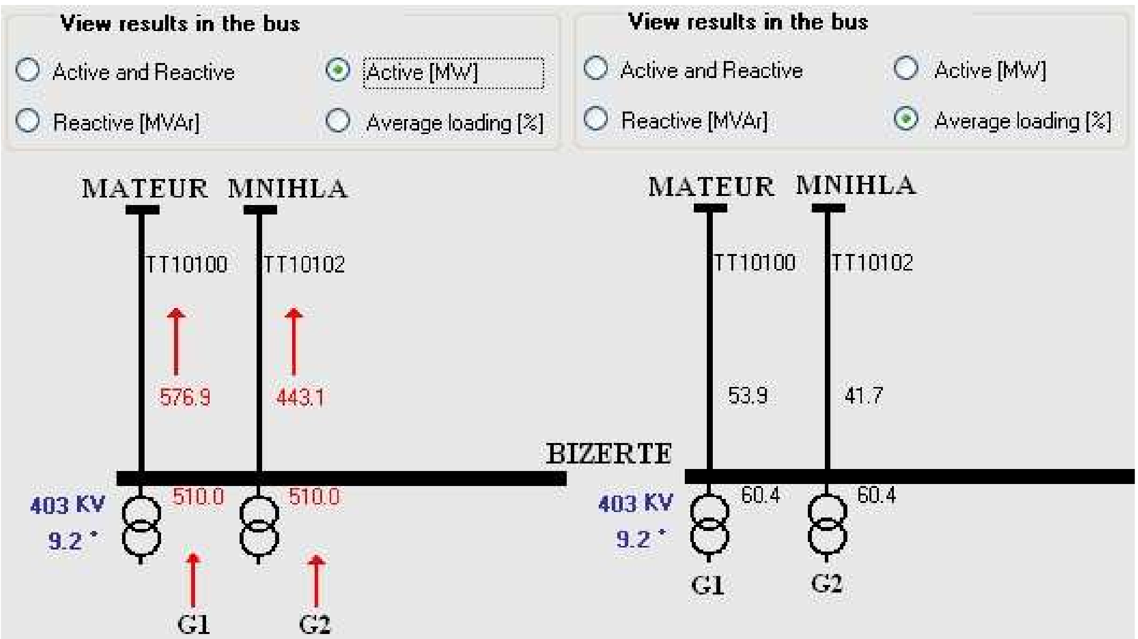


Fig. 4.16 - 1000MW case B - Power flows and average loading on the two new 400kV connections, off peak

The load flow analysis in sound network condition doesn't provide any critical results; in N-1 condition, the already pointed out undervoltage problem is present in El Hawaria after the loss of one 400 kV line

Mornaguia – El Hawaria, as well as the overload on the remaining line. The problem could be solved considering again about 650 Mvar (instead of 370 Mvar at Vn) of capacitive compensation in El Hawaria.

Tab.4-6 - "N-1" security analysis results

Contingency		**Vn (kV)**	**Violation**	**Vn (kV)**	**V_N (kV)**	**V_{N-1} (kV)**	**ΔV (%)**
MORNAGUIA	HAWARIA	400	HAWARIA	400	383.7	292.1	-27
BOUCHEMMA		400/220	BOUCHEMMA	400	418.0	441.3	+10.3

Contingency		**Vn (kV)**	**Overload**		**Vn (kV)**	**I_{N-1} (kA)**	**I_{N-1} (p.u.)**
MORNAGUIA	HAWARIA	400	MORNAGUIA	HAWARIA	400	1.93	1.25

Taking into account the need of high reactive compensation in the converter station, the ESCR parameter is within the range **1.95** ÷ 3.47 p.u.: the extreme values are reached respectively in case of outage of one 400 kV line Mornaguia – El Hawaria and in sound network condition.
<u>The solution is technically feasible but it requires a tuning of the capacitor banks in El Hawaria or specific measures for voltage control.</u>

<u>SOLUTION "C"</u>

The power flows for solution C of power plant connection in Bizerte are displayed in Fig. 4.17. The active flows and loading of the 400 kV lines Bizerte – Mateur and Bizerte – El Hawaria are shown in Fig. 4.18.

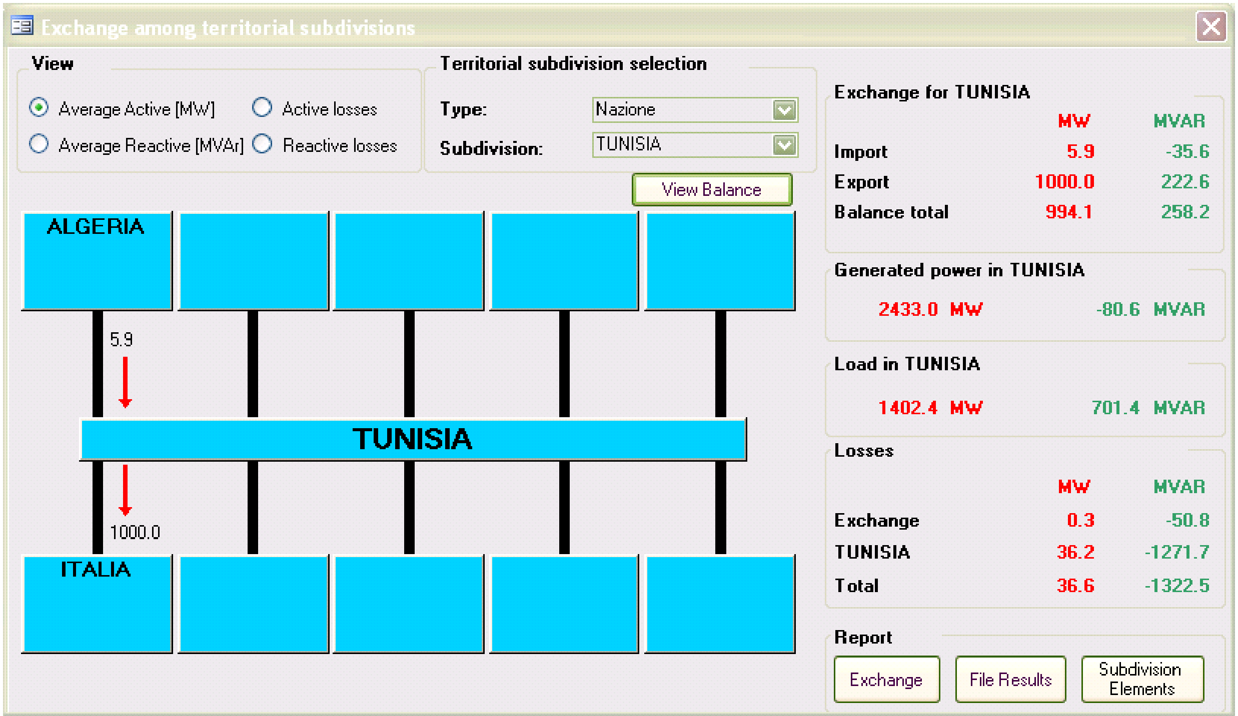


Fig. 4.17 - 1000MW case C - International exchanges and power balances for the Tunisian grid, off peak condition

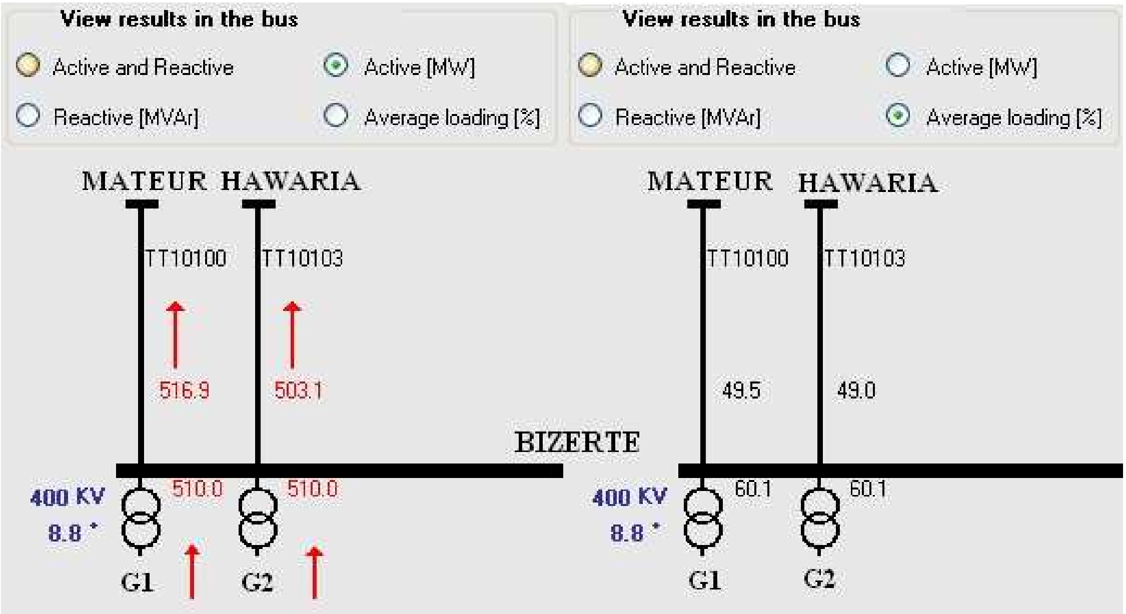


Fig. 4.18 - 1000MW case C - Power flows and average loading on the two new 400kV connections, off peak

In sound network condition, no critical conditions arise from the analysis but voltage in El Hawaria is quite low, at 377.8 kV(-6.8%): this value is however within the acceptable range (±7% Vn).
Even neglecting the already well-known overvoltage in Bouchemma, present also in the case without any DC connection or new PP, the N-1 condition is more critical in the case "C" than the previous cases. Voltage in El Hawaria is lower than the acceptable limit (-10%) in case of loss of the 400 kV line Mornaguia – El Hawaria or the 400 kV lines outgoing from Bizerte.
A shunt compensation in the converter station of 650 Mvar (instead of 370 Mvar, at Vn) allows avoiding the undervoltages in El Hawaria for the outage of Bizerte – El Hawaria and Bizerte – Mateur but the loss of El Hawaria – Mornaguia is critical and a strong overcompensation is needed (up to 1000 Mvar at Vn).

Tab. 4-7 – "N-1" security analysis results

Contingency		Vn (kV)	Violation	Vn (kV)	V_N (kV)	V_{N-1} (kV)	ΔV (%)
BOUCHEMMA	BOUCHEMMA	400/220	BOUCHEMMA	400	418.9	443.1	11%
MORNAGUIA	HAWARIA	400	HAWARIA	400	377.8	275.7	-31%
HAWARIA	BIZERTE	400	HAWARIA	400	377.8	294.0	-27%
MATEUR	BIZERTE	400	HAWARIA	400	377.8	323.5	-19%

The ESCR evaluation confirms the problems on voltage control in El Hawaria since even in sound network condition is lower than 3 p.u.; it is in the range 0.69÷2.88 p.u. and the minimum value is reached in case of loss of the 400 kV line El Hawaria – Mornaguia.
<u>The solution shows high voltage control problems, especially in case of loss of the line El Hawaria – Mornaguia 400 kV.</u>

4.1.3 Bizerte: solutions of network reinforcements and conclusions

In Tab. 4-8 and Tab. 4-9 we shows the network reinforcements obtained from static calculations to connect both the ELMED power plant located in Bizerte and the HVDC interconnection with Sicily.

Among the possible solutions we have disregarded the connection Bizerte - Jendouba which is unfavourable both for its length and because the power generated in Bizerte flows prevailingly in eastwards /south-eastwards direction, both to supply the internal load in Tunisia and to export power to Europe.

As for the three technically feasible retained solutions, we highlight that it turned out possible to avoid the introduction of new 400/225 kV autotransformers, since the planning of STEG already complies with the needs to supply the internal load in Tunisia. Thus, the additional power generated for export will flow through the new 400 kV lines without causing significant additional loading on the underlying voltage levels.

Tab. 4-8 – ELMED power plant in Bizerte: network reinforcements and other ranking elements

Solution	Reinforcements	New lines total length (km) (1)	New ATR 400/225 kV	Losses in peak conditions (MW)	Notes
A	Bizerte-Mateur Bizerte-Mornaguia	**170**	**zero**	**67.7**	ESCR within 1.99 ÷ 3.55 p.u.
	2x El Hawaria-Mornaguia	**300**			
B	Bizerte-Mateur Bizerte- Mnihla	**170**	**zero**	**67.4**	ESCR within 1.95 ÷ 3.47 p.u.:
	2x El Hawaria-Mornaguia	**300**			
C	Bizerte-Mateur Bizerte-El Hawaria	**310**	**zero**	**68.4**	ESCR within 0.69÷2.88 p.u. (2)
	El Hawaria-Mornaguia	**150**			

(1) In the table we have split the km of new lines necessary to connect the ELMED power plant to the Tunisian grid from those necessary to connect the AC/DC substation in El Hawaria to the Tunisian grid. As for the solution "C", we have indicated the estimated length of the proposed new lines. As a matter of fact, the Bizerte-El Hawaria 400 kV line will play a double role, since it is used both for the connection of the ELMED power plant and for the connection of the AC/DC substation.

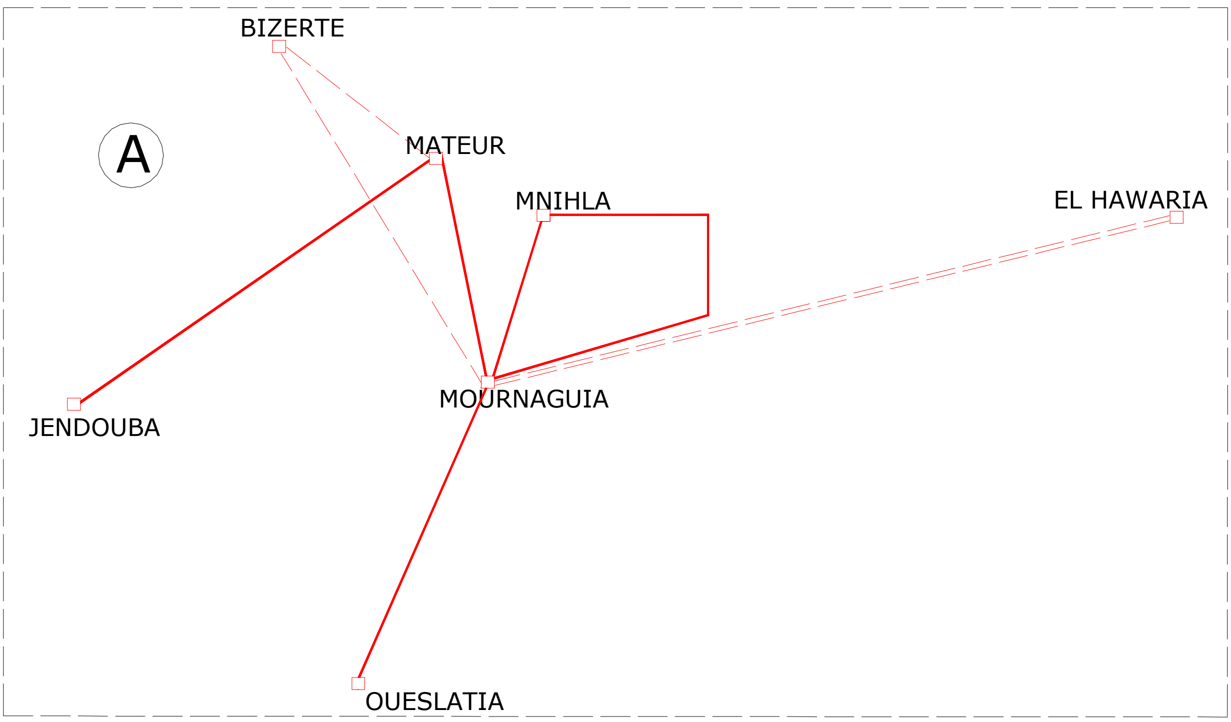
(2) More difficult voltage control in El Hawaria; ESCR in minimum loading conditions exceed the acceptable limits for the solution "C".
Long 400 kV line (Bizerte-El Hawaria: 250 km) the compensation and energisation procedures of which shall be carefully studied.
Possible difficulty in finding a suitable right-of-way.

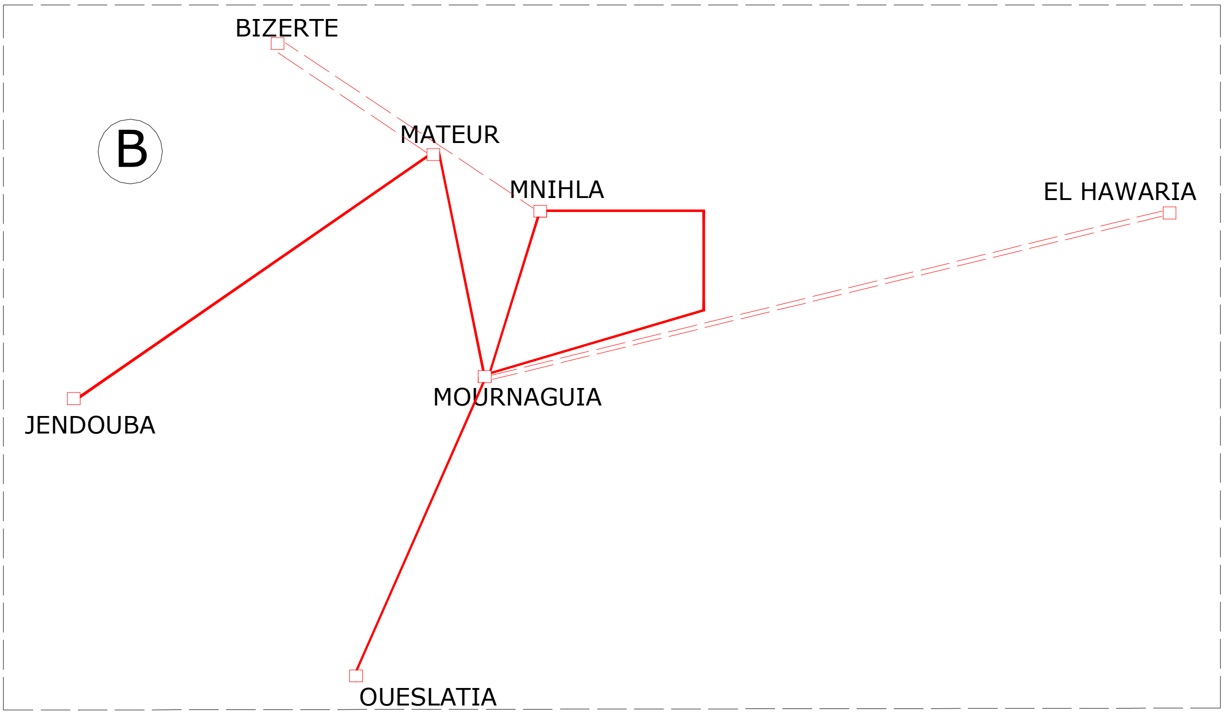
Tab. 4-9 – ELMED power plant in Bizerte: reactive power compensation

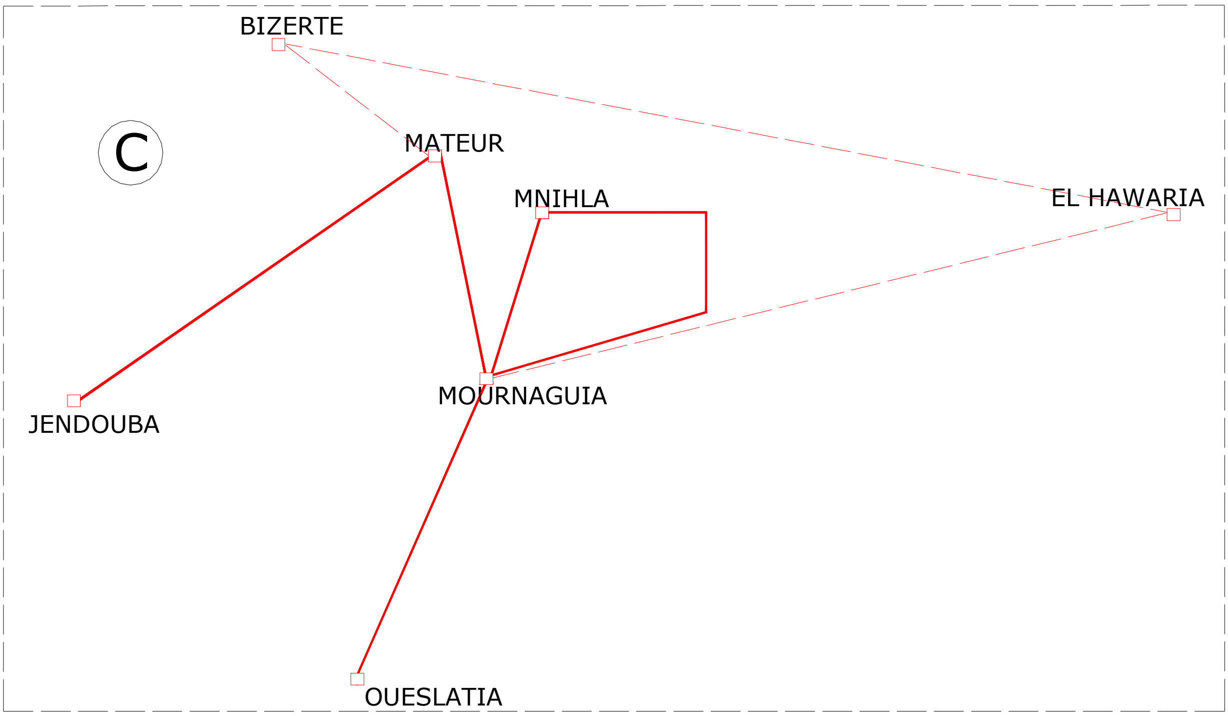
Solution	Reactive power compensation [Mvar]	
	Peak Load	Minimum Load
A	**400**	**650**
B	**400**	**650**
C	**400**	**650**

Note: the shunt Var compensation shown in the above table shall be intended only as indicative, since *the study didn't addressed the optimisation of this equipment.*

As for the ranking among the solutions, we note that solutions "A" and "B" are practically equivalent even considering all the ranking criteria. A possible discriminating element to choose one solution with respect to the other may be related to the environmental impact: difficulty in selection the right-of-ways, number of expropriations, presence of buildings of inhabited areas, crossing of territories having naturalistic values (woods, ponds, etc.).
Solution "C" shows a slightly lower overall new line length, but, on the other hand, its static performances are less favourable than the previous two, especially for the voltage control in El Hawaria and, in general, at the end of the long 400 kV Bizerte-El Hawaria line. Moreover, the selection of right-of-way and the visual impact on the landscape for building this line may reveal to be challenging issues causing probable delays and additional costs.
The ESCR evaluation in El Hawaria confirms the above remarks with very low values out of the acceptable range for the solution "C". Solutions"A" and "B" give comparable results pointing out the need of a careful tuning of voltage control in El Hawaria.







4.2 ELMED power plant in El Hawaria

In this alternative the new power plant of El Hawaria (composed of 3 x 400 MW combined cycle gas turbine generators) and the HVDC link from Tunisia to Italy are connected in the same station of El Hawaria.

In the case of power export to Italy, this configuration permits to send the generation of ELMED power plant directly to the HVDC link without involving other Tunisian network elements.

The particularity of this case is that the two 400 kV transmission lines between El Hawaria and

Mornaguia must be always in service because they have to evacuate 400MW used in Tunisian system.

4.2.1 El Hawaria: peak load conditions

4.2.1.1 Power generation to supply the internal load in Tunisia (400 MW)

The key figures for this alternative are shown below. The Tunisian electric system is connected only to Algeria grid and the importation from it remains close to zero (only 4.5 MW).

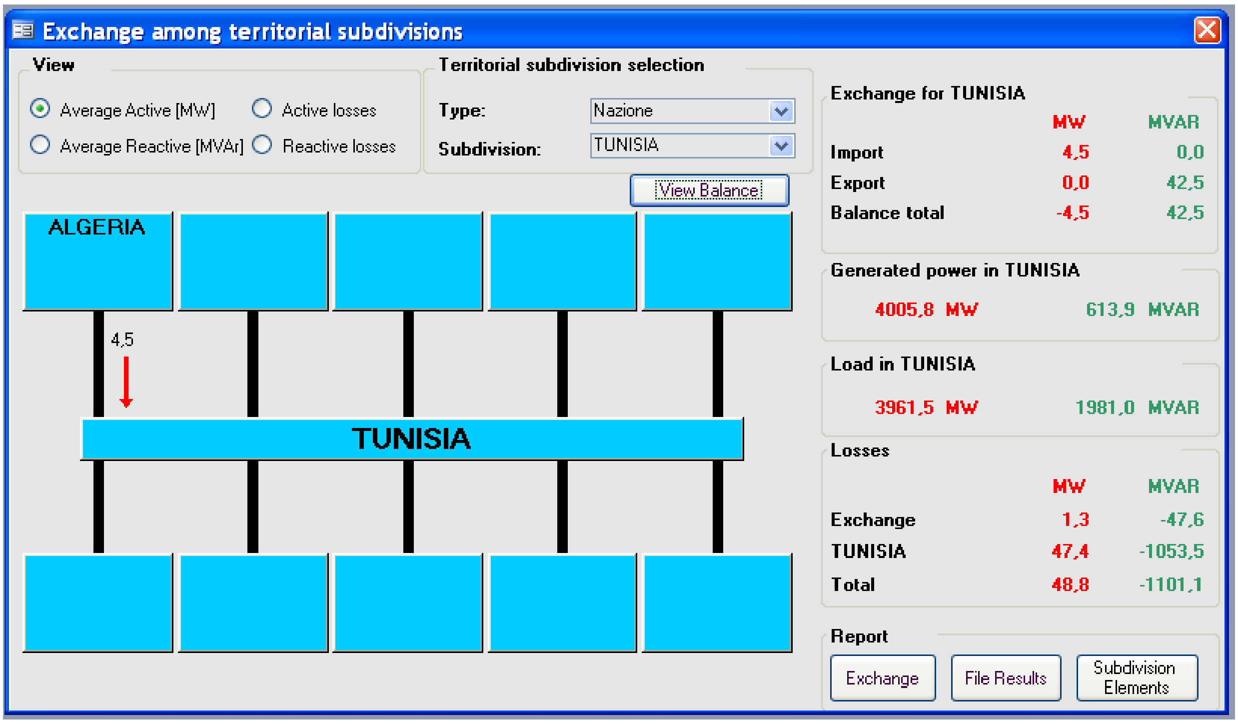


Fig.4.19 - 400 MW case - International exchanges and power balances for the Tunisian grid.

As shown in the figure below, in this case in El Hawaria station only one generating unit is in service: it generates 400 MW that are sent to Tunisian system thorugh the two 400kV lines El Hawaria – Mornaguia. Even though the average loading of these two lines is quite low (only 19.2%) they are both necessary to fulfil the N-1 security criterion.

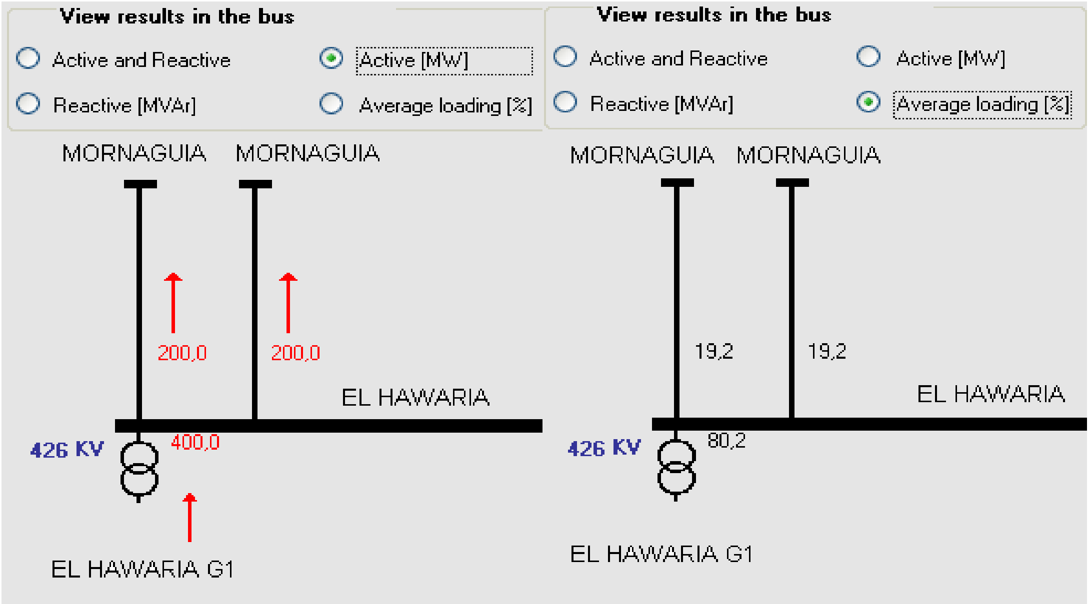


Fig.4.20 - 400 MW case - Power flows and average loading on the two new 400kV connections from EL Hawaria to the Tunisian system

In this configuration and operating condition, after a N-1 security analysis, no constraint violations have been detected, either for bus voltages or for line and transformer overloads: this means that additional network reinforcements to evacuate 400 MW to El Hawaria station to the Tunisian electric system are not requested; only two 400 kV transmission lines El Hawaria – Mornaguia are necessary.

4.2.1.2 Power generation to supply the internal load in Tunisia and for power export (1200 MW)

The key figures for this alternative are shown below. Also in this case the Tunisian electric system is connected to Algeria grid with a power exchange close to zero (only 4.4 MW) and to the Italian transmission grid through the HVDC link: Italy imports from Tunisia an amount of power equal to 800 MW.

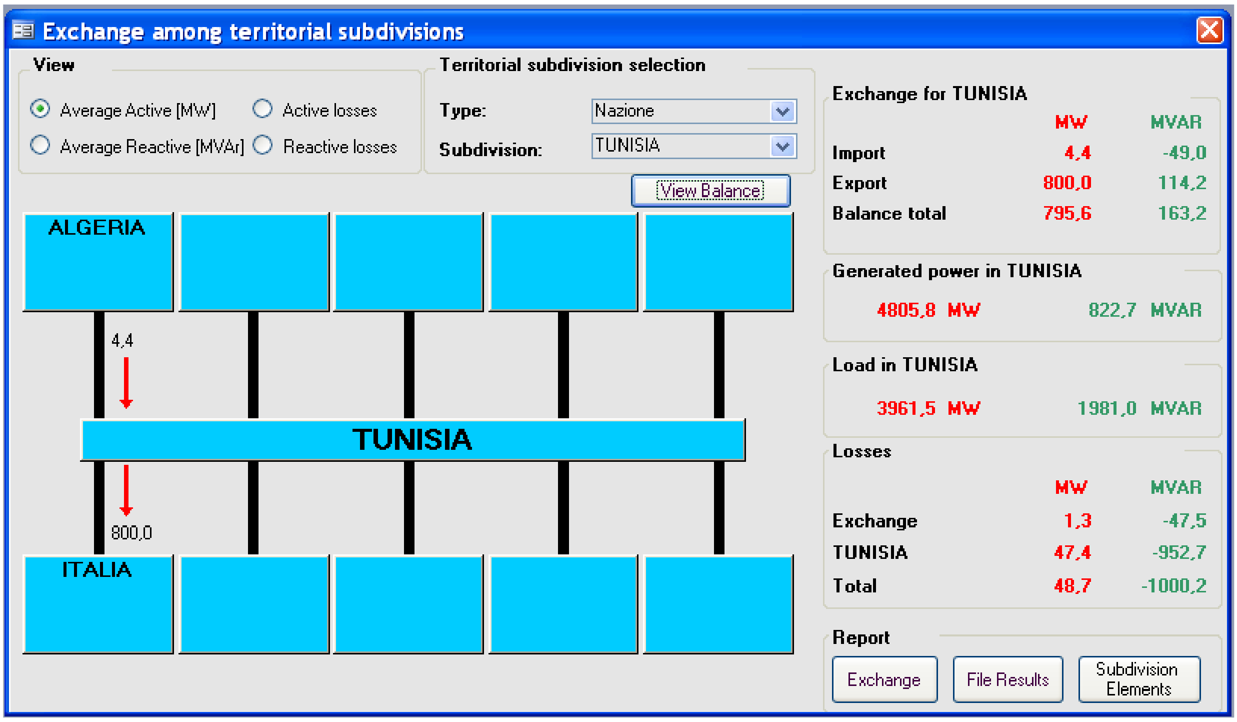


Fig.4.21 - 1200 MW case - International exchanges and power balances for the Tunisian grid.

As shown in the figure below, in this scenario all generating units of El Hawaria power plant are in service. They generate 1200 MW: 400 MW of them are sent to the Tunisian power system through the two lines El Hawaria – Mornaguia and the other 800 MW are sent to Italy with HVDC system.
The particularity of this scenario is that for the Tunisian system there are no differences between the two cases with or without export, because the new power plant is directly connected to HVDC link. A confirmation of this is the same value of total active losses in the two conditions.

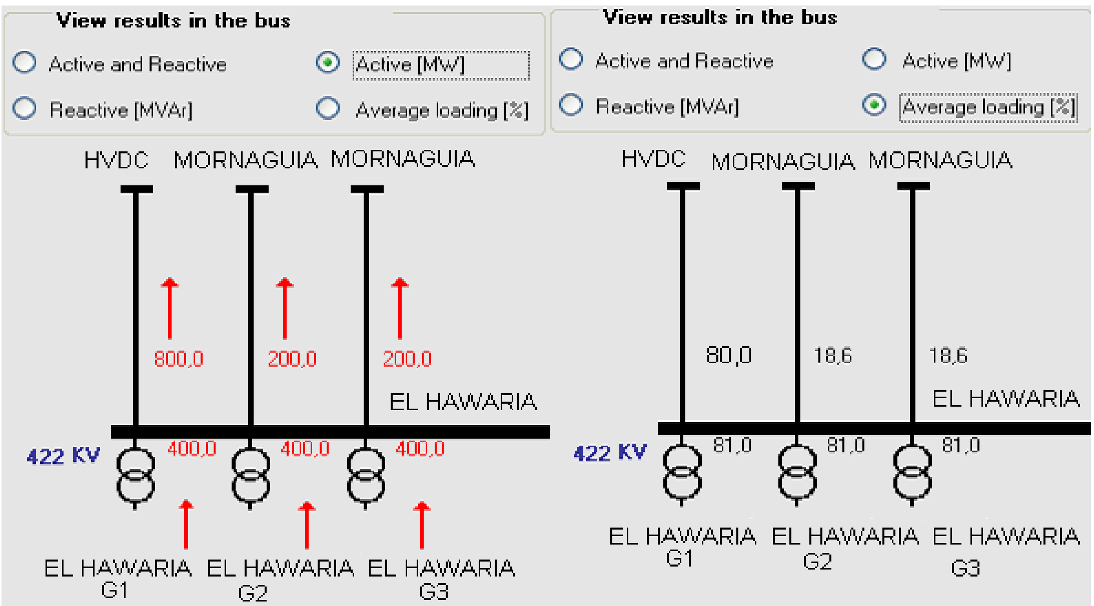


Fig.4.22 - 1200 MW case - Power flows and average loading on the two new 400kV connections from EL Hawaria to the Tunisian system

Similarly to the previous situation, after a N-1 security analysis, no constraint violations have been detected, either for bus voltages or for line and transformer overloads: this means that no additional

network reinforcements to evacuate 800 MW from El Hawaria station to the Italian power system are requested.
Moreover, due to the presence of the new power plant, the ESCR ratio in this scenario is very high and equal to about 7.7: this means that special devices to control the voltage in El Hawaria station are not necessary.

4.2.2 El Hawaria: minimum load conditions

4.2.2.1 Power generation to supply the internal load in Tunisia and for power export (1000 MW)

The power generation of the ELMED plant in El Hawaria is directly exported towards Italy, as shown in Fig.4.23 and Fig.4.24 and the increase of losses is very low if compared with the previous case.

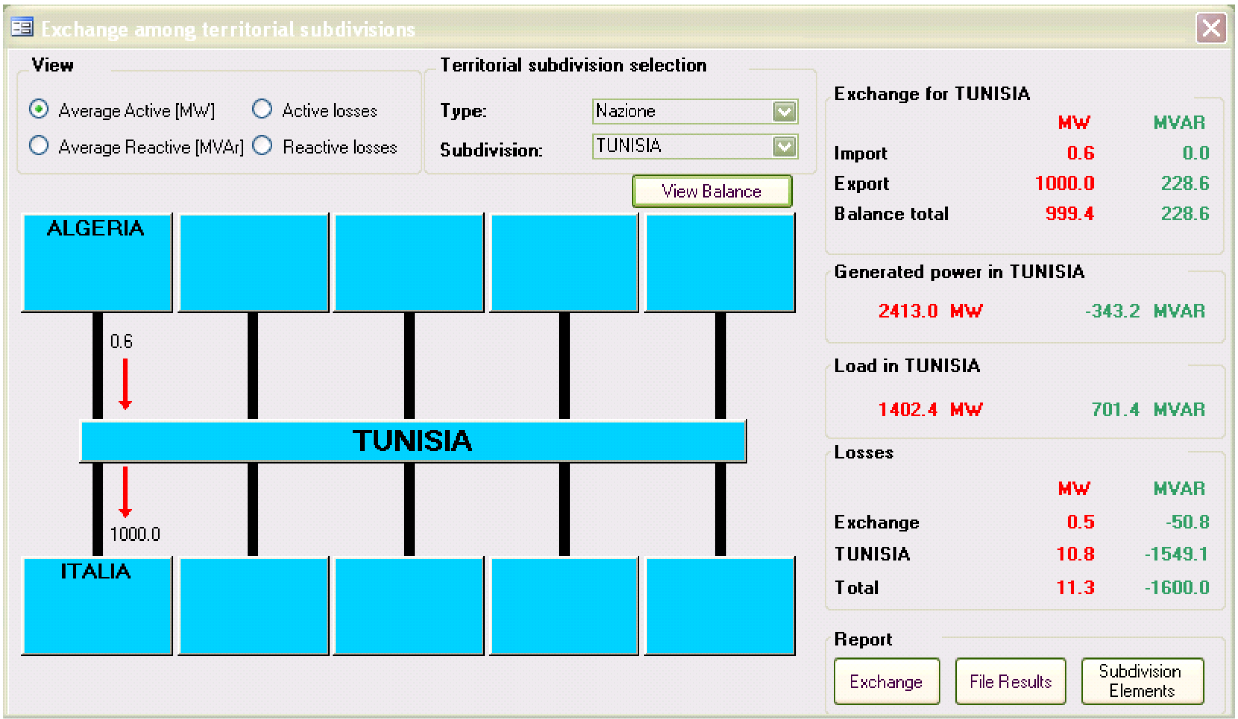


Fig.4.23 - 1000 MW case - International exchanges and power balances for the Tunisian grid, off peak

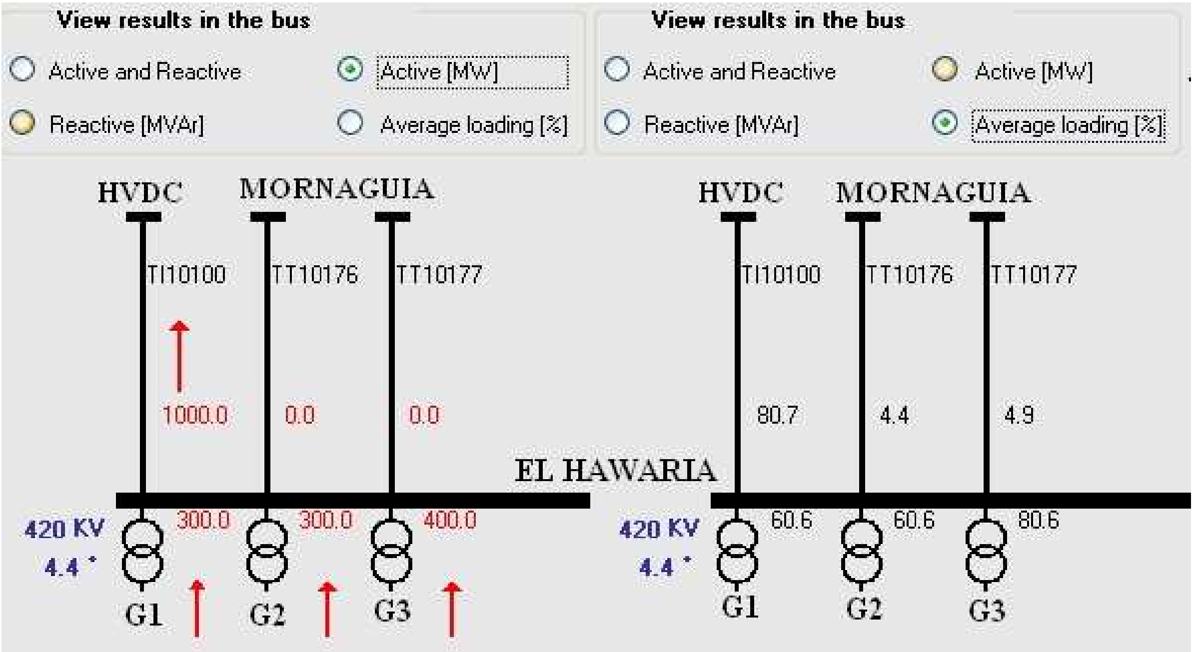


Fig.4.24 - 1000 MW case - Power flows and average loading on the two new 400kV connections from El Hawaria to the Tunisian system, off peak

No particular remarks rise from the load flow analysis both in N and N-1 condition. Voltage control is supplied by the power plant located just close to the converter station and this is confirmed by the ESCR evaluation, since the parameter is within the range 6.25 ÷ 7.50 p.u., respectively in case of outage of one 400 kV line El Hawaria – Mornaguia and in N condition. Even considering a N-2 condition, however, with one line towards Mornaguia and one unit out of service, the parameter is higher than 4 p.u.
<u>The solution is technically feasible.</u>

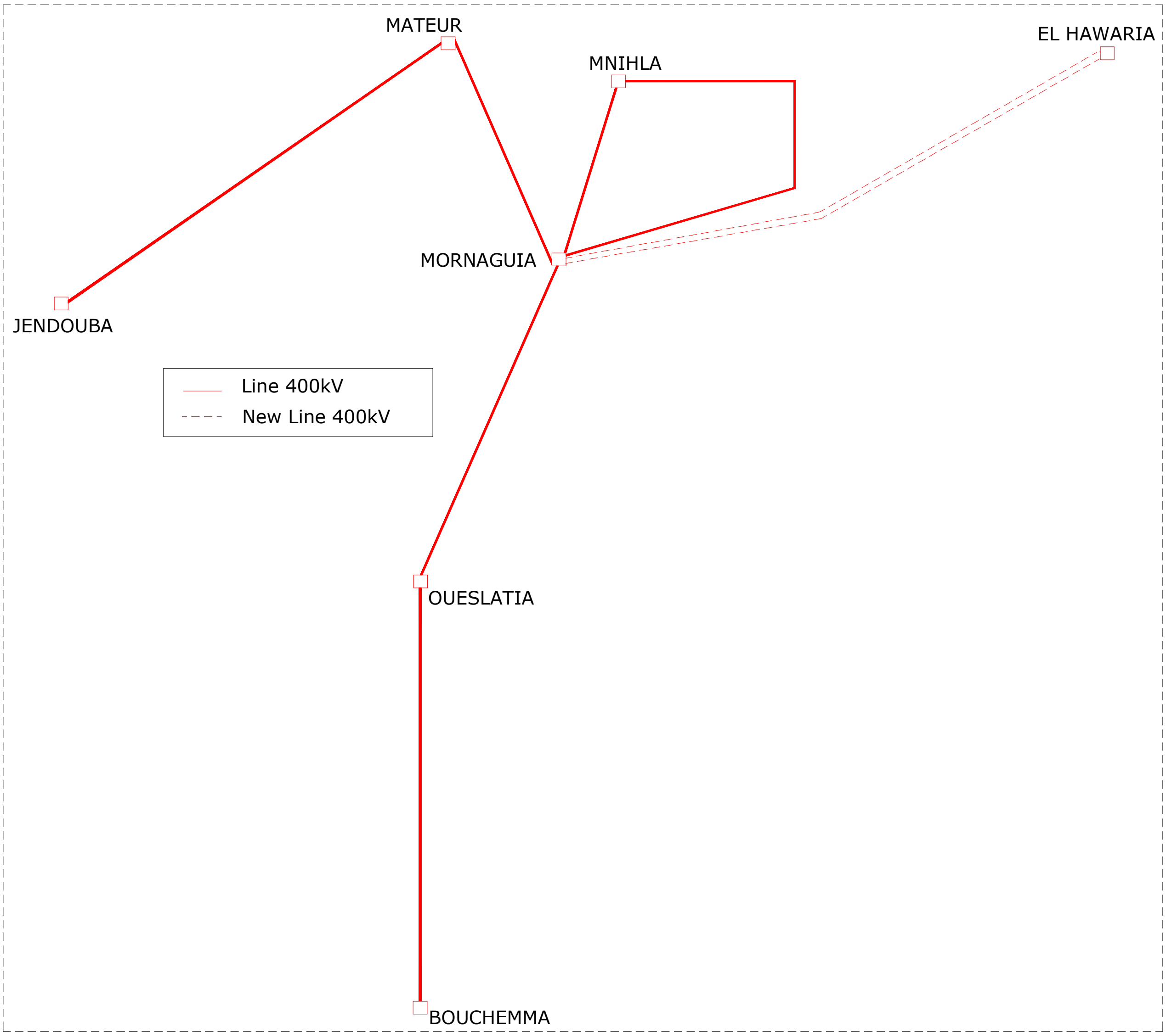
4.2.3 El Hawaria: solutions of network reinforcements and conclusions

For the ELMED power plant alternative in El Hawaria, only one connection solution to the Tunisian system can be retained consisting of the two 400 kV single circuit El Hawaria-Mornaguia lines.
It is worth mentioning that this line is exploited exclusively to feed the internal load in Tunisia from the ELMED power plant and, in case of emergency, for power import from Italy.
This alternative reveals also to be the most favourable from the point of view of the network reinforcements with respect to the other ones.
The connection solution considering the new line El Hawaria-Oueslatia has been disregarded, being very evidently much more unfavourable.

Tab. 4-10 – ELMED power plant in El Hawaria : network reinforcements and other ranking elements

Solution	Reinforcements	New lines total length (km)	New ATR 400/225 kV	Losses in peak conditions (MW)	Notes
A	2x El Hawaria-Mornaguia	**300**	**zero**	**47.4** (1)	High ESCR values (within 7.48 ÷ 7.74 p.u.) related to the number of units in operation at El Hawaria Only one right-of-way necessary

(1) *The losses are independent from the power export to Italy and related only to the power supply for the internal needs in Tunisia.*



4.3 ELMED power plant in Enfidha

In this alternative the ELMED power plant is situated in the area of Enfidha and it's composed of two coal generating units, each of them with a rated power of 750 MVA.
Since different solutions to evacuate the power from this node are proposed in peak load conditions, each of them is tested distinguishing two cases:

- 400 MW ELMED power plant production to satisfy the internal Tunisian needs (only one generating unit in service);
- 1200 MW ELMED power plant production, including the 800 MW for power export to Italy through the HVDC link.

As usual, in minimum loading conditions, the configuration with the ELMED power plant generating 1000 MW is considered.
Each solution entails the addition of new 400 kV both for the connection of the new ELMED power plant and for the connection of the AC/DC substation in El Hawaria. Similarly to the previous cases, to comply with the N-1 security criterion at least two 400 kV lines outcoming for the ELMED power plant and linking the AC/DC converter station are considered.
In particular, both 400 kV lines connected to the AC/DC substation shall always be in operation when exporting/importing power to Italy.

Tab. 4-11 – ELMED power plant in Enfidha: connection alternatives

SOLUTION "A"	two lines from Enfidha to Mornaguia
SOLUTION "B"	line from Enfidha to Mornaguia
	line from Enfidha to Oueslatia
SOLUTION "C"	line from Enfidha to Mornaguia
	line from Enfidha to El Hawaria
SOLUTION "D"	two lines from Enfidha to Hawaria

4.3.1 Enfidha: peak load conditions

4.3.1.1 Power generation to supply the internal load in Tunisia (400 MW)

SOLUTION "A"

In *Fig.4.25* the international exchanges and the internal power balances are represented. The total power exchange with Algeria is close to zero, and as the HVDC connection is disconnected, there's no power export to Italy.
Fig.4.26 shows the active power flows on the new lines and their average loading.
The power produced by the ELMED power plant is obviously shared equally on these two connections, showing about a 20% loading. Even if this value appears to be too low, both lines are necessary in order to avoid the disconnection from the grid of the whole power plant, in case of fault on one of those.
The "N-1" security analysis has been carried out as well, but no voltage violations or overloads have showed up beside those presented in the base case and thus not depending from the installation of the new power plant.

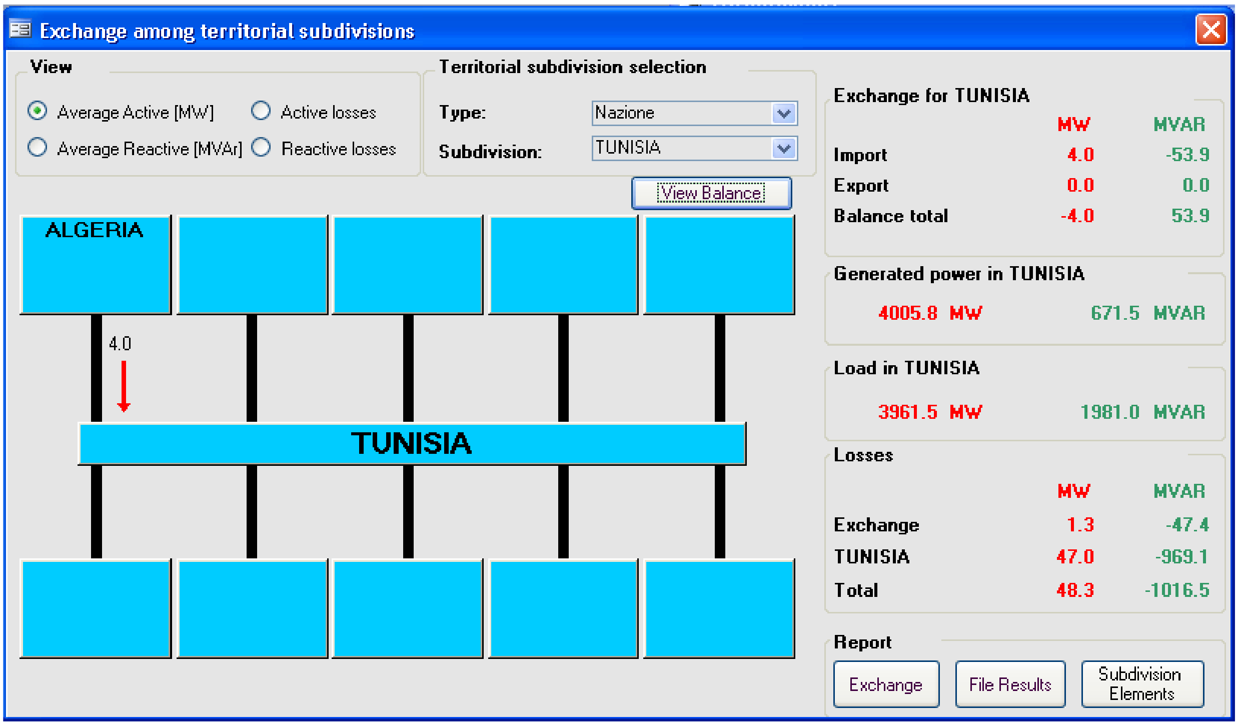


Fig.4.25 - 400 MW case - International exchanges and power balances for the Tunisian grid.

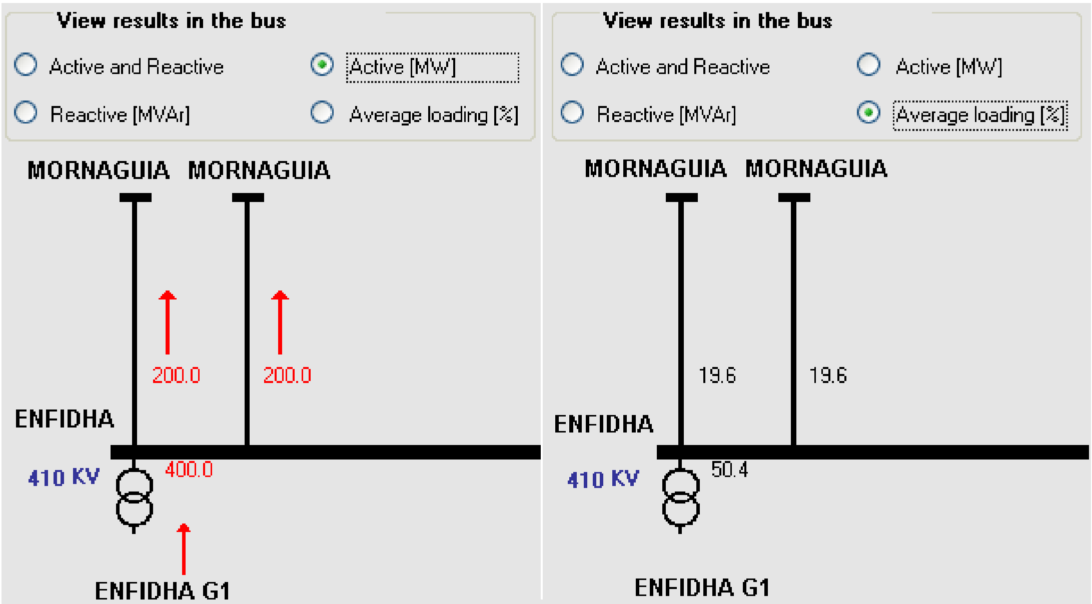


Fig.4.26 - 400 MW case - Power flows and average loading on the two new 400 kV connections.

SOLUTION "B"

This solution provides quite the same results as before. The losses increase slightly (about 1.5 MW) with respect to the previous solution (*Fig.4.27*); that depends on the fact that one of the two connections from Enfidha to Mornaguia has been replaced by one connection of the same length to Oueslatia, which is connected to Mornaguia through another 400kV line (130 km). Thus, the impedance between Enfidha and Mornaguia has grown, and the average loading on the two lines is different (*Fig.4.28*): nearly 300 MW (75% of ELMED power plant production) flow on the connection Enfidha-Mornaguia whilst the other line Enfidha-Oueslatia is lightly loaded.

Moreover, the Oueslatia-Mornaguia line connection was already transmitting some power from south to north beforehand and the connection of the new unit in Enfidha creates a further power flow overlapped to the previous one contributing to increase the losses. On the contrary, only the ELMED generation power flows in Enfidha-Mornaguia line.

The "N-1" security analysis hasn't showed any voltage violation or overload.

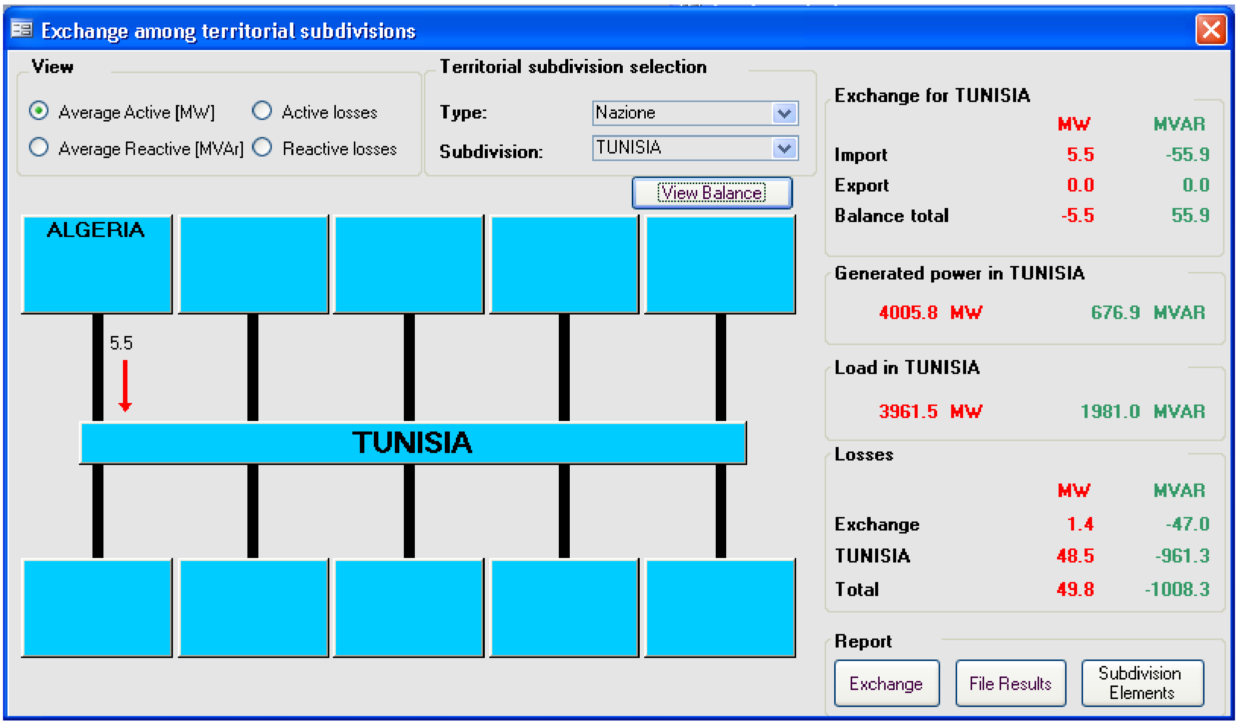


Fig.4.27 - 400 MW case - International exchanges and power balances for the Tunisian grid.

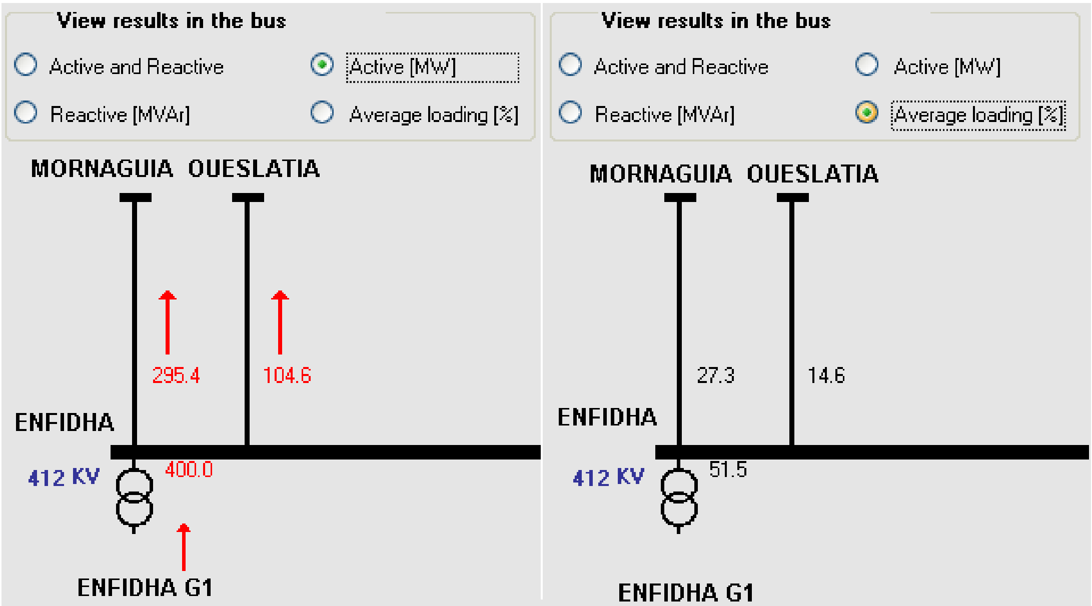


Fig.4.28 - 400 MW case - Power flows and average loading on the two new 400kV connections.

SOLUTION “C”

As this solution entails a direct connection between the ELMED power plant in Enfidha and the converter station in El Hawaria, only one 400 kV line from Mornaguia to El Hawaria has been considered.

In *Fig.4.29* the power balances and the international exchanges are presented. The power losses remain similar to those of solution “A”, even if the configuration is comparable to solution “B”.

The direct connection to Mornaguia is obviously more loaded (30%) than the line between Enfidha and El Hawaria (14%) (*Fig.4.30*).

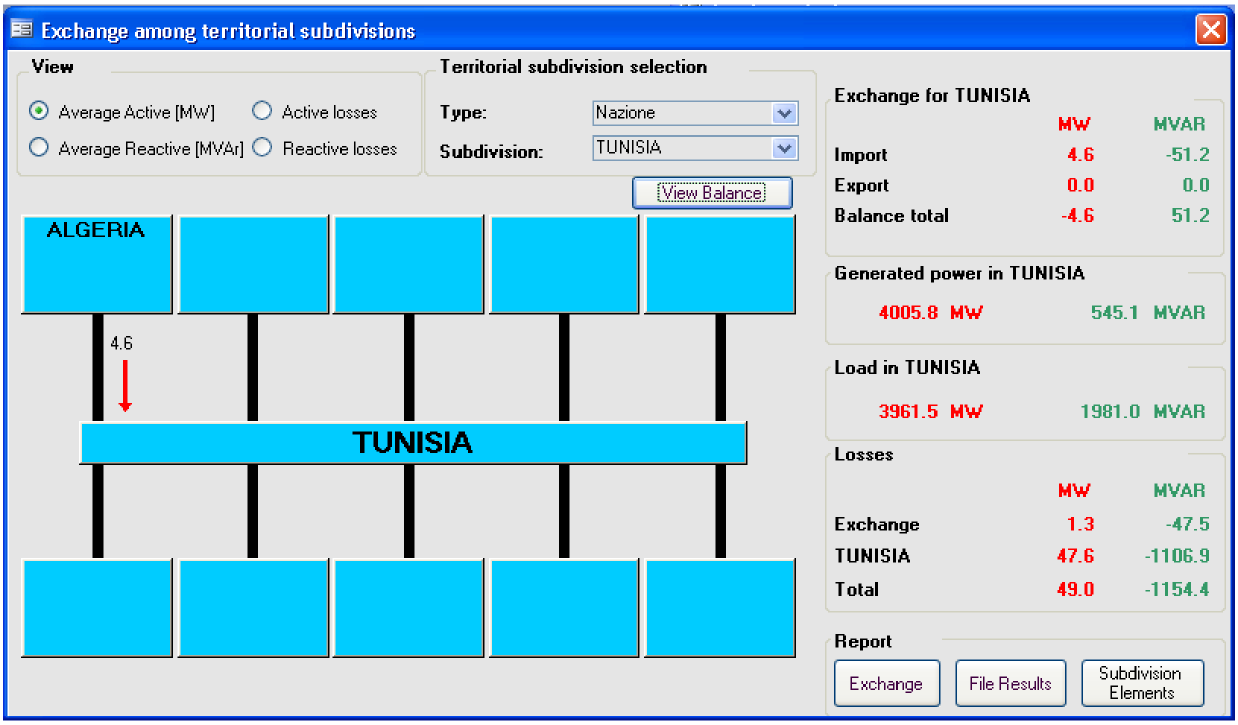


Fig.4.29 - 400 MW case - International exchanges and power balances for the Tunisian grid.

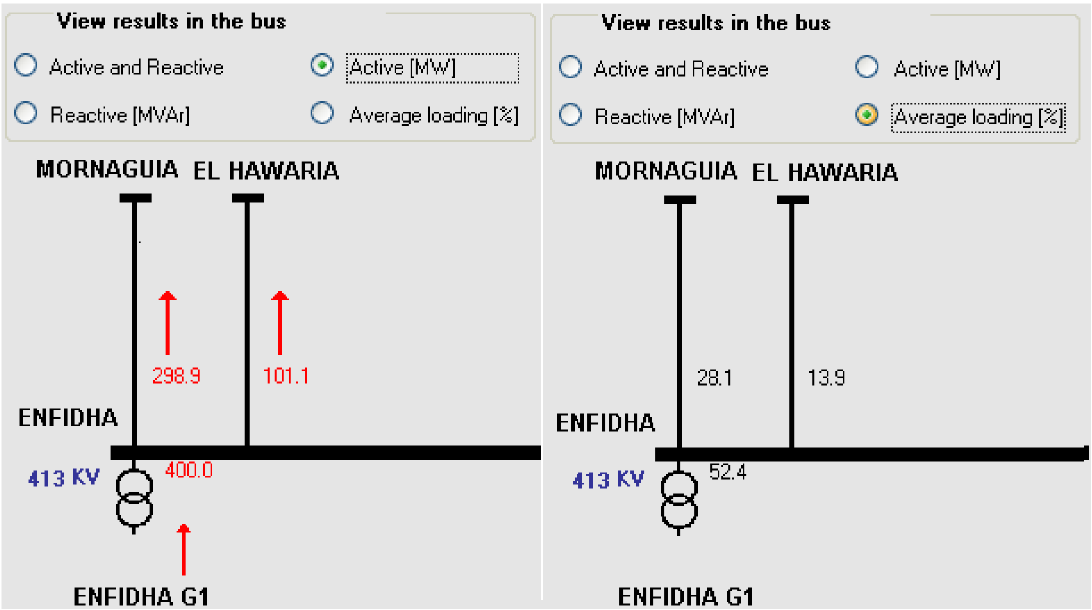


Fig.4.30 - 400 MW case - Power flows and average loading on the two new 400 kV connections.

SOLUTION "D"

This solution entails two direct connections between the ELMED power plant in Enfidha and the converter station in El Hawaria, and only one 400 kV line from Mornaguia to El Hawaria.

In *Fig.4.31* the power balances and the international exchanges are presented. The power losses increases slightly in comparison to the other solutions presented above.

The "N-1" security analysis (*Tab.4-12*) shows an overvoltage on the Enfidha and El Hawaria busses in case of fault of the 400/20 kV ATR of the ELMED power plant, because the loading of the connections Mornaguia-El Hawaria and El Hawaria-Enfidha falls to zero.

A similar situation could be caused by a fault on the 400 kV connection between Mornaguia and El Hawaria which implies a disconnection of the ELMED power plant from the rest of the grid.

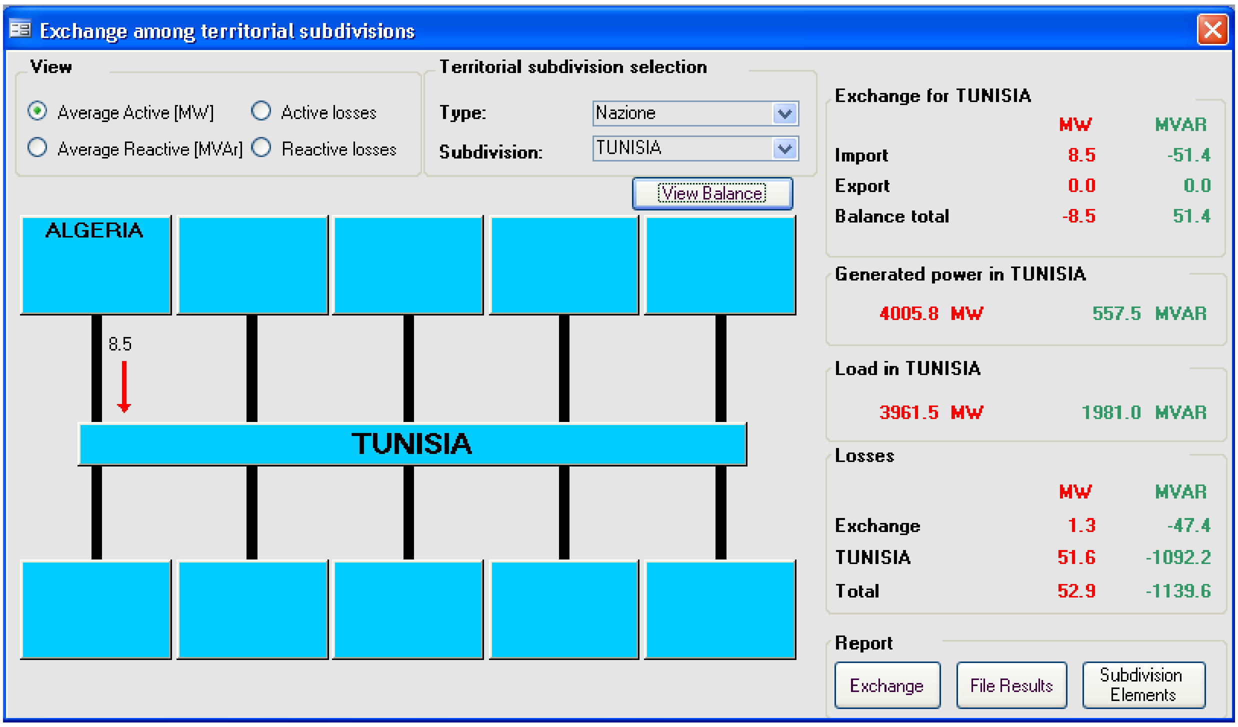


Fig.4.31 - 400 MW case - International exchanges and power balances for the Tunisian grid.

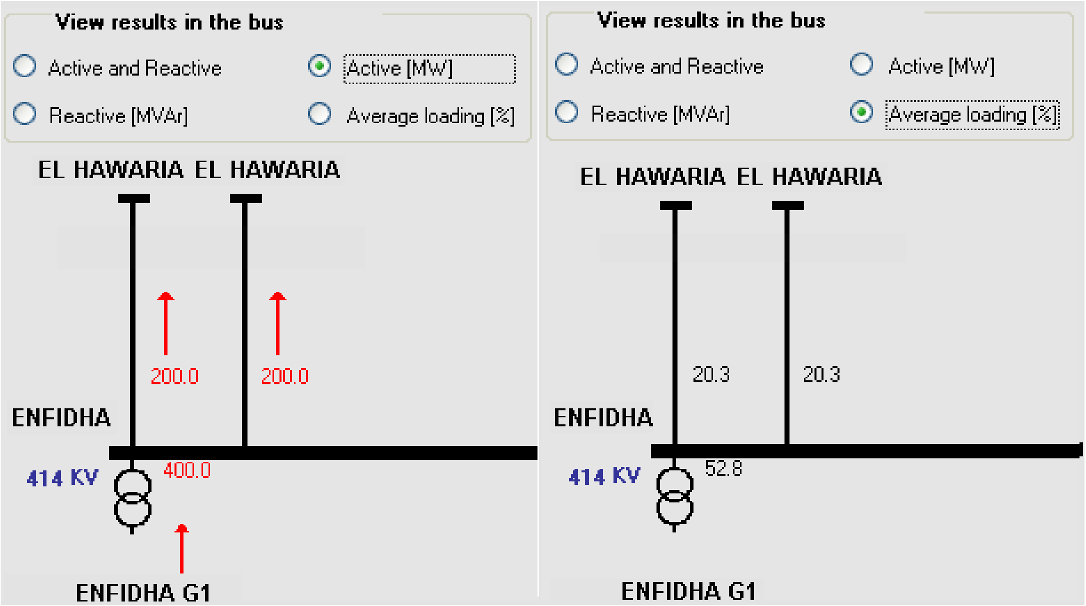


Fig.4.32 - 400 MW case - Power flows and average loading on the two new 400kV connections.

Tab.4-12 - "N-1" security analysis results (violations and overloads).

Contingency		Vn (kV)	Violation	Vn (kV)	V_N (kV)	V_{N-1} (kV)	ΔV (%)
ENFIDHA	ENFIDHA	400/20	ENFIDHA	400	413.9	462.5	15.6%
ENFIDHA	ENFIDHA	400/20	HAWARIA	400	418.9	455.9	13.9%

4.3.1.2 Power generation to supply the internal load in Tunisia and for power export (1200 MW)

SOLUTION "A"

Fig.4.33 shows increased power losses (circa 20 MW greater than before) due to the grown production of the ELMED power plant (1200 MW), which now produces also the 800 MW sent to the HVDC converter station in El Hawaria. Obviously the sharing of the power on the two lines from Enfidha to Mornaguia is the same (*Fig.4.34*).

In *Tab.4-13* the voltage violations obtained from the "N-1" security analysis are listed. The voltage drops can be easily avoided increasing the shunt compensation (till 400 MVar) of the reactive power absorbed by the HVDC connection. The ESCR at the AC/DC converter station remains around 4.

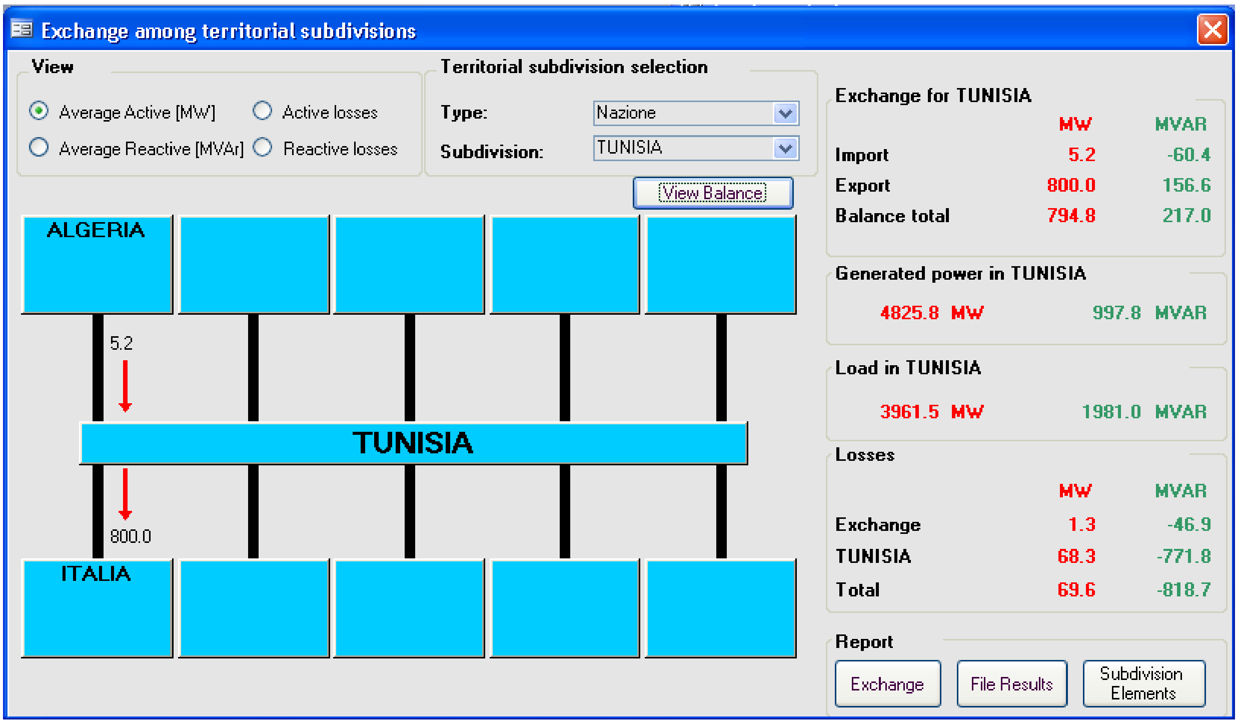


Fig.4.33 - 1200 MW case - International exchanges and power balances for the Tunisian grid.

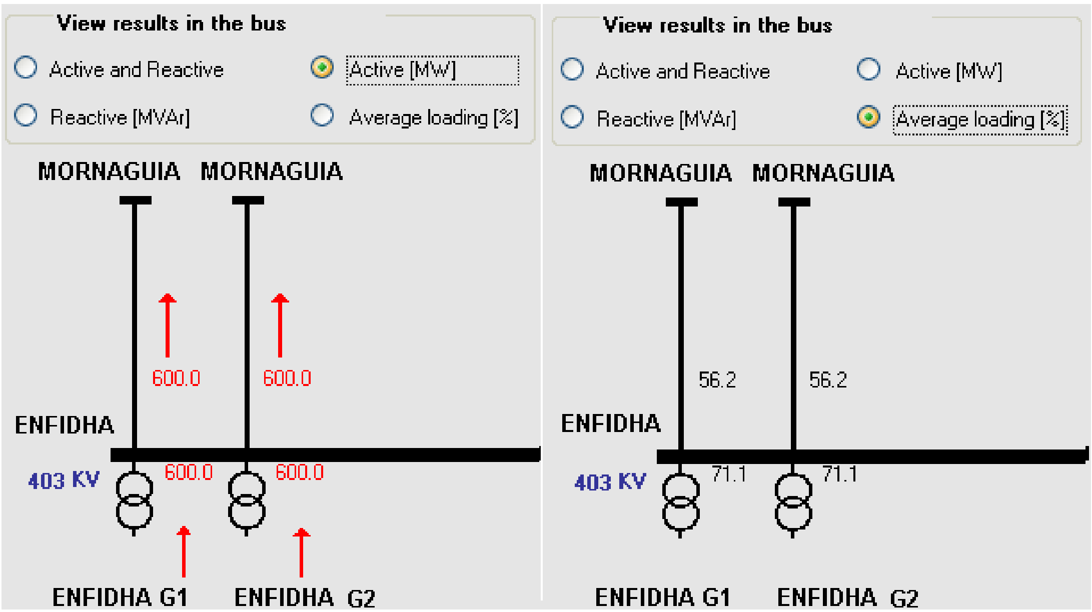


Fig.4.34 - 1200 MW case - Power flows and average loading on the two new 400kV connections.

Tab.4-13 - "N-1" security analysis results (violations and overloads).

Contingency		Vn (kV)	Violation	Vn (kV)	V_N (kV)	V_{N-1} (kV)	ΔV (%)
MORNAGUIA	**HAWARIA**	**400**	**HAWARIA**	**400**	**393.4**	**340.2**	**-14.9**

SOLUTION "B"

The solution "B" shows poorer performances compared to "A" and "C" in terms of power losses (Fig.4.35), which are about 10 MW greater (nearly the 15% more). That implies higher operating costs that a priori should be avoided. Beside that, the other results obtained through the analysis (Fig.4.36, Tab.4-14) are quite similar to those of the previous solution.

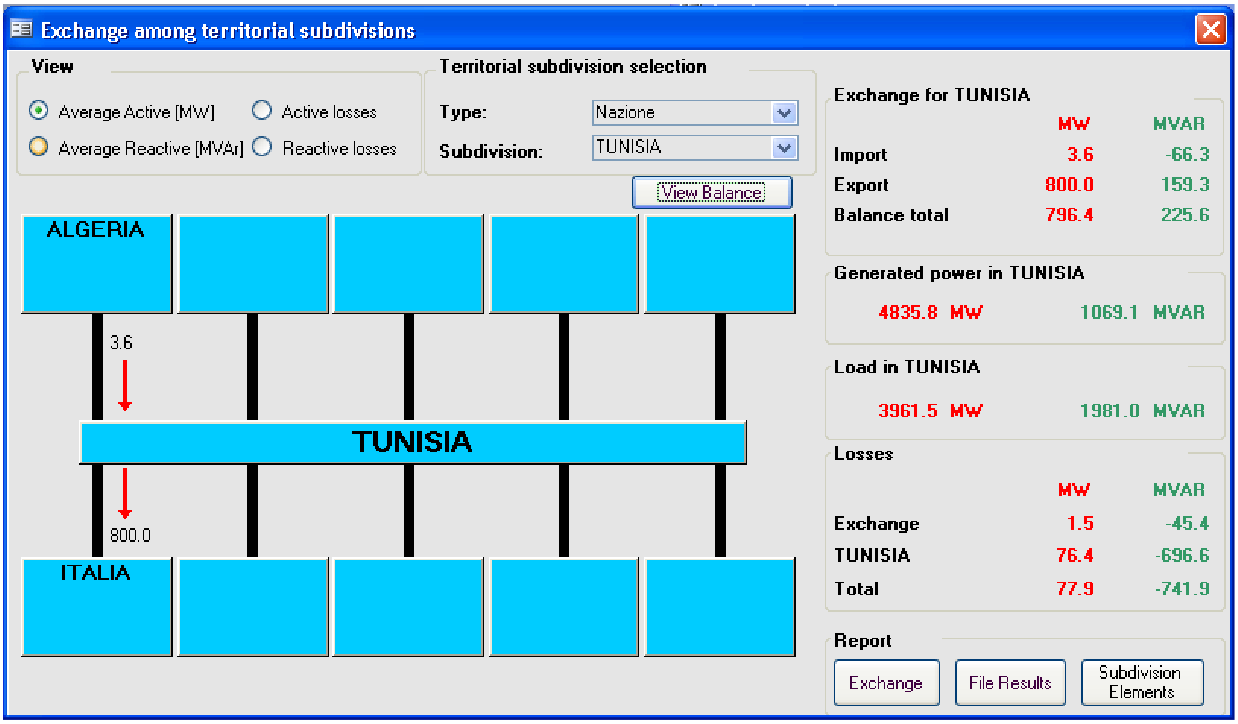


Fig.4.35 - 1200 MW case - International exchanges and power balances for the Tunisian grid.

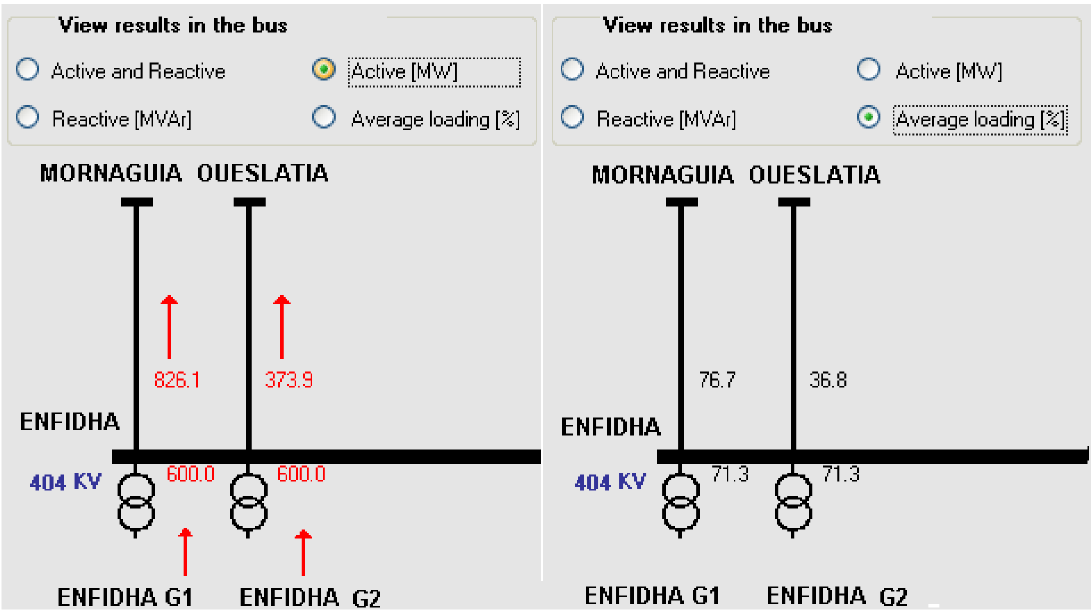


Fig.4.36 - 1200 MW case - Power flows and average loading on the two new 400kV connections.

Contingency		Vn (kV)	Violation	Vn (kV)	V_N (kV)	V_{N-1} (kV)	ΔV (%)
MORNAGUIA	**HAWARIA**	**400**	**HAWARIA**	**400**	**391.5**	**334.6**	**-16.3**

Tab.4-14 - "N-1" security analysis results (violations and overloads).

SOLUTION "C"

Power balances and losses (Fig.4.37) are similar to those of solution "A". Both lines are loaded with the same share of power (Fig.4.38): the 400 MW generated to supply the internal load contribute to equally share the power on the two lines outcoming from Enfidha.

What makes this solution as a problematic one, is the "N-1" security (Tab.4-15). Beside voltage violations in El Hawaria due to a contingency on one of the lines connecting it to the rest of the grid, a fault on the Enfidha-Mornaguia causes a slight overload on Enfidha-El Hawaria connection. However, as already shown in other solutions, simply increasing the reactive power compensation with a shunt capacity (in the order of 400 MVar), not only the voltage level grows in both conditions (N, N-1), but at the same time the overload disappears. ESCR maintains an acceptable value of 4,2.

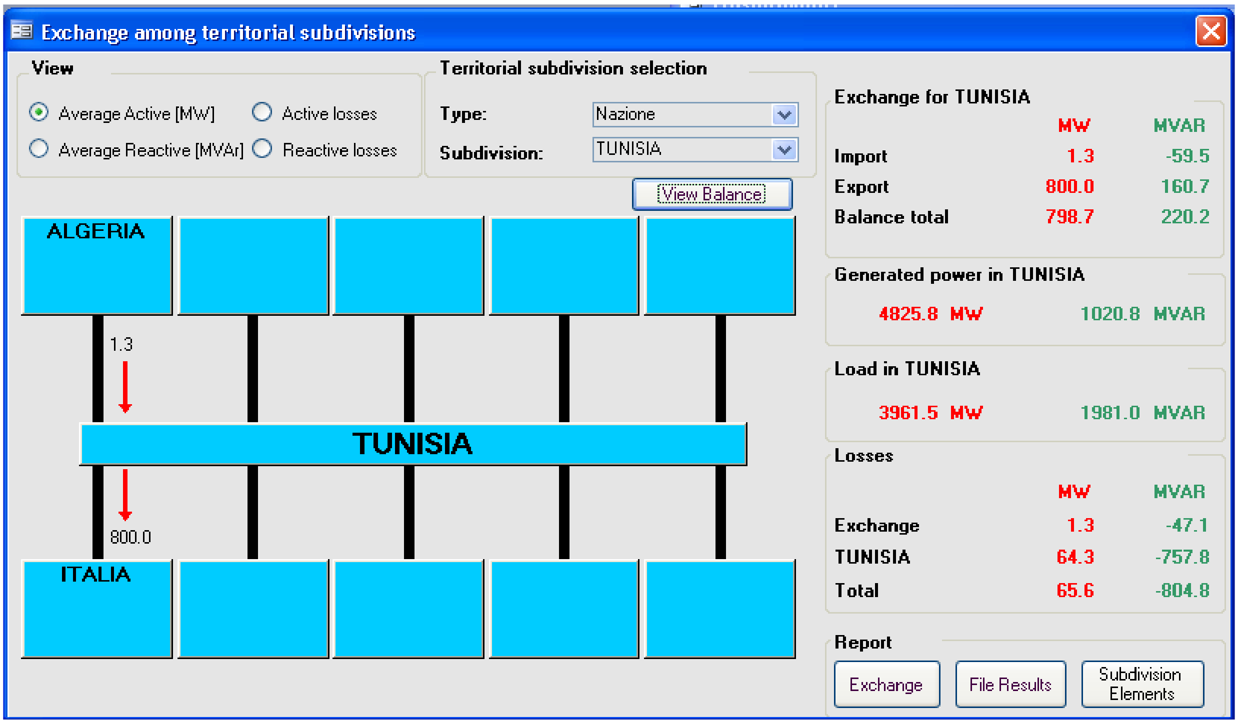


Fig.4.37 - 1200 MW case - International exchanges and power balances for the Tunisian grid.

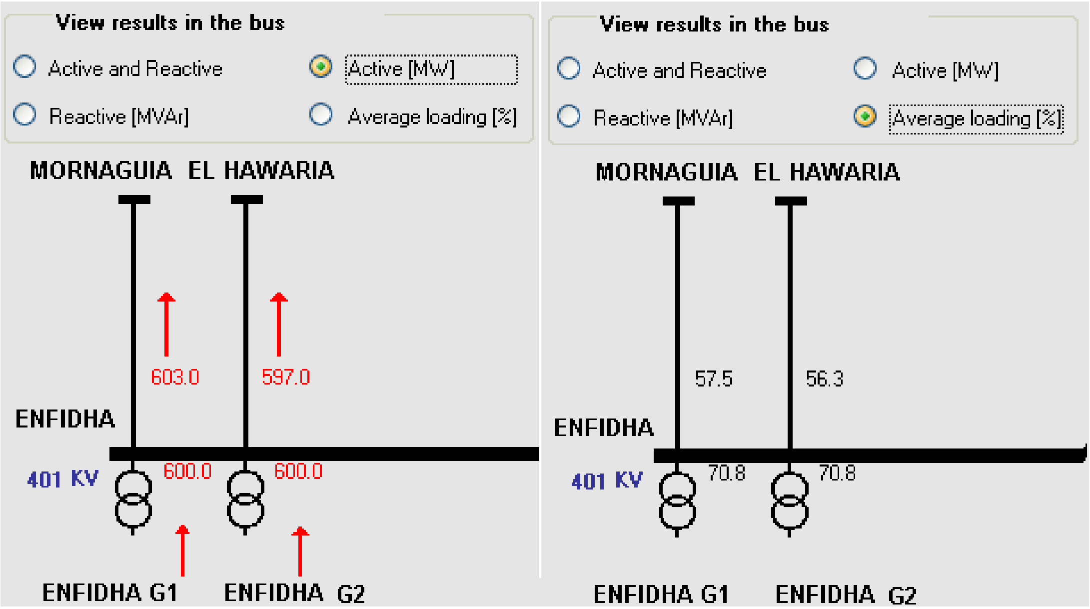


Fig.4.38 - 1200 MW case - Power flows and average loading on the two new 400kV connections.

Tab.4-15 - "N-1" security analysis results (violations and overloads).

Contingency		Vn (kV)	Violation	Vn (kV)	V_N (kV)	V_{N-1} (kV)	ΔV (%)
ENFIDHA	**HAWARIA**	**400**	**HAWARIA**	**400**	**390.5**	**328.7**	**-17.8**
MORNAGUIA	**HAWARIA**	**400**	**HAWARIA**	**400**	**390.5**	**325.6**	**-18.7**

Contingency		Vn (kV)	Overload		Vn (kV)	I_{N-1} (kA)	I_{N-1} (p.u.)
MORNAGUIA	**ENFIDHA**	**400**	**ENFIDHA**	**HAWARIA**	**400**	**1.86**	**1.208**

<u>SOLUTION "D"</u>

Power balances (*Fig.4.39*) are similar to those of solution "A", even if active power losses are slightly higher. Both lines are loaded with the same share of power (*Fig.4.40*): the 400 MW generated to supply the internal load contribute to equally share the power on the two lines outcoming from Enfidha.

What makes this solution as a problematic one, is the "N-1" security (Tab.4-15). Beside that, a fault on one of the Enfidha-El Hawaria causes a slight overload on the other similar connection, the case of fault of the line Mournaguia-El Hawaria has not to be underestimated, as it causes a splitting into two islands, one of these consisting of the HVDC connection and the ELMED power plant.

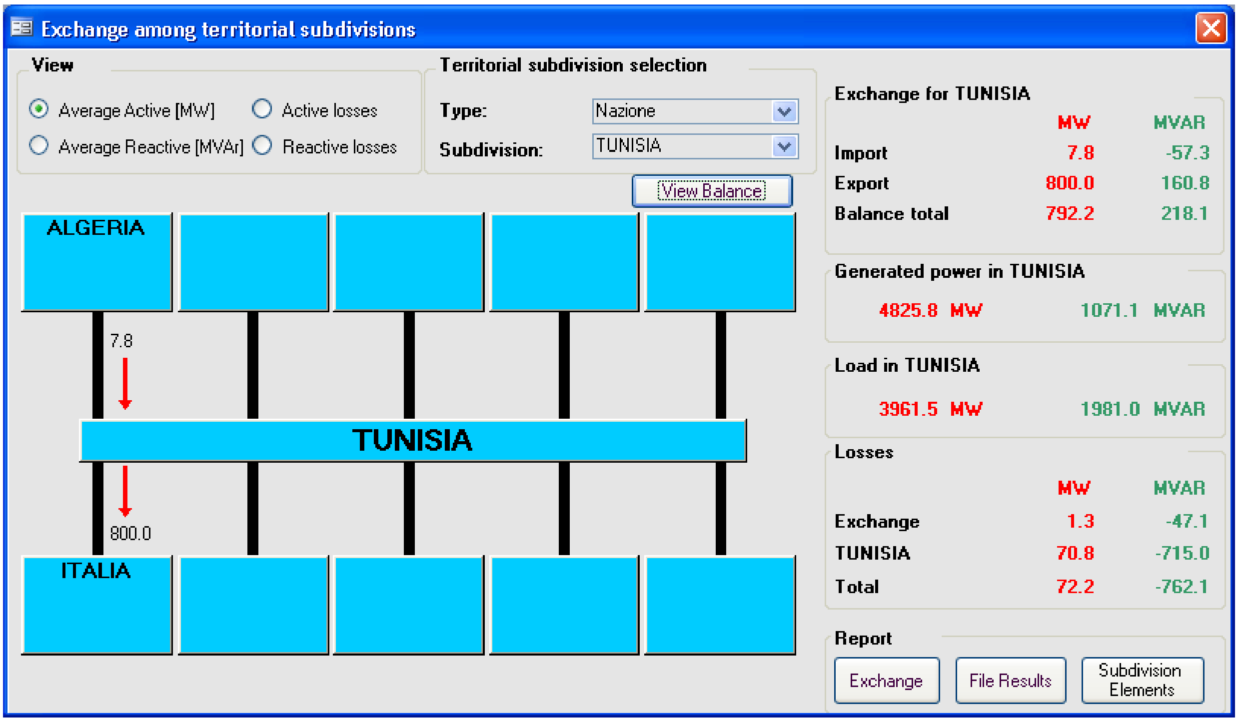


Fig.4.39 - 1200 MW case - International exchanges and power balances for the Tunisian grid.

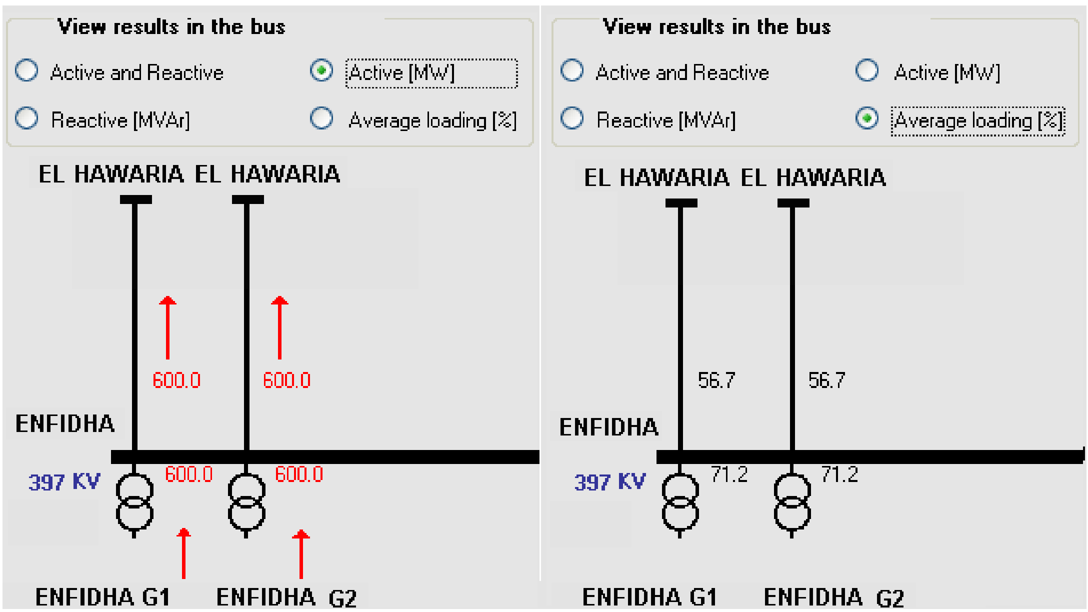


Fig.4.40 - 1200 MW case - Power flows and average loading on the two new 400kV connections.

Tab.4-16 - "N-1" security analysis results (violations and overloads).

Contingency		Vn (kV)	Overload		Vn (kV)	I_{N-1} (kA)	I_{N-1} (p.u.)
MORNAGUIA	**ENFIDHA**	**400**	**ENFIDHA**	**HAWARIA**	**400**	**1.86**	**1.208**

4.3.2 Enfidha: minimum load conditions

4.3.2.1 Power generation to supply the internal load in Tunisia and for power export (1000 MW)

SOLUTION "A"

The power balance of Tunisian grid in this scenario is shown in Fig.4.41, while Fig. 4.49 shows the active power flow and the loading on the 400 kV lines Enfidha – Mornaguia.

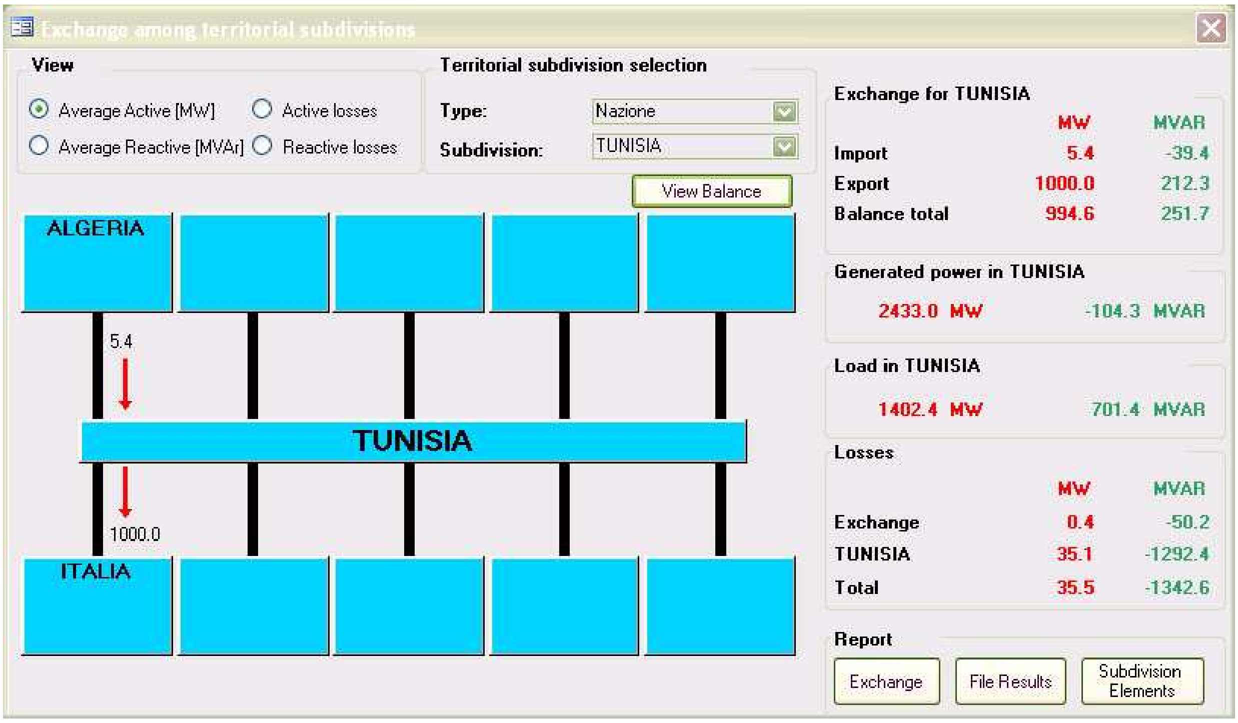


Fig.4.41 - 1000 MW case A - International exchanges and power balances for the Tunisian grid, off peak

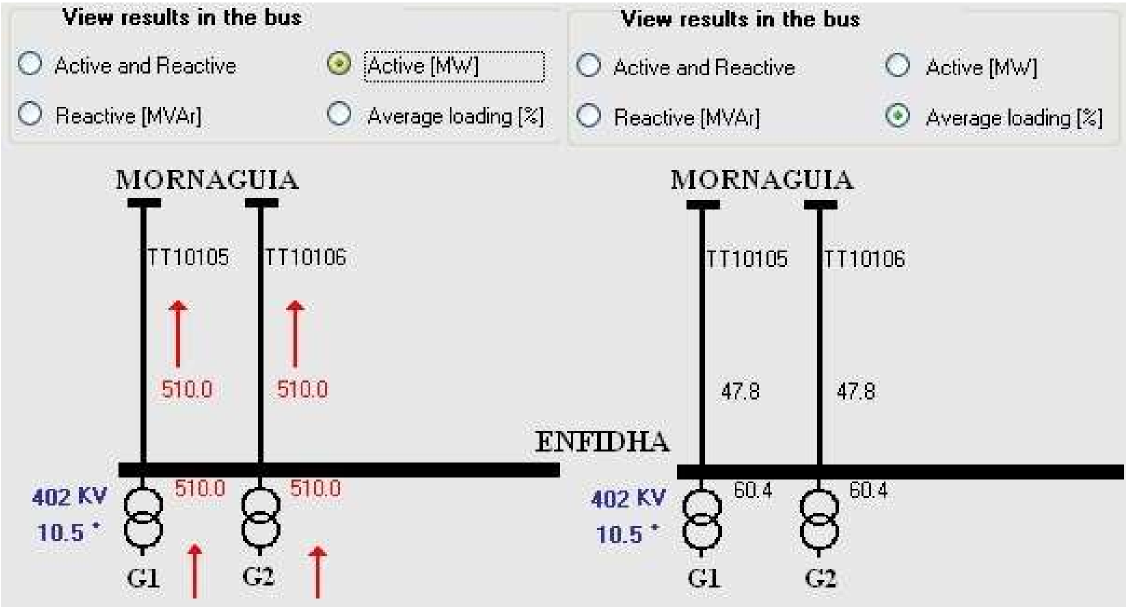


Fig.4.42 - 1000 MW case A - Power flows and average loading on the two new 400kV connections, off peak

The load flow analysis doesn't point out overloads or voltage violations in sound network condition, but the contingency on one 400 kV line El Hawaria – Mornaguia gives rise to an undervoltage in El Hawaria and to an overload on the remaining line due to the high reactive power flow. The critical state can be avoided hypothesising a higher level of reactive power compensation (about 650 Mvar at Vn, instead of 370 Mvar) in the converter station.

Tab.4-17 - "N-1" security analysis results (violations and overloads)

Contingency		Vn (kV)	Violation	Vn (kV)	V_N (kV)	V_{N-1} (kV)	ΔV (%)
BOUCHEMMA	BOUCHEMMA	400/220	BOUCHEMMA	400	418.0	441.3	10%
MORNAGUIA	HAWARIA	400	HAWARIA	400	383.8	291.0	-27%
MORNAGUIA	HAWARIA	400	HAWARIA	400	383.8	291.0	-27%

With this high level of capacitor banks in El Hawaria, the ESCR parameter is in the range 1.98 – 3.53 p.u., that is a result quite similar to the cases "A" and "B" of power plant in Bizerte, but surely lower than the scenario with power plant in El Hawaria. Therefore, the same remark can be applied: <u>the solution is technically feasible but it requires a tuning of the capacitor banks in El Hawaria and specific measures for voltage control could be needed.</u>

<u>SOLUTION "B"</u>

Fig.4.43 shows the power balance on Tunisian network in this scenario with generation in Enfidha, while Fig.4.44 represents the active power and consequent loading on the 400 kV lines outgoing from the new station of Enfidha 400 kV towards Oueslatia and Mornaguia.

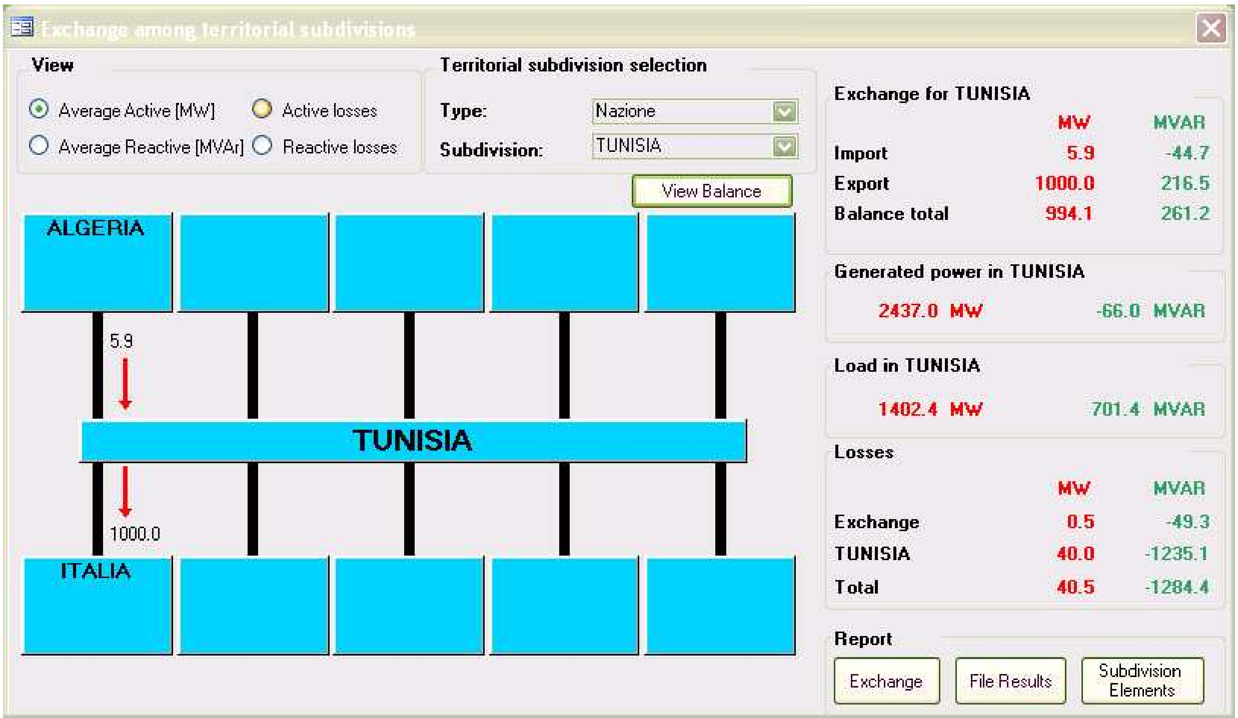


Fig.4.43 - 1000 MW case B - International exchanges and power balances for the Tunisian grid, off peak

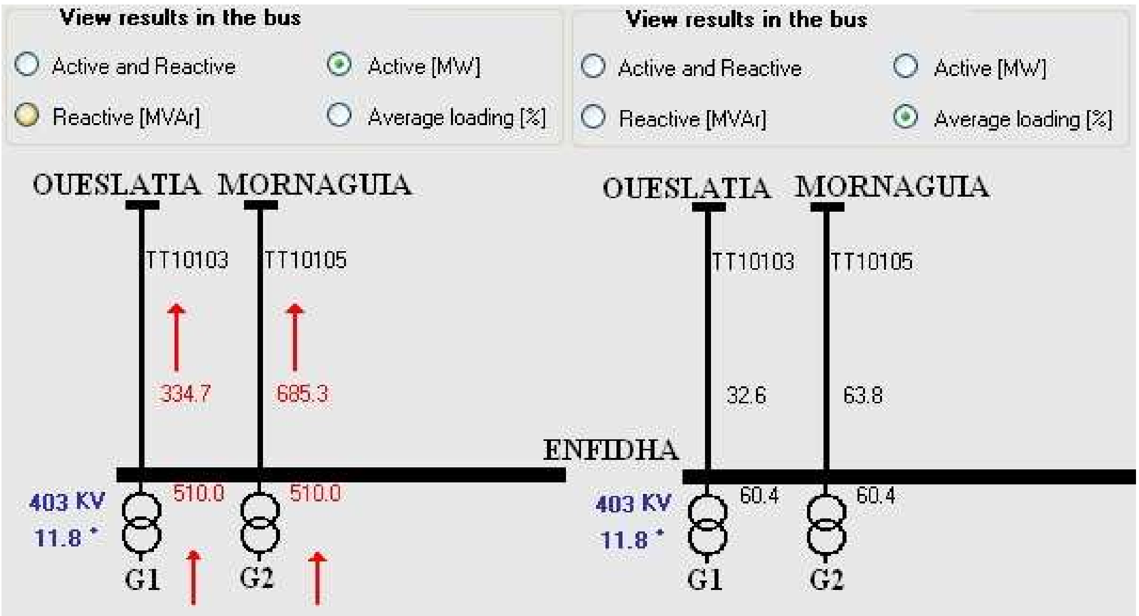


Fig.4.44 - 1000 MW case B - Power flows and average loading on the two new 400 kV connections, off peak

Also in this scenario the network in sound condition doesn't point out any critical state, but the outage of one 400 kV line El Hawaria – Mornaguia gives again rise to a low voltage level in El Hawaria. With a higher compensation in the converter station, at about 650 Mvar (instead of 370 Mvar, at Vn) the voltage is kept within the acceptable range.

Tab.4-18 - "N-1" security analysis results (violations and overloads)

Contingency		Vn (kV)	Violation	Vn (kV)	V_N (kV)	V_{N-1} (kV)	ΔV (%)
MORNAGUIA	HAWARIA	400	HAWARIA	400	381.4	292.3	-27%

ESCR parameter evaluation gives results similar to the previous scenario with values within the range 1.93 ÷ 3.41 p.u., so the same remark can be applied: <u>the solution is technically feasible even if the careful tuning of the capacitor banks in El Hawaria or specific measures for voltage control is needed.</u>

<u>SOLUTION "C"</u>

As presented in Fig.4.45, the active power losses decrease in comparison to the two solutions described above. The average loading of the two lines outgoing from Enfidha is showed in Fig.4.46.
During the "N-1" security analysis two main overloads have been noticed (Tab.4-19), both concerning a critical low voltage in El Hawaria due to a tripping of the 400 kV connections to Mornaguia or Enfidha.
In order to prevent these effects, the reactive power compensation in the converter station could be increased to 650 MVar, caausing a ESCR value's drop to a value within the range 1.93 ÷ 3.41.
Therefore, the same conclusion as Solution "A" and "C" has been reached: <u>the solution is technically feasible even if the careful tuning of the capacitor banks in El Hawaria or specific measures for voltage control is needed.</u>

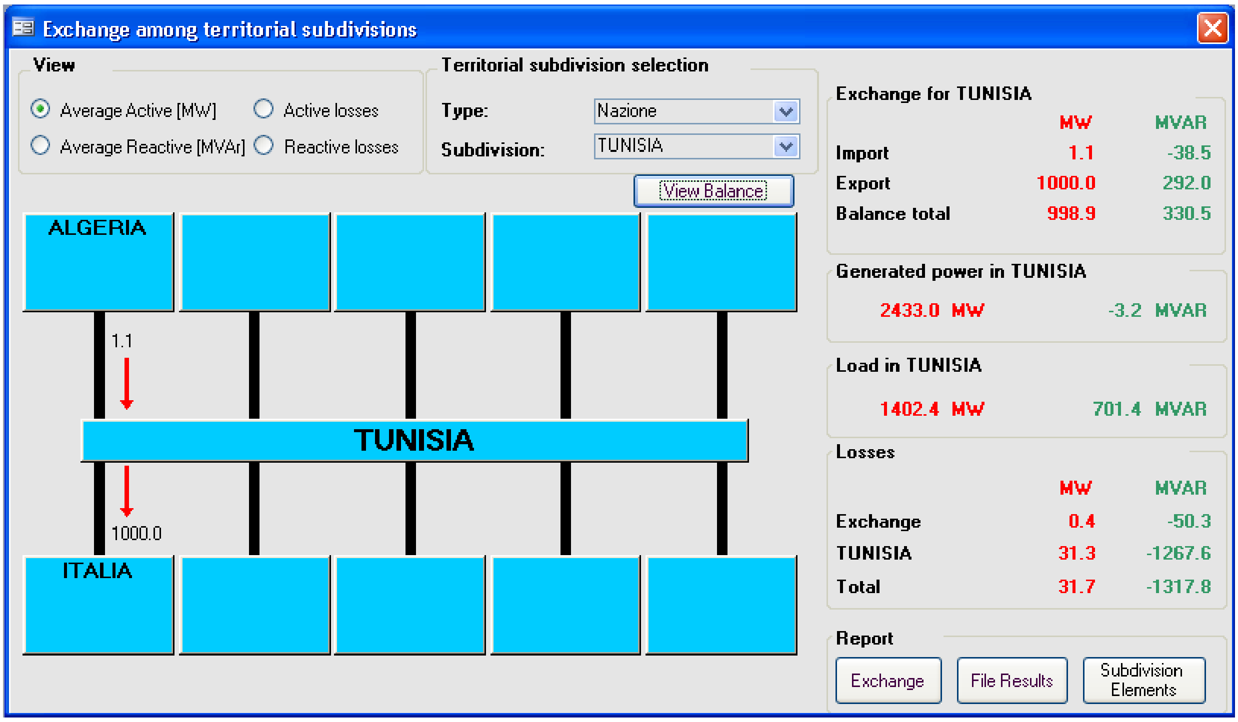


Fig.4.45 - 1000 MW case C - International exchanges and power balances for the Tunisian grid, off peak

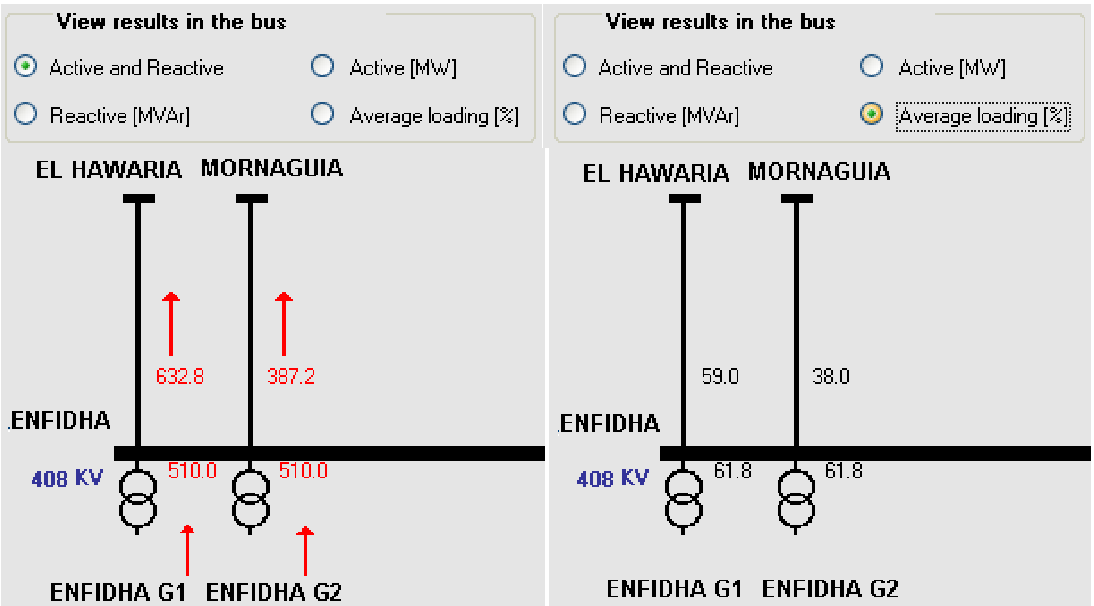


Fig.4.46 - 1000 MW case C - Power flows and average loading on the two new 400kV connections, off peak

Tab.4-19 - "N-1" security analysis results (violations and overloads)

Contingency		Vn (kV)	Violation	Vn (kV)	V_N (kV)	V_{N-1} (kV)	ΔV (%)
BOUCHEMMA	BOUCHEMMA	400/220	BOUCHEMMA	400	418.0	441.3	10%
ENFIDHA	HAWARIA	400	HAWARIA	400	375	283	-29%
MORNAGUIA	HAWARIA	400	HAWARIA	400	375	278.3	-30%

SOLUTION "D"

As presented in Fig.4.47, the active power losses decrease considerably in comparison to the solutions described above. The average loading of the two lines outgoing from Enfidha is showed in Fig.4.48.

During the "N-1" security analysis no problematic overload has been noticed (Tab.4-20), except that one in Bouchemma already described.

However, the grid splitting in case of fault of the line El Hawaria – Mornaguia remains a problematic issue to be carefully investigated.

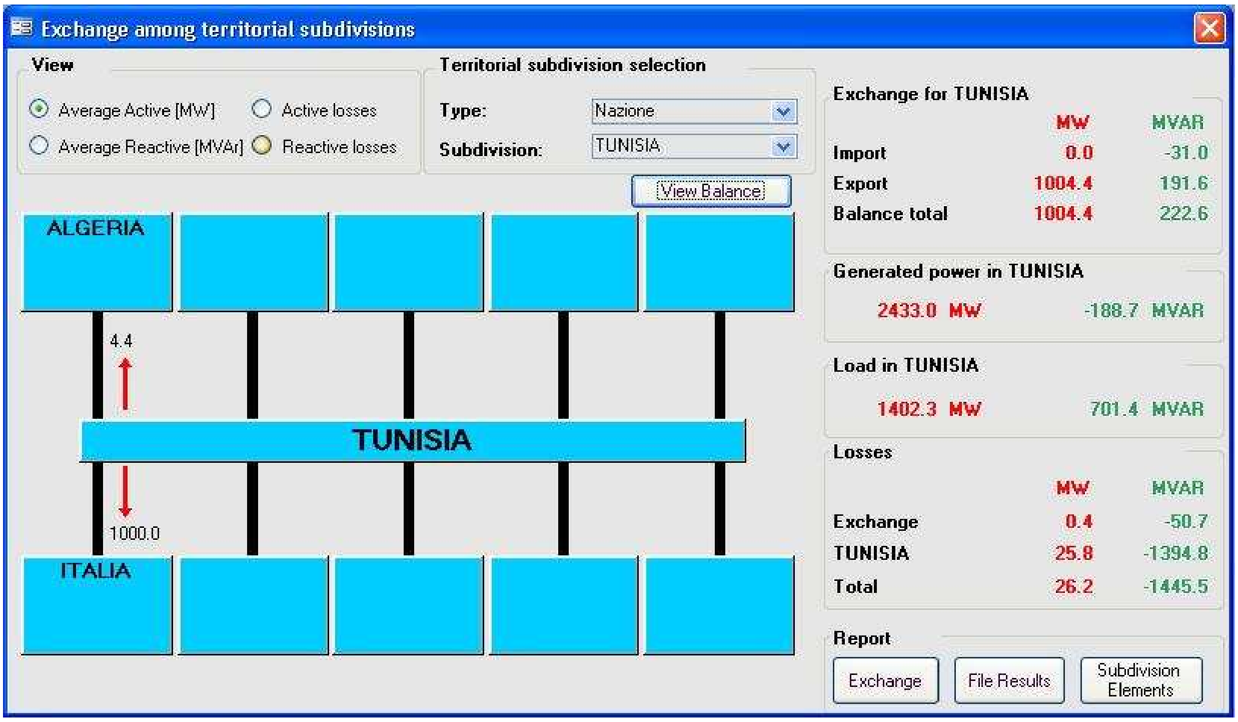


Fig.4.47 - 1000 MW case D - International exchanges and power balances for the Tunisian grid, off peak

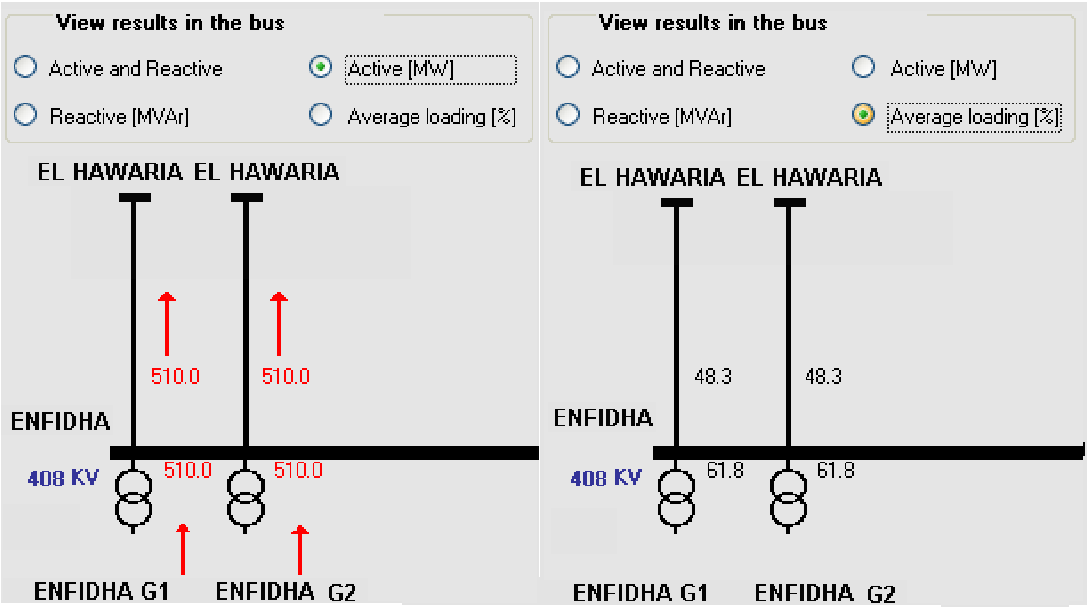


Fig.4.48 - 1000 MW case D - Power flows and average loading on the two new 400kV connections, off peak

Tab.4-20 - "N-1" security analysis results (violations and overloads)

Contingency		Vn (kV)	Violation	Vn (kV)	V_N (kV)	V_{N-1} (kV)	ΔV (%)
BOUCHEMMA	BOUCHEMMA	400/220	BOUCHEMMA	400	418.0	441.3	10%

4.3.3 *Enfidha: solutions of network reinforcements and conclusions*

Tab. 4-21 shows the network reinforcements obtained from static calculations to connect both the ELMED power plant located in Enfidha and the HVDC interconnection with Sicily. The four solutions are all technically possible, but the performances of solution "A" are more favourable either from the technical (no critical problems detected in N-1 conditions) and environmental point of view (only two right-of-ways for the new lines).

As for the power losses, solution "C" is the most favourable one when considering the power export to Italy, even if power losses difference with solution "A" is not remarkable.

Since solution "D" does not guarantee the satisfaction of internal needs (400 MW in peak conditions) in case of loss of El Hawaria - Mornaguia connection ("N-1" security analysis), a solution "D1" has been analysed, adding a new grid reinforcement (Enfidha – Mornaguia). The situation avoids the loss of Tunisian supply in case of El Hawaria – Mornaguia line trip, improves evidently the static system performance as the losses decrease and the ESCR increases, however the new lines total length becomes too high (550 km) hence this solution is less favourable in comparison to solution "C".

Tab. 4-21 – ELMED power plant in Enfidha : network reinforcements and other ranking elements

Solution	Reinforcements	New lines total length (km) (1)	New ATR 400/225 kV	Losses in peak conditions (MW)	Notes
A	2x Enfidha-Mornaguia	**200**	**zero**	**68.3**	Only two right-of-way necessary ESCR within 3.53 ÷ 3.99 p.u.
	2x El Hawaria-Mornaguia	**300**			
B	Enfidha-Mornaguia Enfidha-Oueslatia	**210**	**zero**	**76.4**	ESCR within 3.41 ÷ 3.88 p.u
	2x El Hawaria-Mornaguia	**300**			
C	Enfidha-Mornaguia Enfidha-El Hawaria	**250**	**zero**	**64.3**	ESCR within 3.74 ÷ 4.15 p.u
	El Hawaria-Mornaguia (2)	**150**			
D	2x Enfidha-El Hawaria	**300**	**zero**	**70.8**	ESCR within 4.83 ÷ 5.05 p.u
	El Hawaria-Mornaguia	**150**			
D1	2x Enfidha-El Hawaria Enfidha - Mornaguia	**400**	**zero**	**57.4**	ESCR whitin 5.09 ÷ 5.25 p.u.
	El Hawaria-Mornaguia	**150**			

(1) In the table we have split the km of new lines necessary to connect the ELMED power plant to the Tunisian grid from those necessary to connect the AC/DC substation in El Hawaria to the Tunisian grid. As for the

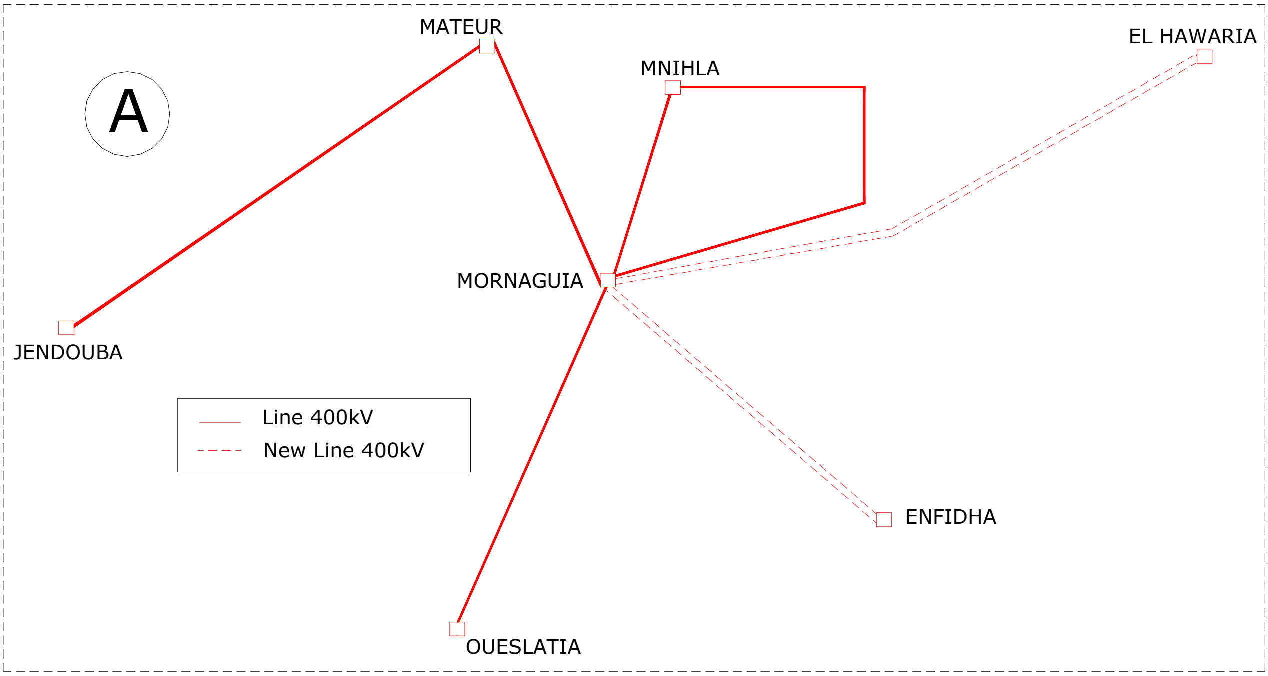
solution "C", we have attributed half of the line length Enfidha-El Hawaria (150 km) to the connection of the ELMED power plant and half to the connection of the AC/DC substation, since this line will play a double role.

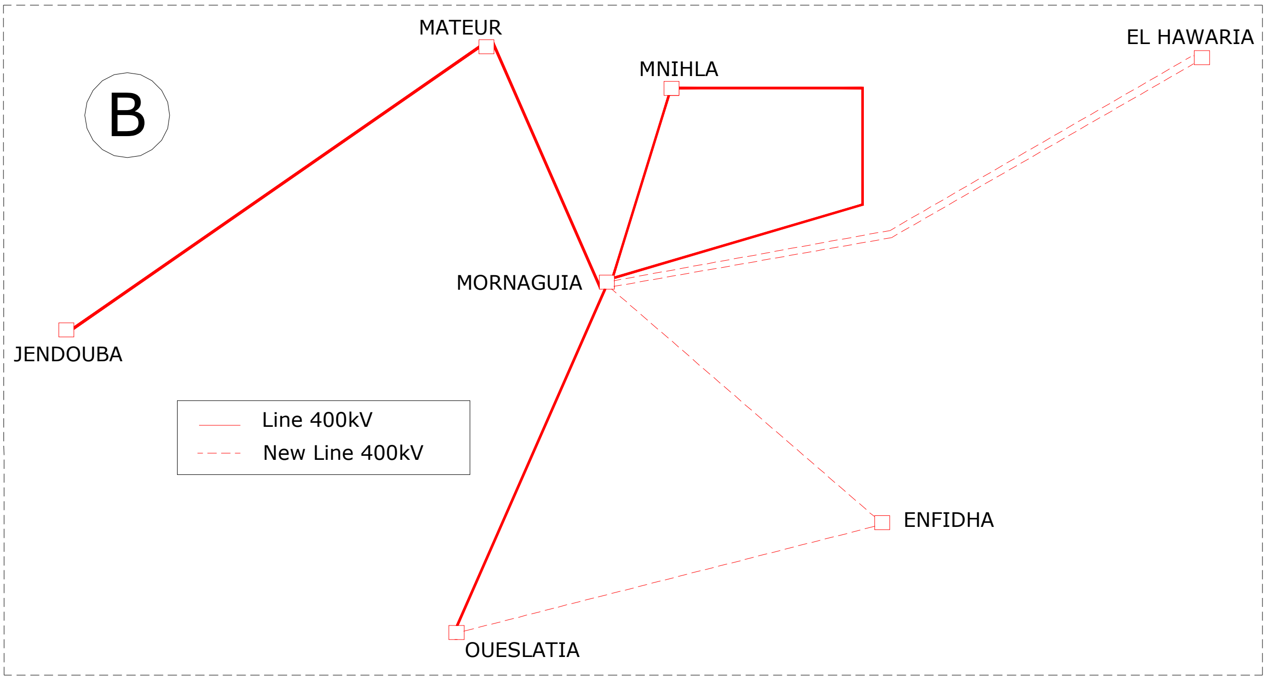
(2) *This new line is necessary not only for Tunisian demand, but also to assure the N-1 security criterion in case of exportation to Italy.*

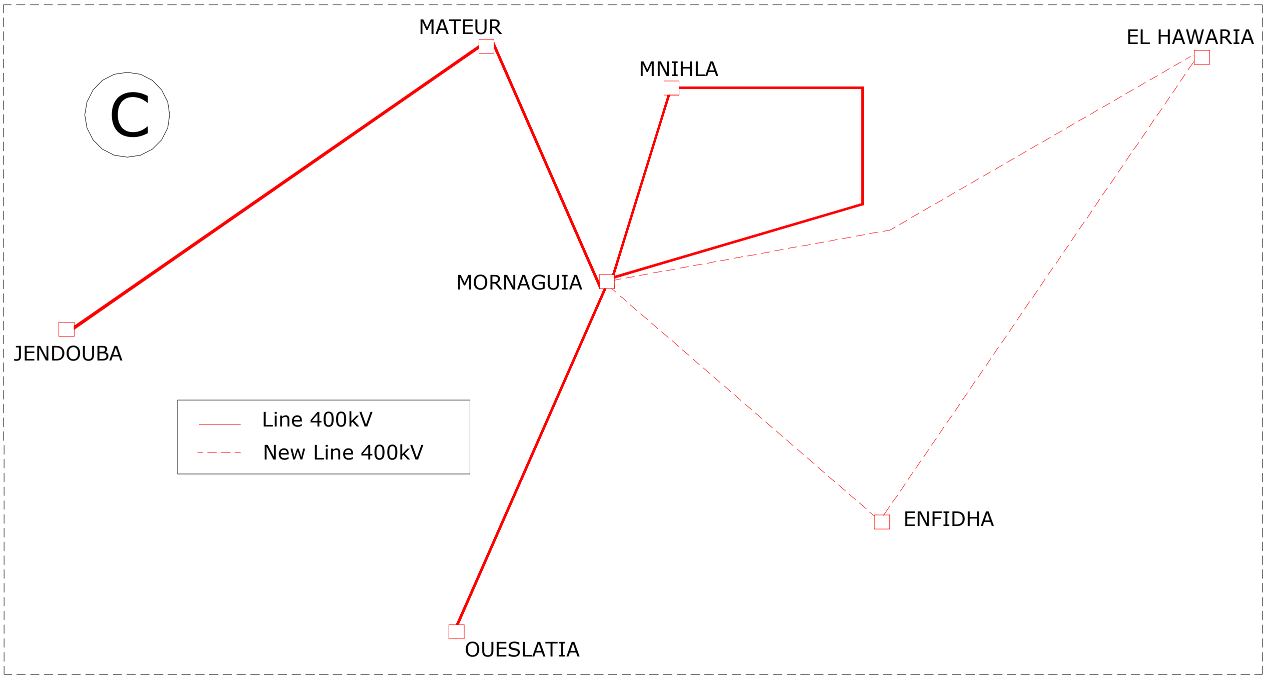
Tab. 4-22 – ELMED power plant in Enfidha : reactive power compensation

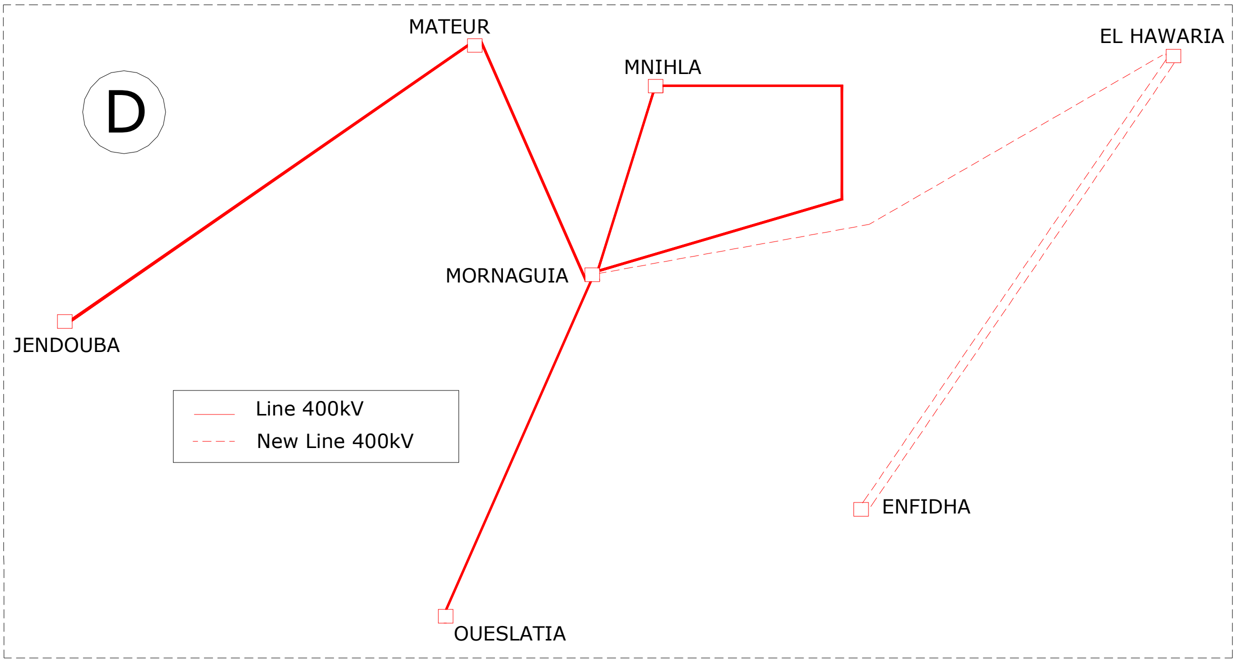
Solution	Reactive power compensation [Mvar]	
	Peak Load	Minimum Load
A	400	650
B	400	650
C	400	650
D	293	370

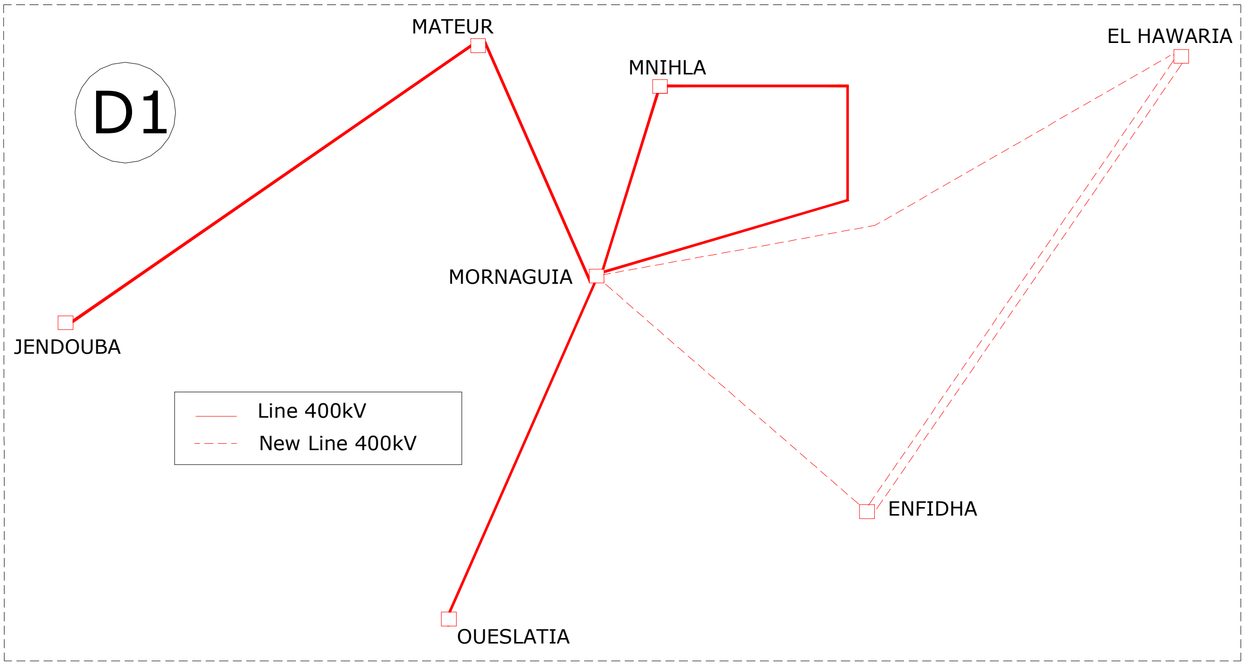
Note: the shunt Var compensation shown in the above table shall be intended only as indicative, since the study didn't addressed the optimisation of this equipment.




MATEUR
EL HAWARIA
MNIHLA
B
MORNAGUIA
JENDOUBA
Line 400kV
New Line 400kV
ENFIDHA
OUESLATIA


MATEUR
EL HAWARIA
MNIHLA
C
MORNAGUIA
JENDOUBA
Line 400kV
New Line 400kV
ENFIDHA
OUESLATIA





4.4 ELMED power plant in Skhira

In this scenario the ELMED power plant is situated in the area of Skhira and it's composed of two coal units, each of them with a rated power of 750 MVA.

As usual, in our analysis we distinguish the case of power production to supply the internal load to Tunisia (400 MW) from the case where the ELMED power plant supplies both power to Tunisia and for export to Sicily (1200 MW). This enables us to discriminate between the reinforcements needed for the security of supply of the Tunisian system and the additional reinforcements required for power export. As highlighted in some other alternatives, it may occur that some reinforcements play a double role: for the internal power supply and for export.

We anticipate that for this alternative the connection scheme are generally different in the two mentioned cases (400 MW and 1200 MW).
Each solution includes a turn-in/turn-out substation (E/S[8]) on the Bouchemma – Sidi Mansour 225 kV double circuit line. This new in/out substation will be located nearby the Skhira power plant (connection length about 20 km) and will be equipped with two 400 MVA transformers[9].

Tab. 4-23 – ELMED power plant in Skhira : connection alternatives

Solution	ELMED power plant production	Preliminary network reinforcements in addition to the E/S substation on the 225 kV line Bouchemma-Sidi Mansour **
SOLUTION “A0”	400 MW	No new lines; only 2x400 MVA ATR on the Bouchemma-Sidi Mansour line
SOLUTION “A1”	400 MW	line from Skhira to Maknassy
	1200 MW	two lines from Skhira to Maknassy
SOLUTION “A2”	400 MW*	line from Skhira to Maknassy
	1200 MW	line from Skhira to El Hawaria
SOLUTION “B”	400 MW	line from Skhira to Mornaguia
	1200 MW	line from Skhira to Maknassy
		line from Skhira to Mornaguia
SOLUTION “C”	400 MW	line from Skhira to Bouchemma
	1200 MW	two lines from Skhira to Bouchemma
SOLUTION “D”	400 MW	line from Skhira to E/S line Bouchemma – Oueslatia
	1200 MW	line from Skhira to E/S line Bouchemma – Oueslatia line Skhira – Oueslatia

** Same solution as in “A1”*
*** All the new lines are at 400 kV. All the solutions from “A1” to “D” include the 2X400 MVA transformers on the Bouchemma-Sidi Mansour line, in order to have a better flexibility in the operation of the ELMED power plant, especially for the supply of the internal load in Tunisia through the 225 kV voltage level.*

4.4.1 Skhira: peak load conditions

4.4.1.1 Power generation to supply the internal load in Tunisia (400 MW)

SOLUTION “A0”

In this configuration the ELMED power plant is connected only to the 225 kV line Bouchemma – Sidi Mansour in turn-in/turn-out configuration with two 400 MVA transformers.
The N and N-1 security analysis showed that this solution is acceptable[10].
On the other end, the total active losses attain 75.2 MW. Obviously the absence of any new 400 kV transmission line increases significantly the total active power losses (75.2 MW with respect to 64.1 MW in solutions “A1” and “A2”), but no major problems were found.
Thus, strictly referring to the internal needs for the supplying of the internal load in Tunisia, this solution

[8] E/S: entrée-sortie
[9] This solution fulfils the N-1 security criterion in case of outage of one transformer, shows symmetry in the connection scheme with the double circuit 225 kV line and helps to increase the stability of the Skhira units facing a fault on the grid. As a matter of fact, when considering also the 400 kV line(s), one could consider the introduction of one 400/225 kV interconnection transformer only (solution to be checked to assess the reliability level and the performance in dynamic conditions).
[10] A slight overload of Rades – P2-TSC 225 kV line is detected after the trip of the double line Rades – Goulette equal to 127%, but this situation goes beyond the security standards presently applied by STEG.

is acceptable. However, for the selection of the best connection alternative for the internal needs of Tunisia only, one shall take also into account the cost of the losses.

SOLUTIONS "A1" and "A2"

In Fig. 4.49 the international exchanges and the internal power balances are presented. The total exchange with Algeria is close to zero, and as the HVDC connection is disconnected, there's no power export to Italy.

Fig.4.50 shows the active power flows on the new line and on the new 400/225 kV transformers and their average loading.

It is worth noting that the power produced by the ELMED power plant is distributed mainly on the new Skhira – Maknassy 400 kV line, causing about a 30% line loading while the 400/225 kV transformers are about 14% loaded. Even if this value appears to be very low, both the interconnections are necessary in order to avoid the disconnection from the grid of the power plant, in case of fault on one 400 kV line.

The N-1 security conditions are fulfilled. Only in case we apply the tripping of double circuit lines, this scenario highlights an overload on Rades – P2-TSC 225 kV line after the trip of the 225 kV double line Rades – Goulette (Tab.4-24). In this situation the line loading is equal to about 124%; a possible reinforcement of Rades – P2-TSC 225 kV line or other local measures to alleviate this slight overload shall be ascribed to the internal needs of the Tunisian system.

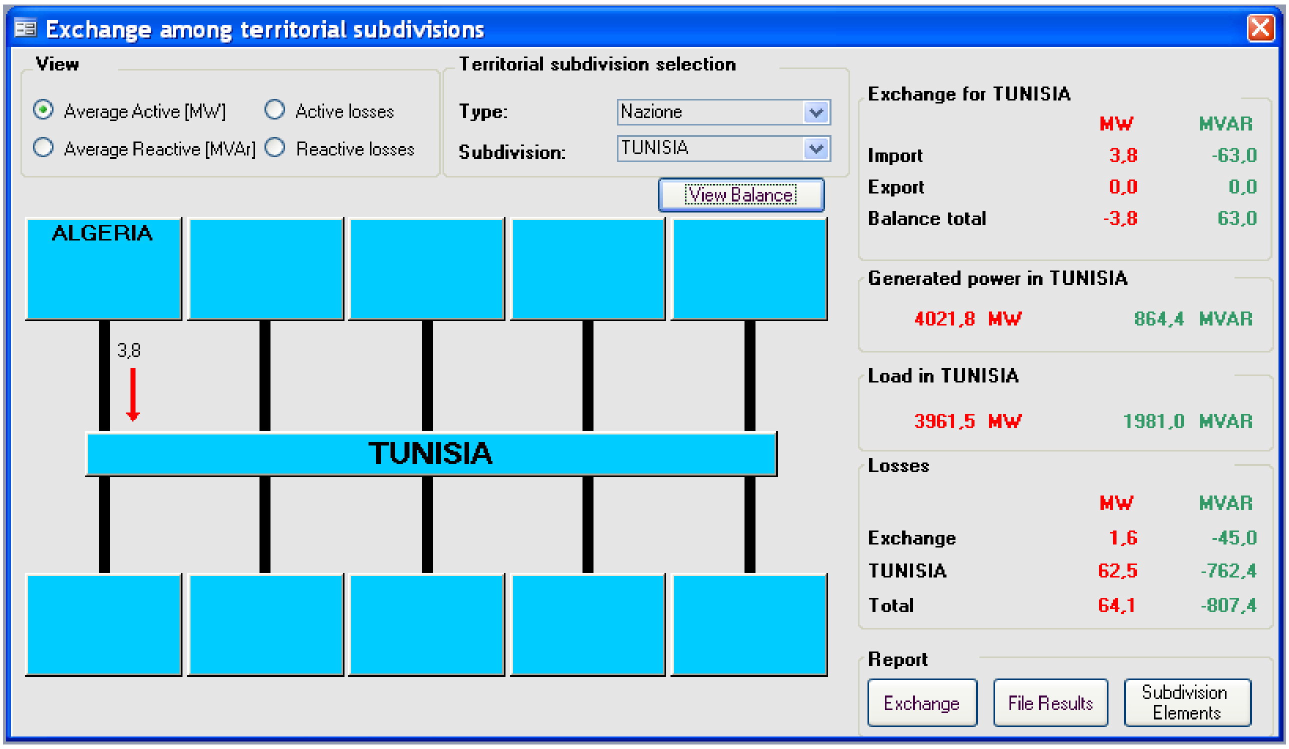


Fig. 4.49: 400 MW case - International exchanges and power balances for the Tunisian grid.

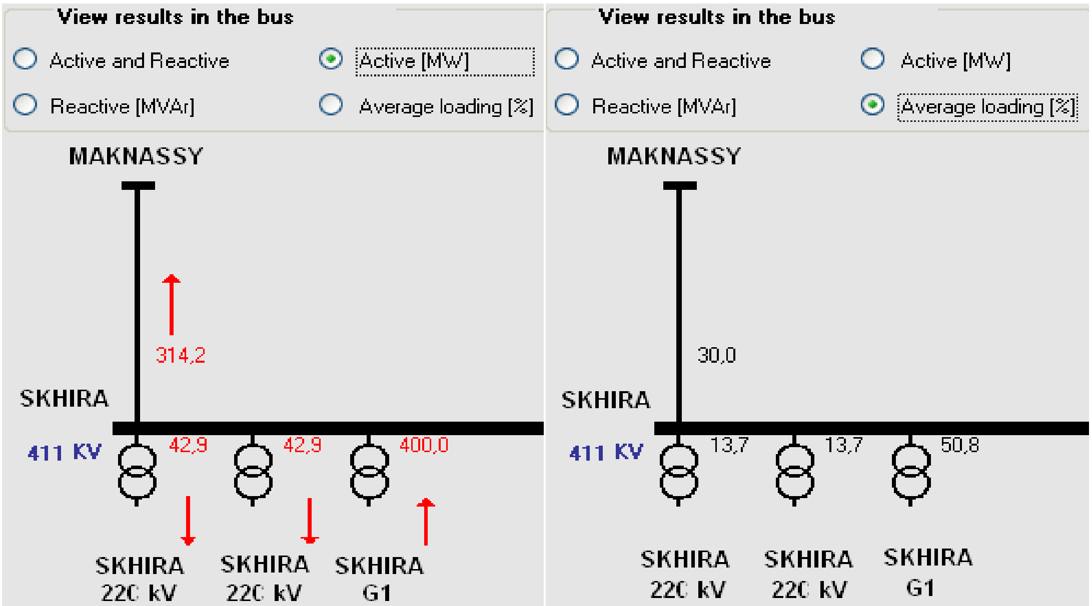


Fig.4.50 - 400 MW case - Power flows and average loading on the two new 400kV connections.

Tab.4-24 - “N-1” security analysis results (violations and overloads).

Contingency		Vn (kV)	Overload		Vn (kV)	I_{N-1} (kA)	I_{N-1} (p.u.)
RADES	**GOULETTE**	**220**	**RADES**	**P2-TSC**	**220**	**1.2**	**1.24**
RADES	**GOULETTE**	**220**					

<u>SOLUTION “B”</u>

In Fig.4.51 the international exchanges and the internal power balances are represented. The total exchange with Algeria is close to zero, and as the HVDC connection is disconnected, there’s no power export to Italy.

Fig.4.52 shows the active power flows on the new line and on the new 400/225 kV transformers and their average loading.

The power produced by the ELMED power plant is distributed mainly on new Skhira – Mornaguia 400 kV line, causing about a 26% line loading and about 20% transformer loading. Even if this value appears to be very low, both the interconnections are necessary in order to avoid the disconnection from the grid of the power plant, in case of fault on one of those.

A “N-1” security analysis has been carried out as well, but no voltage violation or overload have showed up beside those presented in the base case and thus not depending from the installation of the new power plant.

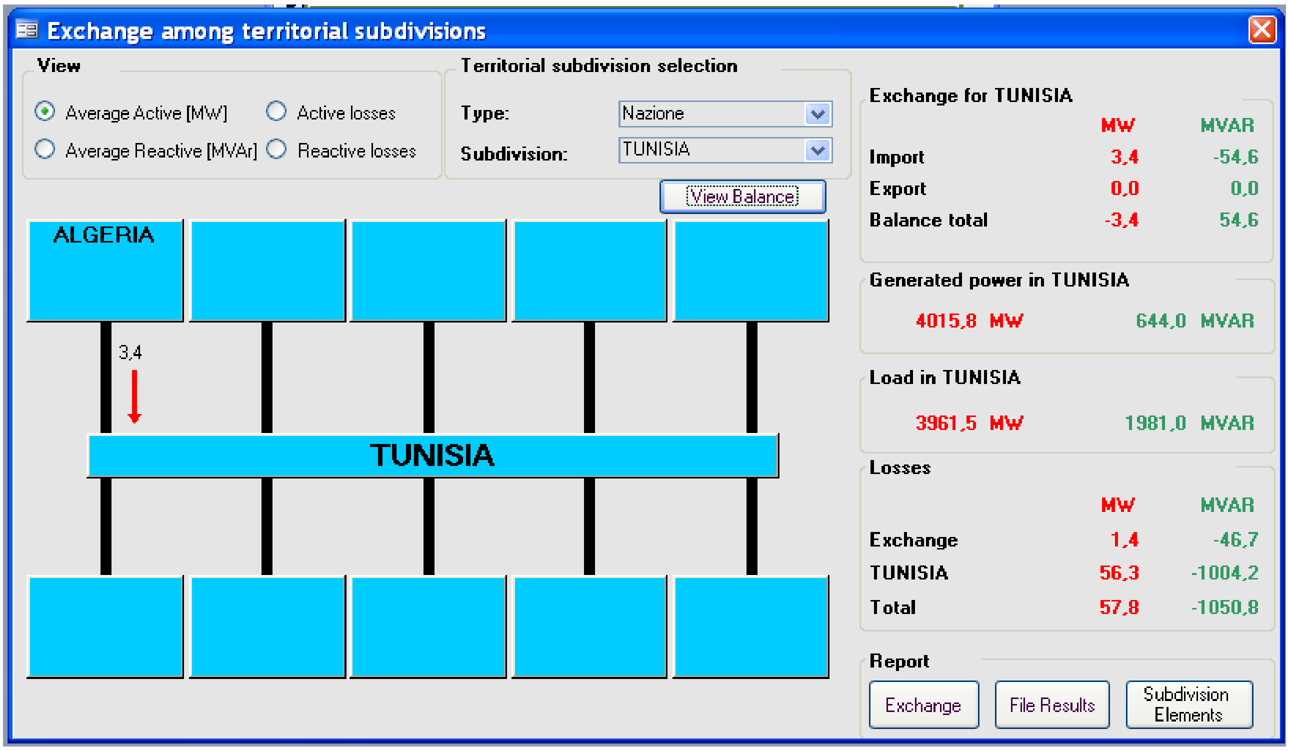


Fig.4.51 - 400 MW case - International exchanges and power balances for the Tunisian grid.

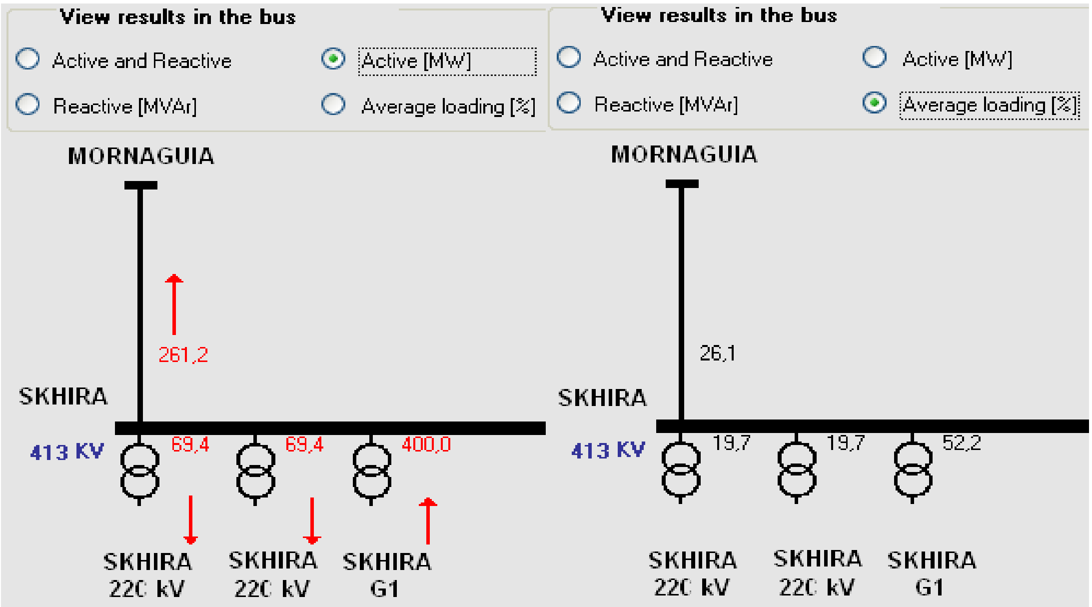


Fig.4.52 - 400 MW case - Power flows and average loading on the two new 400kV connections.

SOLUTION "C"

In Fig.4.53 the international exchanges and the internal power balances are represented. The total exchange with Algeria is close to zero, and as the HVDC connection is disconnected, there's no power export to Italy.

Fig.4.54 shows the active power flows on the new line and on the new 400/225 kV transformers and their average loading.

The power produced by ELMED power plant is distributed mainly on new Skhira – Bouchemma 400 kV

line, causing about a 24% line loading and about 21% transformer loading. In this case the percentage of total power flowing on 400 kV line is lower than in the previous cases because the total impedance of the 400 kV corridor Skhira-Bouchemma-Oueslatia-Mornaguia is higher: we remind that most of the internal load in Tunisia is concentrated in the North and supply from the Mornaguia s/s.
The "extended" N-1 security analysis[11] performed in this scenario highlights an overload on Rades – P2-TSC 225 kV line after the trip of the double line Rades – Goulette (Tab.4-25): the line loading is about equal to 125%. A possible reinforcement of Rades – P2-TSC 225 kV line or other local measures to alleviate this slight overload shall be ascribed to the internal needs of the Tunisian system.

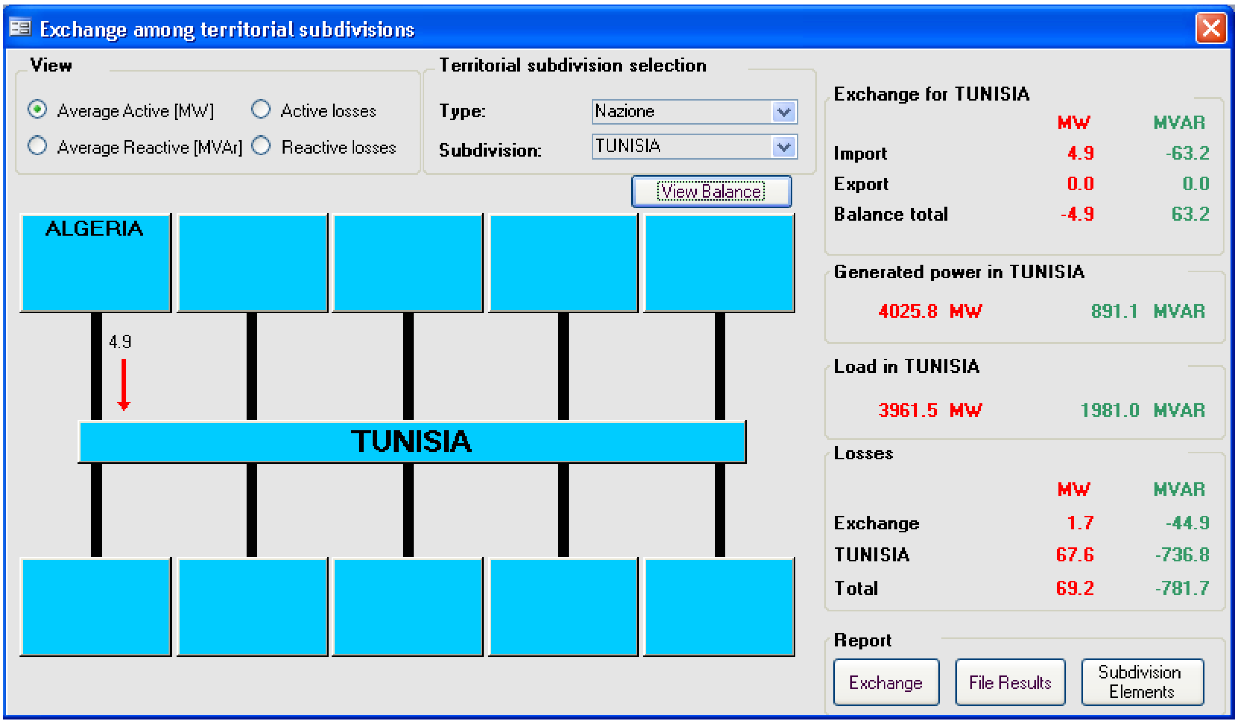


Fig.4.53 - 400 MW case - International exchanges and power balances for the Tunisian grid.

[11] Including the tripping of double circuit lines

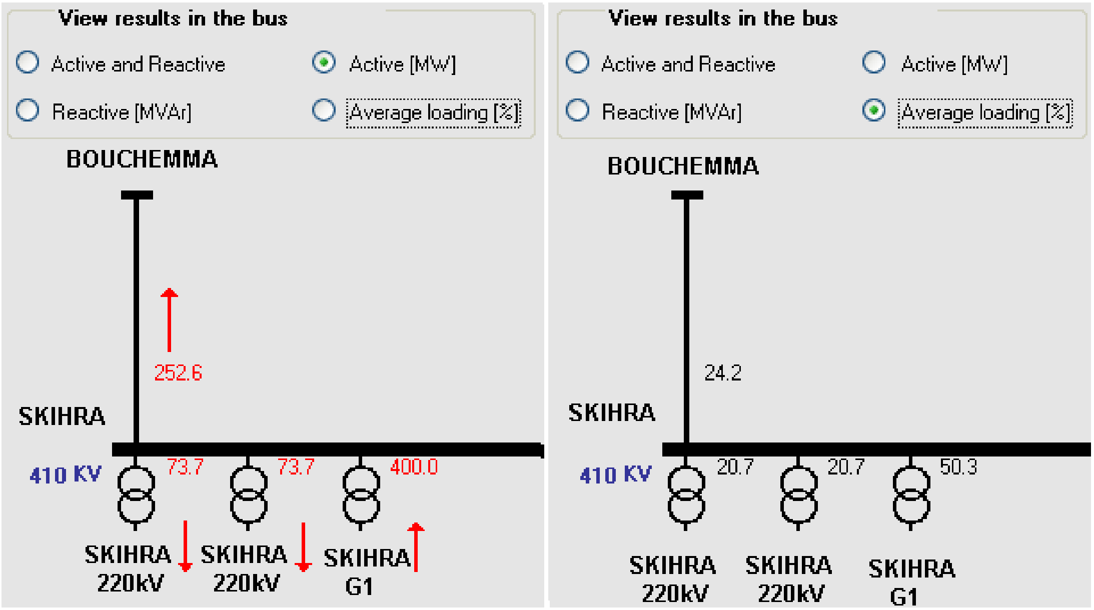


Fig.4.54 - 400 MW case - Power flows and average loading on the two new 400kV connections.

Tab.4-25 - "N-1" security analysis results (violations and overloads).

Contingency		Vn (kV)	Overload		Vn (kV)	I_{N-1} (kA)	I_{N-1} (p.u.)
RADES	**GOULETTE**	**220**	**RADES**	**P2-TSC**	**220**	**1.2**	**1.25**
RADES	**GOULETTE**	**220**					

SOLUTION "D"

In Fig.4.55 the international exchanges and the internal power balances are represented. The total exchange with Algeria is close to zero, and as the HVDC connection is disconnected, there's no power export to Italy. Fig.4.56 shows the active power flows on the new line and on the new 400/225 kV transformers and their average loading.

The power produced by ELMED power plant is distributed mainly on the new Skhira – Oueslatia 400 kV line, causing about a 30% line loading and about 12% transformer loading; the percentage of power flowing to Bouchemma station is very low.

The N-1 security analysis performed in this scenario highlights the usual overload on Rades – P2-TSC 225 kV line after the trip of the double line Rades – Goulette (Tab.4-26).

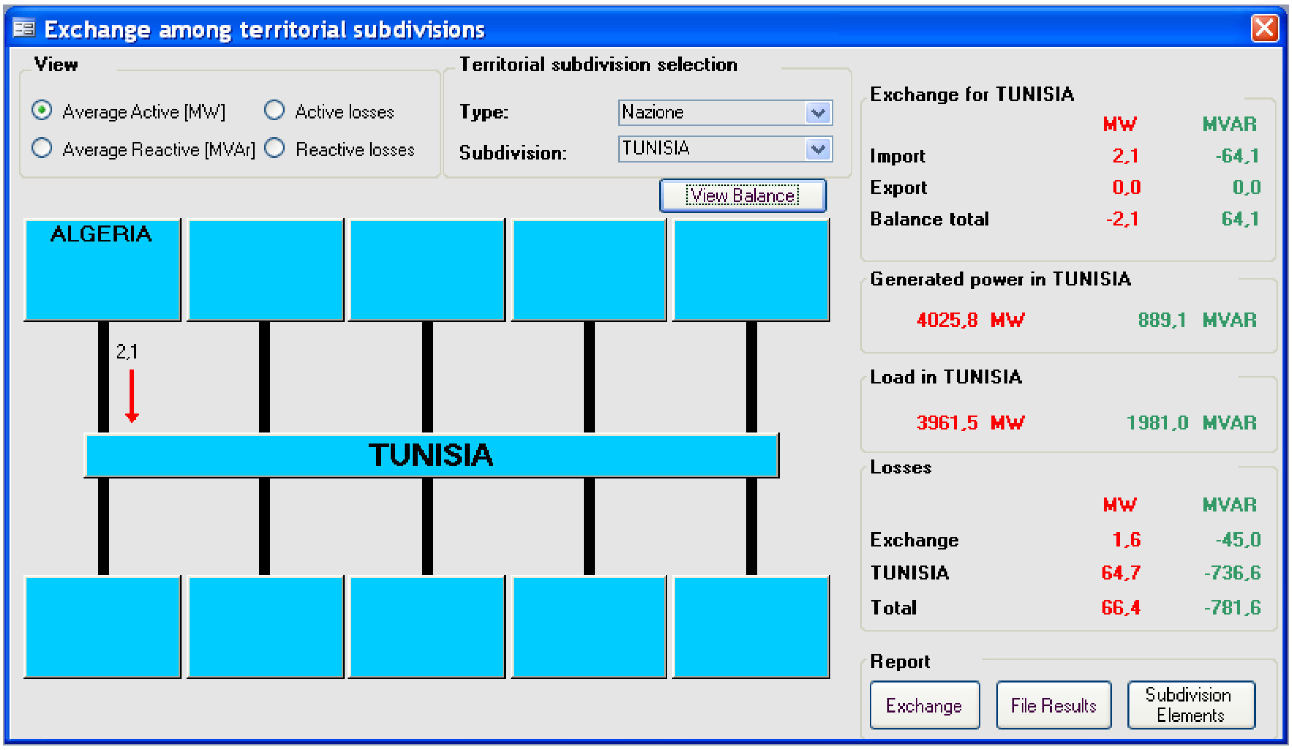


Fig.4.55 - 400 MW case - International exchanges and power balances for the Tunisian grid.

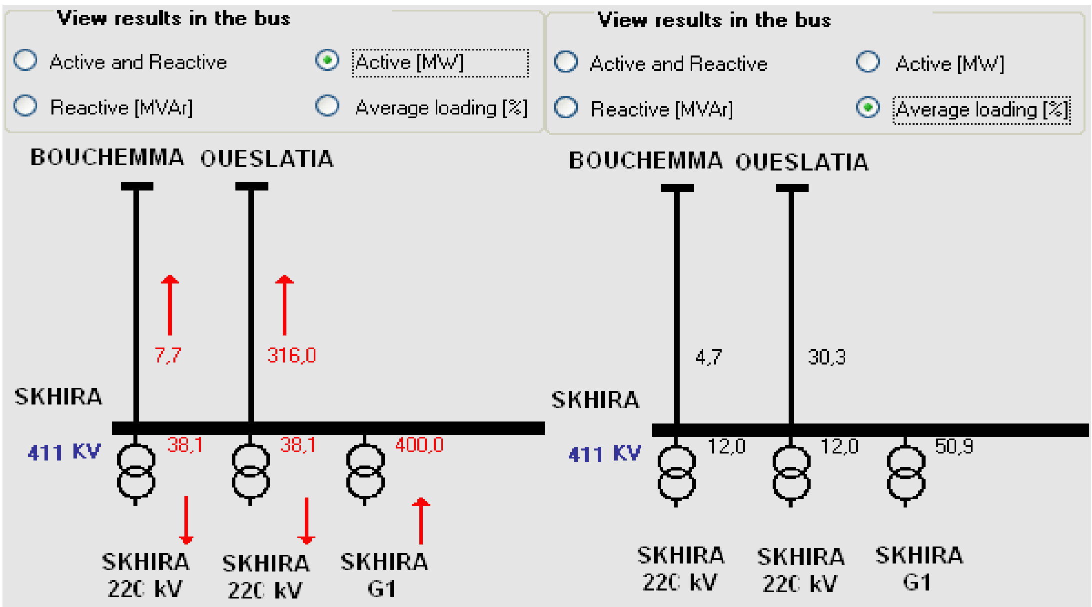


Fig.4.56 - 400 MW case - Power flows and average loading on the two new 400kV connections.

Tab.4-26 - “N-1” security analysis results (violations and overloads).

Contingency		Vn (kV)	Overload		Vn (kV)	I_{N-1} (kA)	I_{N-1} (p.u.)
RADES	**GOULETTE**	**220**	**RADES**	**P2-TSC**	**220**	**1.20**	**1.24**
RADES	**GOULETTE**	**220**					

4.4.1.2 Power generation to supply the internal load in Tunisia and for power export (1200 MW)

The 1200 MW generation at the ELMED power plant in Skhira needs additional network reinforcements respect to those described in the case of 400 MW production only. The additional network reinforcements indicated in this paragraph are directly connected to the power exported to Sicily.

SOLUTION "A1"

This solution needs to double the 400 kV corridor between Skhira and Mornaguia: this implies to erect two 400 kV lines from Skhira to Maknassy and one additional circuit[12] Maknassy – Oueslatia and Oueslatia – Mornaguia. Moreover, two 400 kV lines from Mornaguia to El Hawaria are necessary for the exportation to Italy.

Fig.4.57 shows increased power losses (about 51 MW greater than before in spite of the double of all 400 kV connections from Skhira to Mornaguia) due to the larger production of the ELMED power plant (1200 MW), which now produces also the 800 MW sent to the HVDC converter station in El Hawaria. Also in this case the greatest part of generated active power flows to 400 kV lines without creating too high loading on the 400/225 kV transformers (Fig.4.58) and the underlying 225 kV network. This issue is a positive outcome of the proposed reinforcement scheme, since the power produced by the ELMED power plant and conveyed abroad shall preferably flow on the new 400 kV corridor without creating much interference with the local power flows.

In Tab.4-27 the voltage violation obtained from the "N-1" security analysis is presented. The limited voltage drops can be easily avoided increasing the shunt compensation (till 400 MVar) of the reactive power absorbed by the HVDC connection. The ESCR in El Hawaria remains around 3.7.

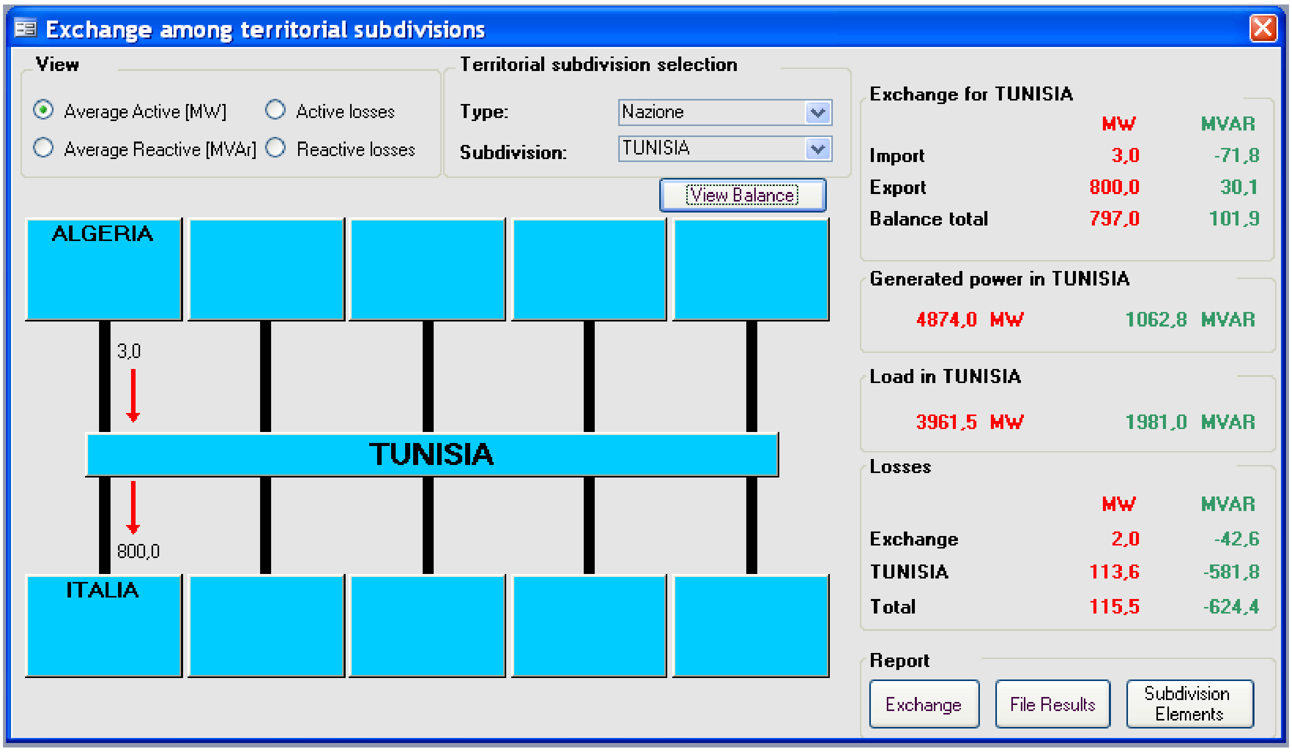


Fig.4.57 - 1200 MW case - International exchanges and power balances for the Tunisian grid.

[12] "one additional circuit" means one circuit more with respect to what already planned by STEG at the year 2016. We recall that all our analyses start from the system configuration planned by STEG for the selected horizon year.

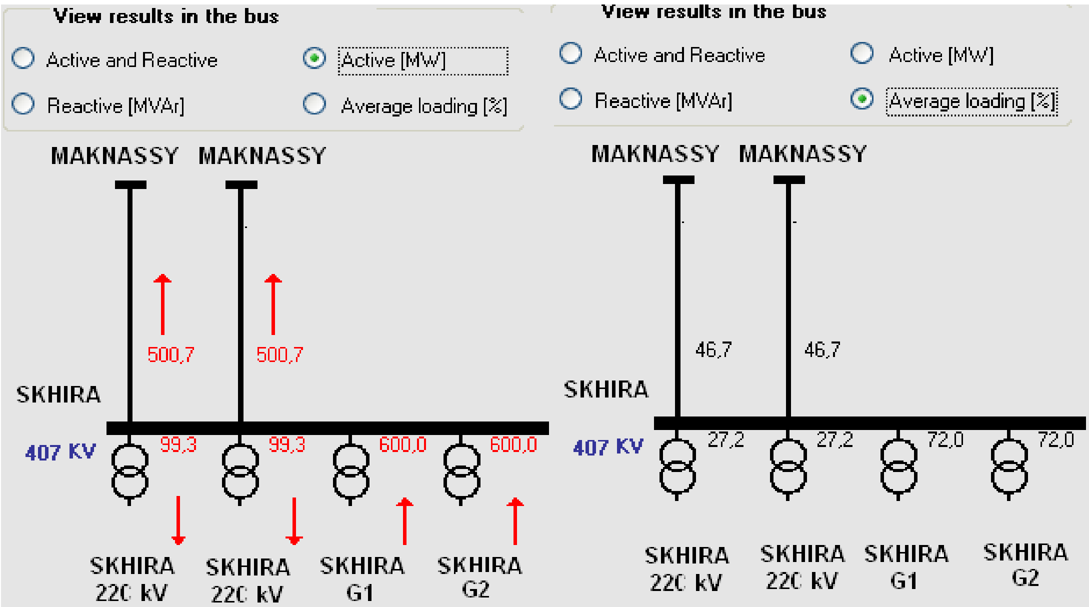


Fig.4.58 - 1200 MW case - Power flows and average loading on the two new 400kV connections.

Tab.4-27 - "N-1" security analysis results (violations and overloads).

Contingency		Vn (kV)	Violation	Vn (kV)	V_N (kV)	V_{N-1} (kV)	ΔV (%)
MORNAGUIA	**HAWARIA**	**400**	**HAWARIA**	**400**	**391.4**	**329.3**	**-17.7**
MNIHLA	**MENZEL J.**	**220**	**MENZEL J.**	**220**	**222.8**	**197.7**	**-10.1**
KORBA	**A. KMICHA**	**90**	**A. KMICHA**	**90**	**89.5**	**80.6**	**-10.4**

Contingency		Vn (kV)	Overload		Vn (kV)	I_{N-1} (kA)	I_{N-1} (p.u.)
RADES	**GOULETTE**	**220**	**RADES**	**P2-TSC**	**220**	**0.62**	**1.36**
RADES	**GOULETTE**	**220**					

SOLUTION "A2"

This solution differs from the one just presented, as it doesn't need any doubling of the corridor from Maknassy to Mornaguia. That depends on the direct connection between Skihra and El Hawaria, that represents an alternative way to the HVDC system (as well as when connecting directly Skhira to Mornaguia) in case of tripping of one of the 400 kV connection among Skihra-Maknassy, Maknassy-Oueslatia, Oueslatia-Mornaguia.

In Fig.4.11 and Fig.4.12 the key figures are presented in terms of international exchange, active power losses, and power flows' distribution.

We underline that the "N-1" security analysis (Tab. 4-28) shows that the voltage drop in El Hawaria, due to a fault on the connection Skihra-El Hawaria, is quite remarkable and a Var compensation scheme shall be investigated. Moreover, the ESCR is approaching the limit value (as it reaches about 3.1) even in peak conditions.

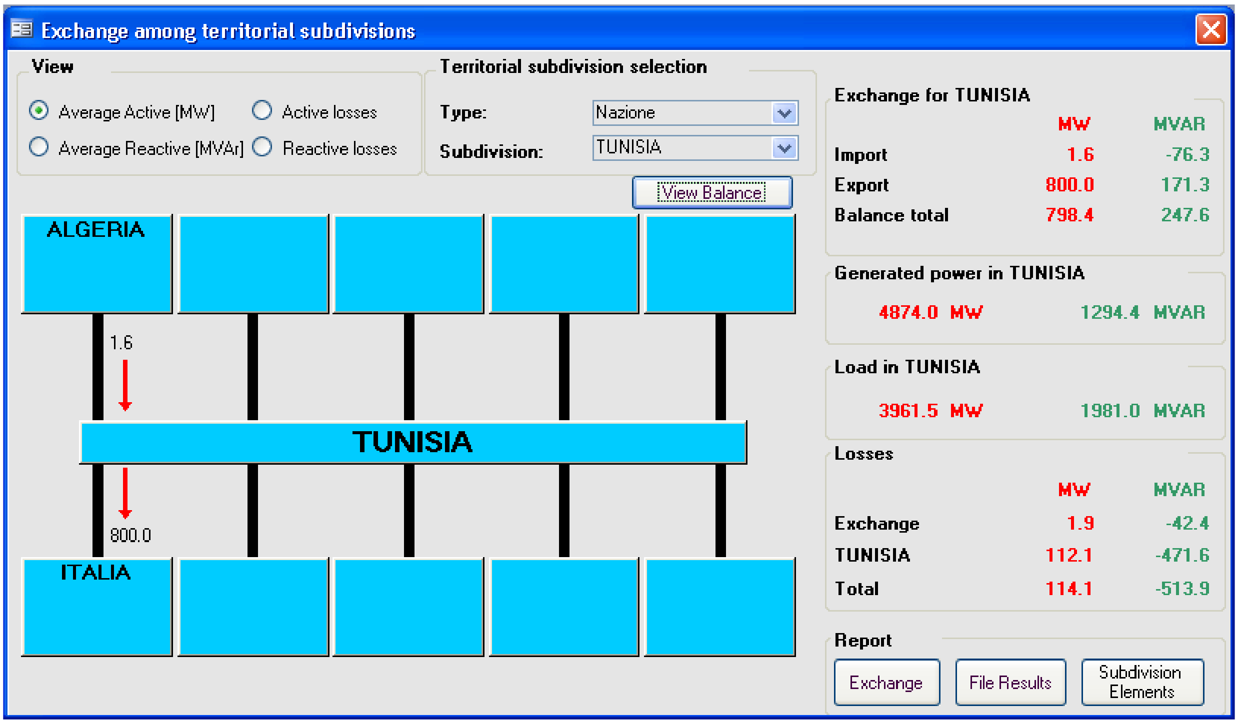


Fig.4.59 - 1200 MW case - International exchanges and power balances for the Tunisian grid.

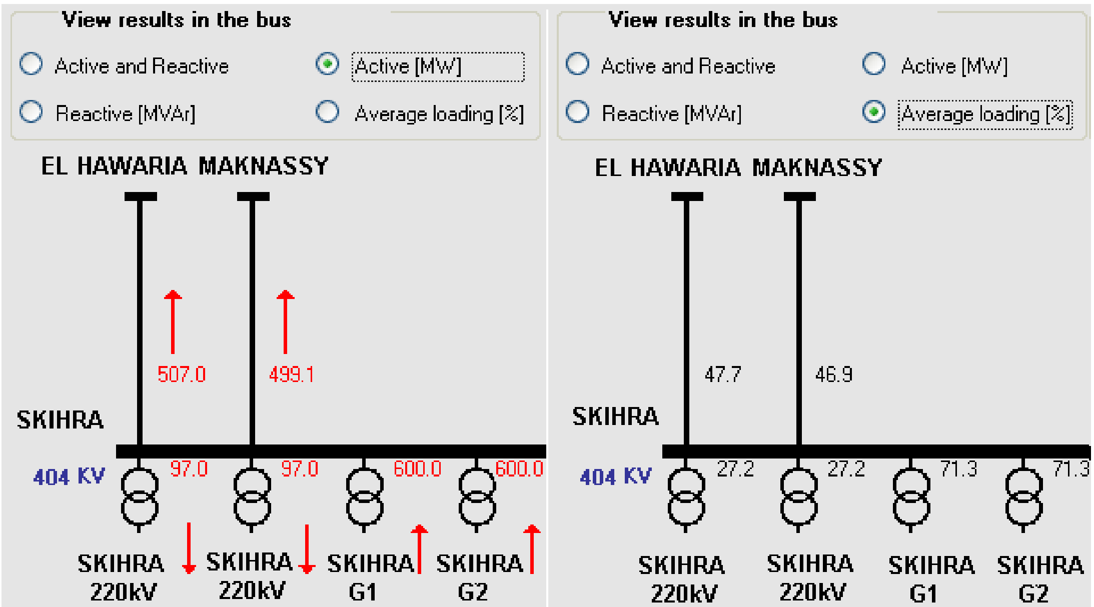


Fig.4.60 - 1200 MW case - Power flows and average loading on the two new 400kV connections.

Tab. 4-28 Voltage violations and overloads in post contingency situations

Contingency		Vn (kV)	Violation	Vn (kV)	V_N (kV)	V_{N-1} (kV)	ΔV (%)
SKIHRA	**HAWARIA**	**400**	**HAWARIA**	**400**	**383.4**	**294.6**	**-26.3**

Contingency		Vn (kV)	Violation	Vn (kV)	V_N (kV)	V_{N-1} (kV)	ΔV (%)
SKIHRA	**HAWARIA**	**400**	**HAWARIA**	**400**	**401.14**	**341.5**	**-14.6**
MNIHLA	**MENZEL J.**	**220**	**MENZEL J.**	**220**	**222.5**	**197.2**	**-10.3**
KORBA	**A. KMICHA**	**90**	**A. KMICHA**	**90**	**89.5**	**80.6**	**-10.4**

Contingency		Vn (kV)	Overload		Vn (kV)	I_{N-1} (kA)	I_{N-1} (p.u.)
RADES	**GOULETTE**	**220**	**RADES**	**P2-TSC**	**220**	**1.34**	**1.29**
RADES	**GOULETTE**	**220**					

SHUNT = 400 MVar   ESCR = 3.13

SOLUTION “B”

This solution foresees two 400 kV transmission lines from Skhira to Maknassy and Mornaguia stations. Fig.4.61 shows, first of all, an increased in power losses (about 58 MW greater than before in spite of the new network reinforcements) due to the grown production of ELMED power plant (1200 MW), which now produces also the 800 MW flowing to the HVDC converter station in El Hawaria. Also in this case the greatest part of generated active power flows to 400 kV lines respect to the 400/225 kV transformers (Fig.4.62).

In Tab.4-29 the voltage violation derived from the “N-1” security analysis is presented. This voltage drop can be easily avoided increasing the shunt compensation (till 400 MVar) of the reactive power absorbed by the HVDC connection. The ESCR, which estimates the voltage control capacity in HVDC station (ESCR > 3), remains around 3.7.

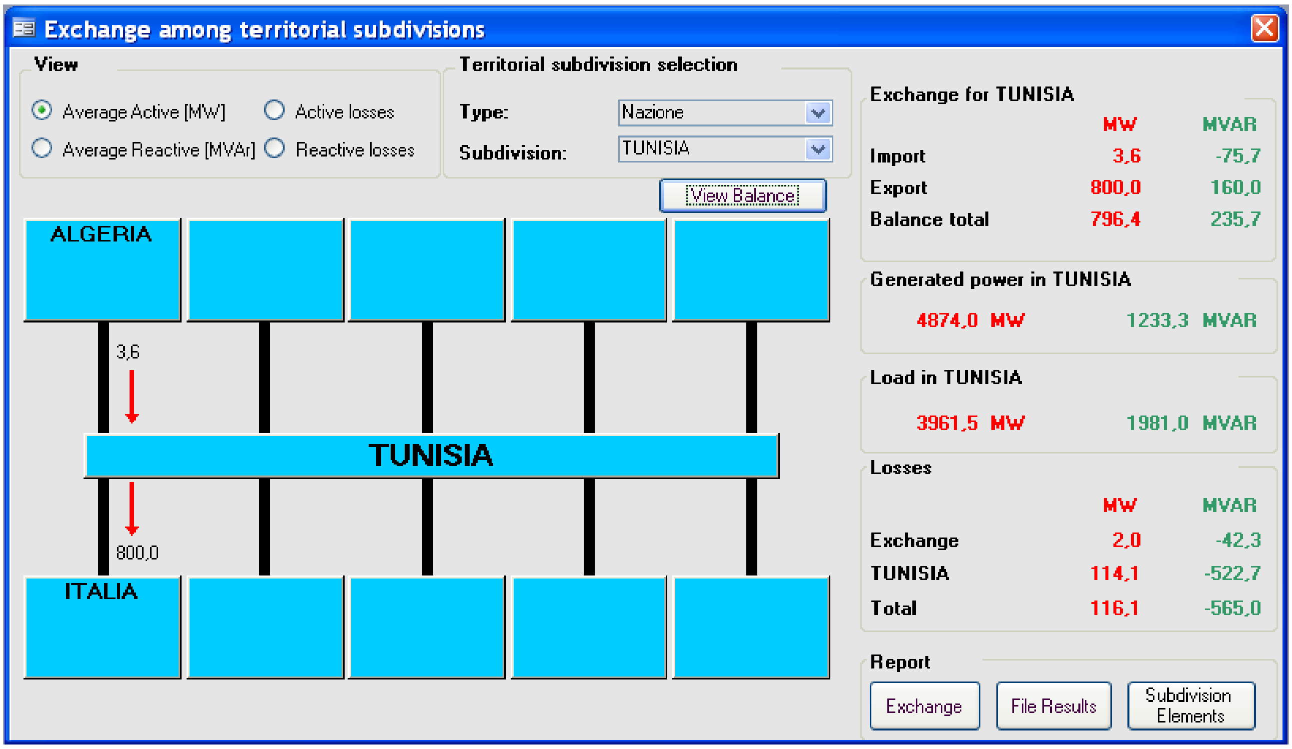


Fig.4.61 - 1200 MW case - International exchanges and power balances for the Tunisian grid.

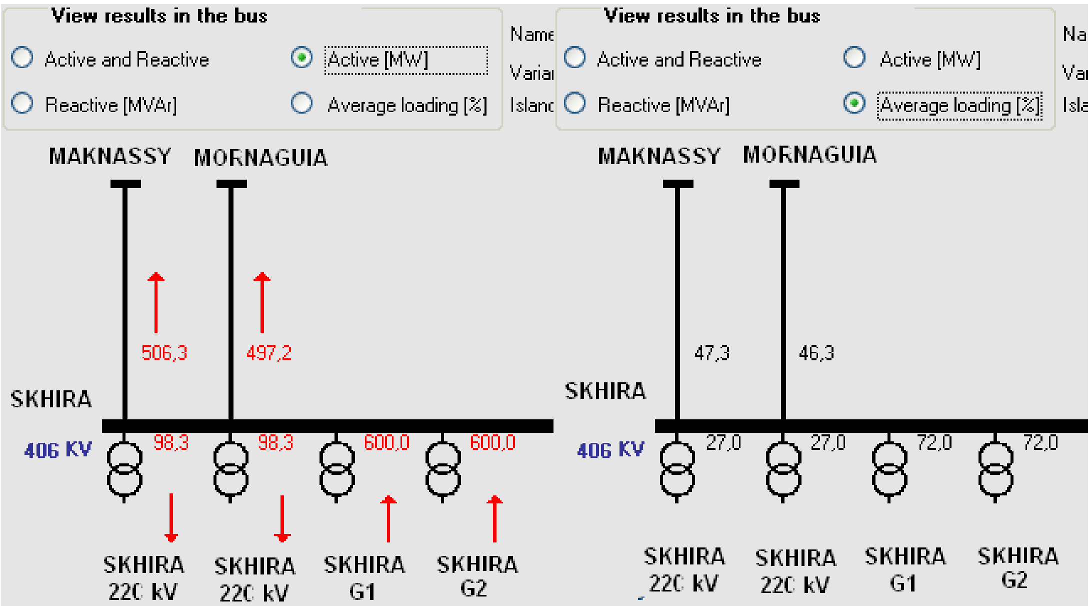


Fig.4.62 - 1200 MW case - Power flows and average loading on the two new 400kV connections.

Tab.4-29 - "N-1" security analysis results (violations and overloads).

Contingency		Vn (kV)	Violation	Vn (kV)	V_N (kV)	V_{N-1} (kV)	ΔV (%)
MORNAGUIA	**HAWARIA**	**400**	**HAWARIA**	**400**	**391.0**	**328.4**	**-17.9**
MNIHLA	**MENZEL J.**	**220**	**MENZEL J.**	**220**	**222.8**	**197.6**	**-10.2**
KORBA	**A. KMICHA**	**90**	**A. KMICHA**	**90**	**89.5**	**80.6**	**-10.4**

Contingency		Vn (kV)	Overload		Vn (kV)	I_{N-1} (kA)	I_{N-1} (p.u.)
RADES	**GOULETTE**	**220**	**RADES**	**P2-TSC**	**220**	**1.30**	**1.35**
RADES	**GOULETTE**	**220**					

SOLUTION "C"

This solution involves the doubling of all the 400kV lines between Skhira and Mornaguia, in order to deliver the total power of 800 MW to the HVDC connection even in "N-1" condition.

The active power losses are the highest among the considered solutions (130 MW). Indeed, it had to be expected because the impedance from Skihra to Mornaguia includes also those of the double 400kV lines Skihra-Bouchemma, Bouchemma-Oueslatia and Oueslatia-Mornaguia, inevitably increasing the losses.

Beside that, the "N-1" security analysis shows the same voltage drops of the previous solutions, still avoidable with a higher reactive power compensation (400 MVar).

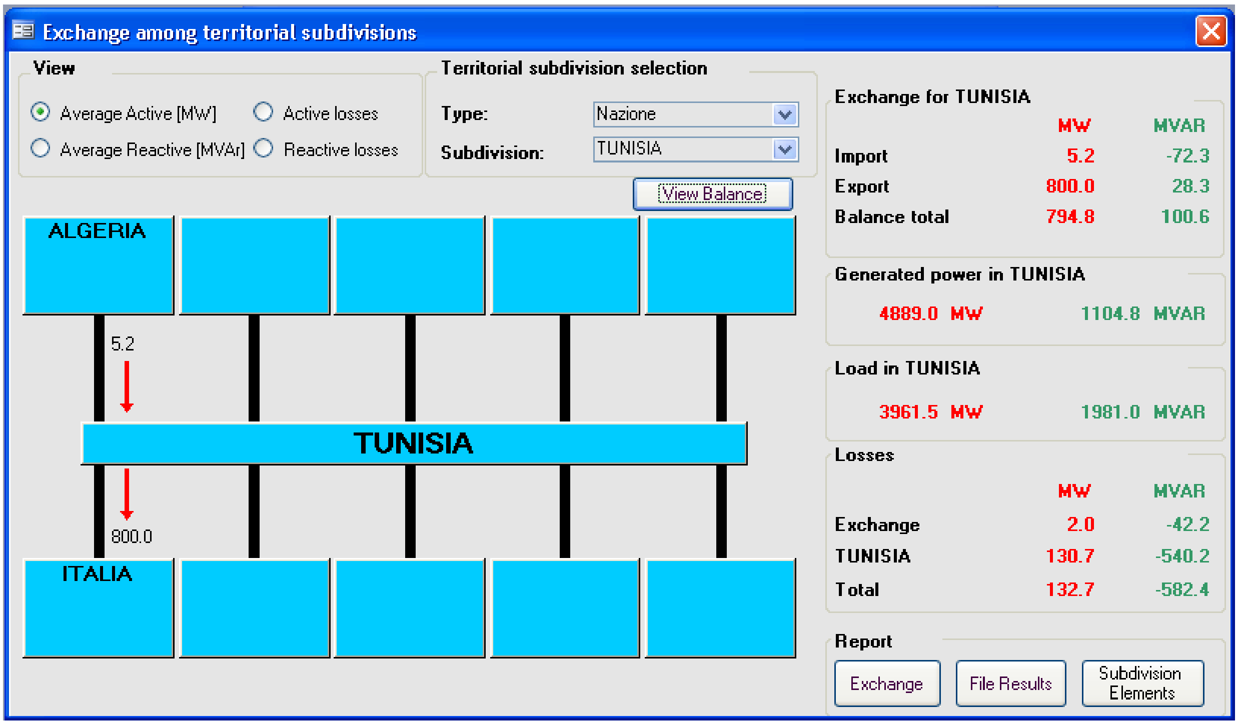


Fig.4.63 - 1200 MW case - International exchanges and power balances for the Tunisian grid.

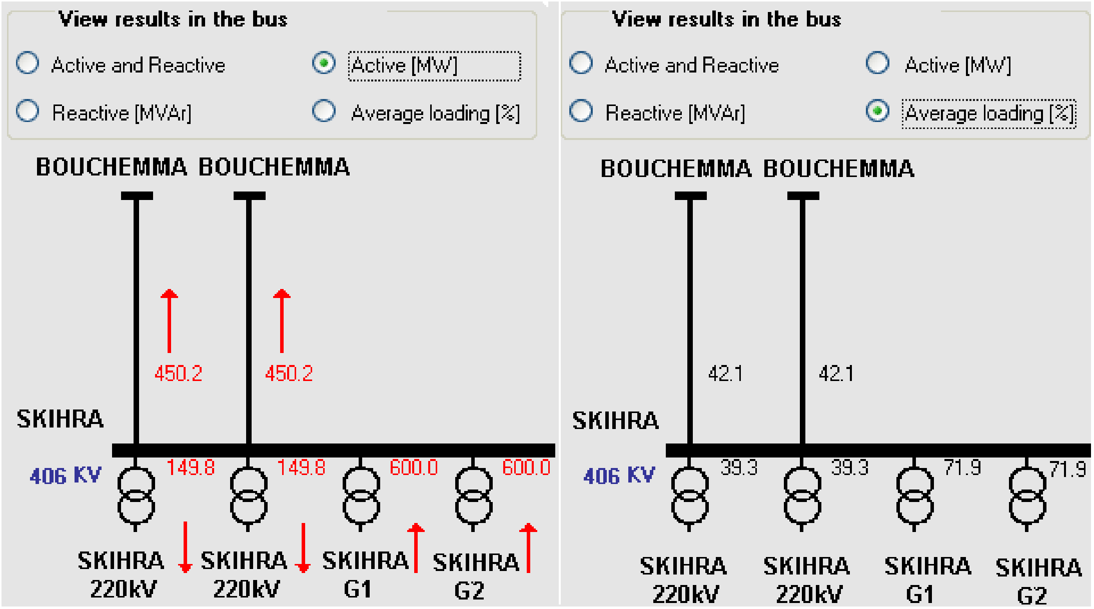


Fig.4.64 - 1200 MW case - Power flows and average loading on the two new 400kV connections.

Tab.4-30 - “N-1” security analysis results (violations and overloads).

Contingency		Vn (kV)	Violation	Vn (kV)	V_N (kV)	V_{N-1} (kV)	ΔV (%)
MORNAGUIA	**HAWARIA**	**400**	**HAWARIA**	**400**	**391.4**	**329.3**	**-17.7**
MNIHLA	**MENZEL J.**	**220**	**MENZEL J.**	**220**	**222.9**	**197.9**	**-10**
KORBA	**A. KMICHA**	**90**	**A. KMICHA**	**90**	**89.5**	**80.4**	**-10.6**

<table>
<tr><th colspan="2">Contingency</th><th>Vn (kV)</th><th colspan="2">Overload</th><th>Vn (kV)</th><th>I_{N-1} (kA)</th><th>I_{N-1} (p.u.)</th></tr>
<tr><td>RADES</td><td>GOULETTE</td><td>220</td><td rowspan="2">RADES</td><td rowspan="2">P2-TSC</td><td rowspan="2">220</td><td rowspan="2">1.33</td><td rowspan="2">1.38</td></tr>
<tr><td>RADES</td><td>GOULETTE</td><td>220</td></tr>
</table>

SOLUTION “D”

As usual, with the ELMED power plant at full production, the connection solution requires two outgoing 400 kV lines, which in this case are: a 400 kV line from Skhira to Oueslatia and a 400 kV line from Skhira to a new turn-in/turn-out substation along the line Oueslatia-Bouchemma. The section from Oueslatia to Mornaguia shall consists of two 400 kV lines.

Finally, two 400 kV lines from Mornaguia to El Hawaria are necessary for the export to Italy in N-1 security conditions.

Fig.4.65 shows, first of all, an increase in power losses (about 55 MW greater than before in spite of the double of all 400 kV connections) due to the grown production of ELMED power plant (1200 MW), which now produces also the 800 MW headed to the HVDC converter station in El Hawaria. Also in this case the greatest part of generated active power flow to 400 kV lines respect to 400/225 kV transformers (Fig.4.66).

In Tab.4-31 the voltage violation derived from the “N-1” security analysis is presented. The voltage drops can be easily avoided increasing the shunt compensation (till 400 MVar) of the reactive power absorbed by the HVDC connection. The ESCR remains around 3.7.

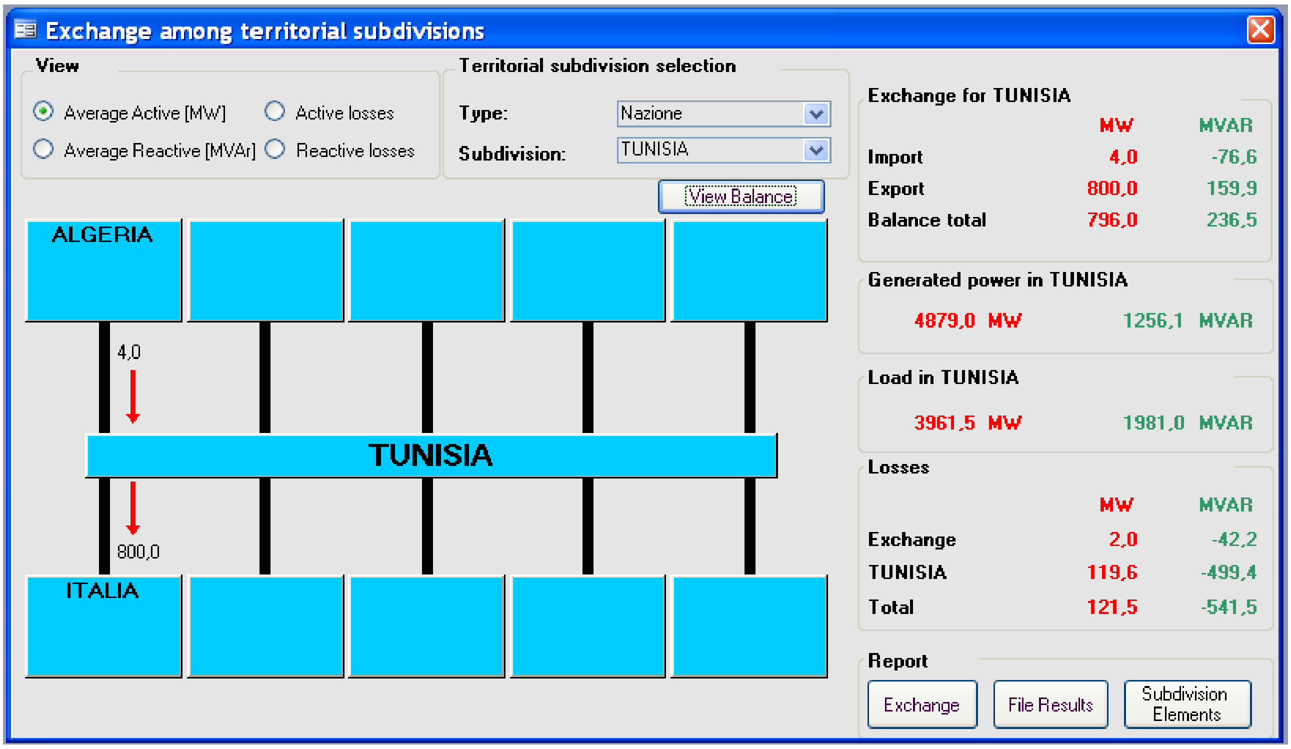


Fig.4.65 - 1200 MW case - International exchanges and power balances for the Tunisian grid.

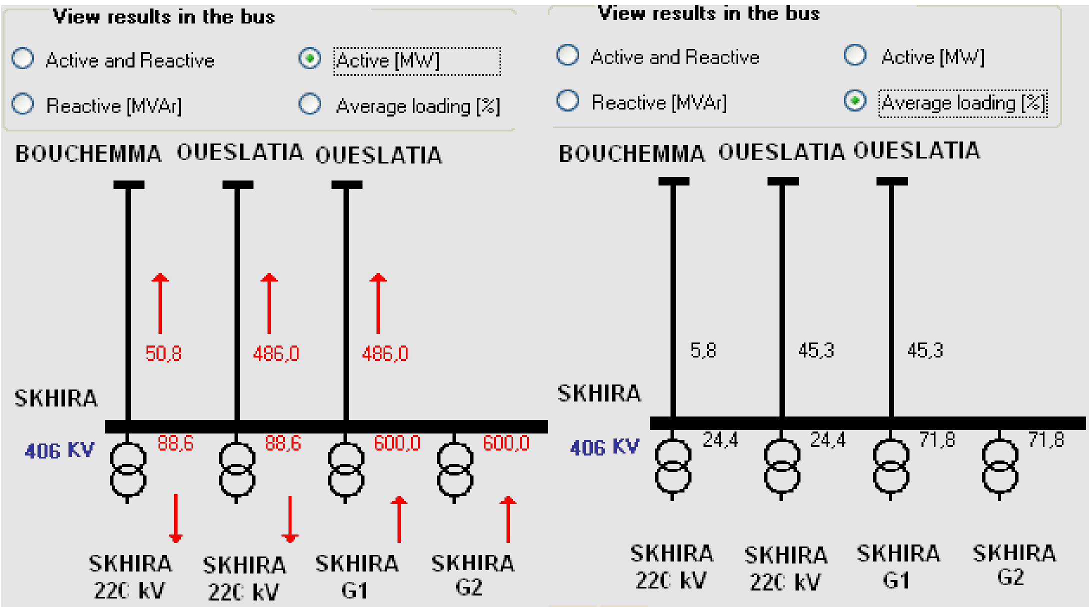


Fig.4.66 - 1200 MW case - Power flows and average loading on the two new 400kV connections.

Tab.4-31 - "N-1" security analysis results (violations and overloads).

Contingency		Vn (kV)	Violation	Vn (kV)	V_N (kV)	V_{N-1} (kV)	ΔV (%)
MORNAGUIA	**HAWARIA**	**400**	**HAWARIA**	**400**	**391.1**	**328.2**	**-17.9**
MNIHLA	**MENZEL J.**	**220**	**MENZEL J.**	**220**	**222.7**	**197.5**	**-10.2**
KORBA	**A. KMICHA**	**90**	**A. KMICHA**	**90**	**89.5**	**80.5**	**-10.5**

Contingency		Vn (kV)	Overload		Vn (kV)	I_{N-1} (kA)	I_{N-1} (p.u.)
RADES	**GOULETTE**	**220**	**RADES**	**P2-TSC**	**220**	**1.31**	**1.36**
RADES	**GOULETTE**	**220**					

4.4.2 Skhira: minimum load conditions

4.4.2.1 Power generation to supply the internal load in Tunisia and for power export (1000 MW)

<u>SOLUTION "A1"</u>

The power balance of Tunisian grid in this scenario is in *Fig.4.67*, while *Fig.4.68* shows the active power flow and the loading on the 400 kV lines Skhira – Maknassy.

The "N-1" security analysis shows a low voltage level in El Hawaria in case of tripping of one of the 400 kV connection Mornaguia – El Hawaria, which can be avoided increasing the reactive power compensation in the converter station to 650 MVar. The ESCR maintains an acceptable value (greater then 3 p.u.).

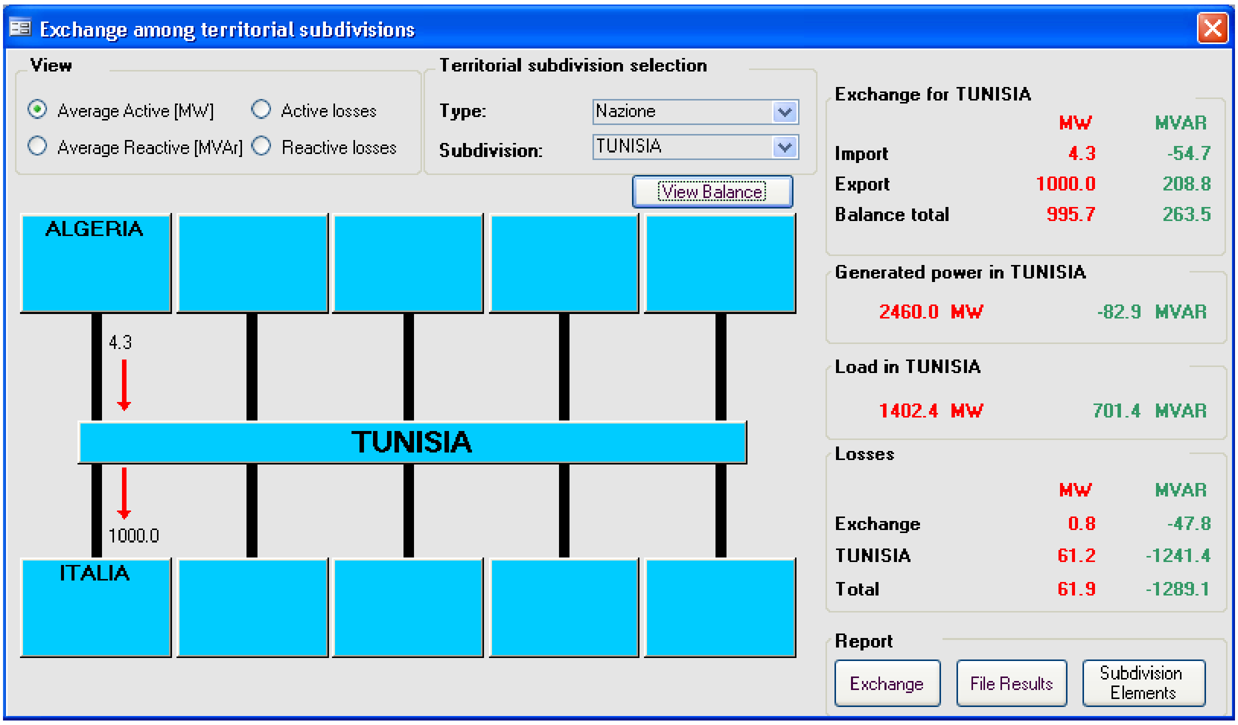


Fig.4.67 - 1000 MW case - International exchanges and power balances for the Tunisian grid.

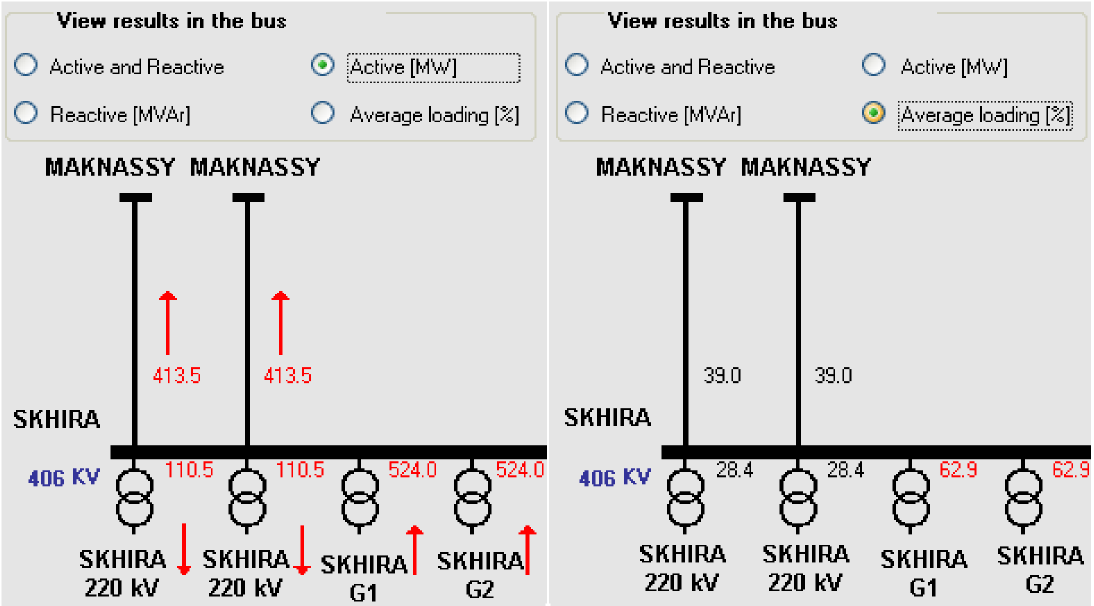


Fig.4.68 - 1000 MW case - Power flows and average loading on the two new 400kV connections.

Tab.4-32 - “N-1” security analysis results (violations and overloads).

Contingency		Vn (kV)	Violation	Vn (kV)	V_N (kV)	V_{N-1} (kV)	ΔV (%)
MORNAGUIA	**HAWARIA**	**400**	**HAWARIA**	**400**	**384.1**	**295.6**	**-26**

SOLUTION “A2”

The minimum load analysis for this solution highlights a voltage problem related to the “N-1” security conditions. As reported in *Tab.4-33*, in case of fault on the 400 kV connection Mornaguia – El Hawaria, the high line charging of the Skhira – El Hawaria line makes the voltage in El Hawaria grow considerably (+60%). The voltage control along this very long 400 kV line will likely require a dynamic Var compensation device to cope with fast voltage variations at the occurrence of perturbation; moreover, an additional potentially critical issue may be related to the energisation procedure of this lines, especially in low load conditions. Should one pursue this solution, dedicated study addressing the above aspects shall be undertaken.

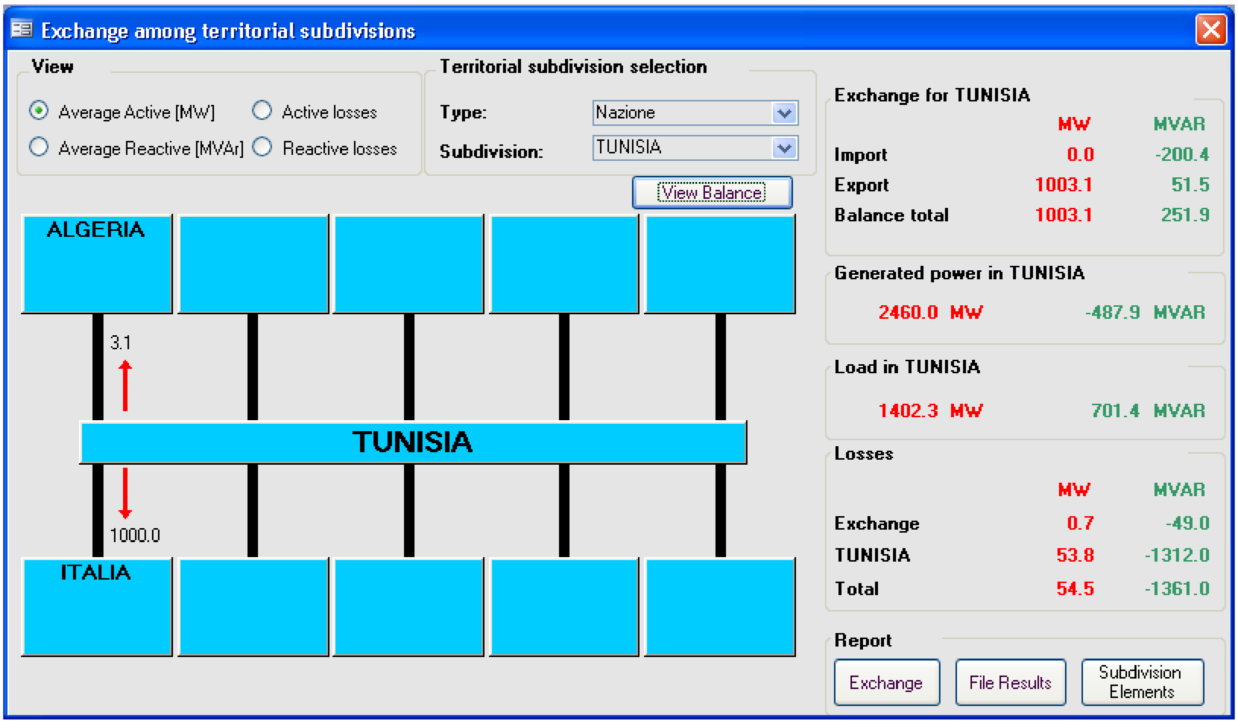


Fig.4.69 - 1000 MW case - International exchanges and power balances for the Tunisian grid.

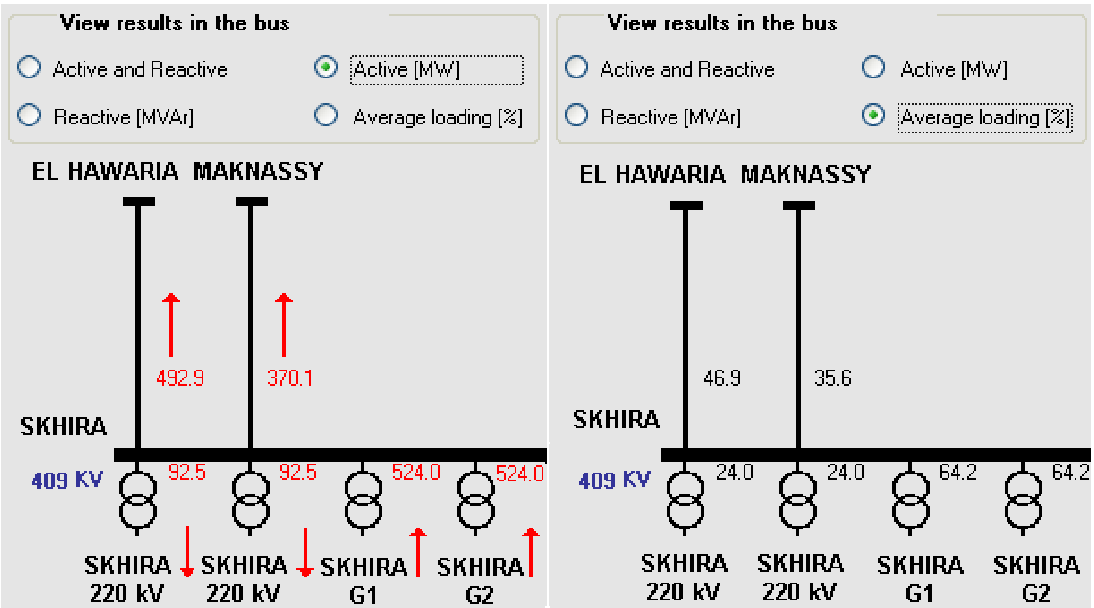


Fig.4.70 - 1000 MW case - Power flows and average loading on the two new 400kV connections.

Tab.4-33 - "N-1" security analysis results (violations and overloads).

Contingency		Vn (kV)	Violation	Vn (kV)	V_N (kV)	V_{N-1} (kV)	ΔV (%)
SKHIRA	**HAWARIA**	**400**	**HAWARIA**	**400**	**376**	**295**	**-26.2**

SOLUTION “B”

For what concern the minimum load condition analysis, this solution presents the same results as Solution “A1”.

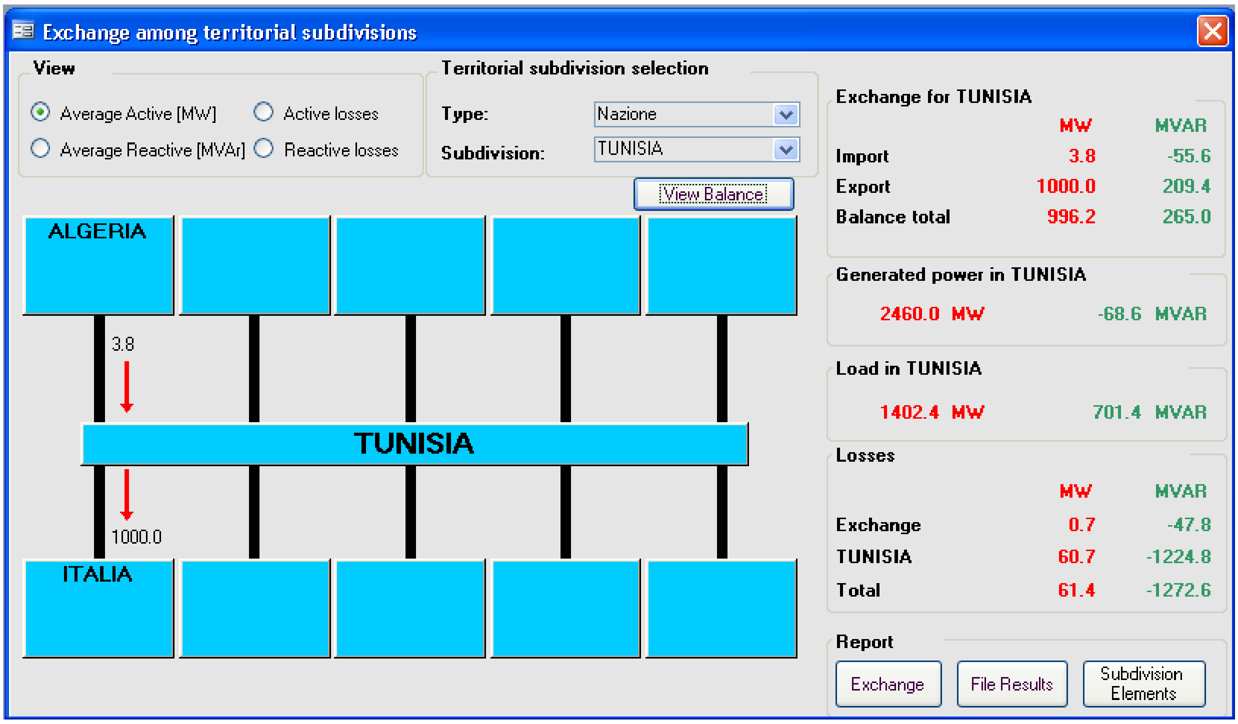


Fig.4.71 - 1000 MW case - International exchanges and power balances for the Tunisian grid.

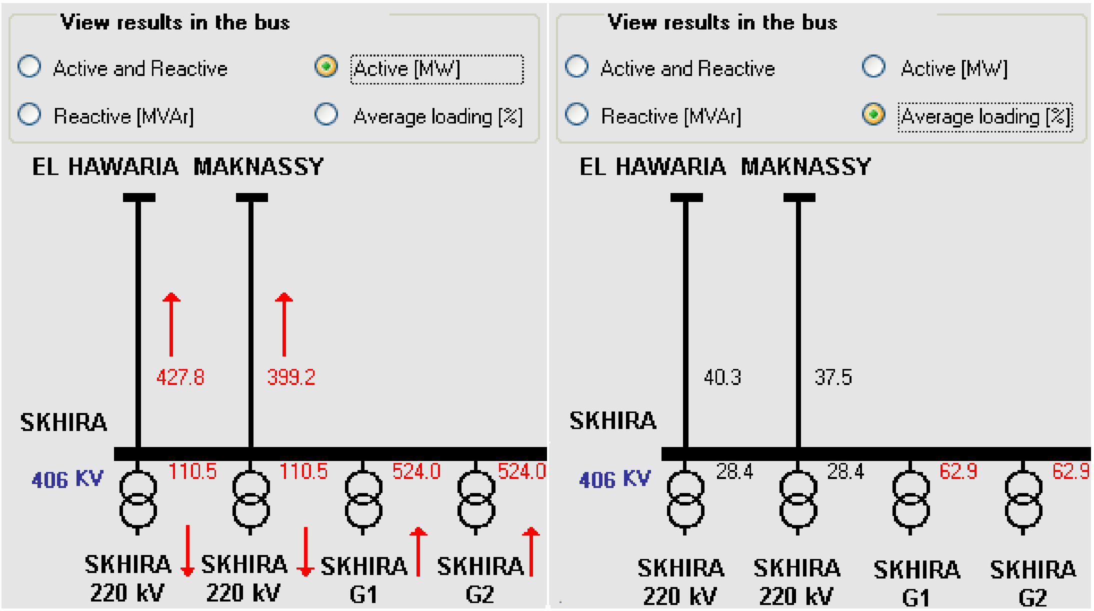


Fig.4.72 - 1000 MW case - Power flows and average loading on the two new 400kV connections.

Tab.4-34 - “N-1” security analysis results (violations and overloads).

Contingency		Vn (kV)	Violation	Vn (kV)	V_N (kV)	V_{N-1} (kV)	ΔV (%)
MORNAGUIA	**HAWARIA**	**400**	**HAWARIA**	**400**	**383.8**	**295.5**	**-26**

Note: the above table depicts only the contingencies causing overloads or voltage violations

SOLUTION "C"

For what concerns the minimum load condition analysis, this solution presents results very similar to those of Solution "A1".

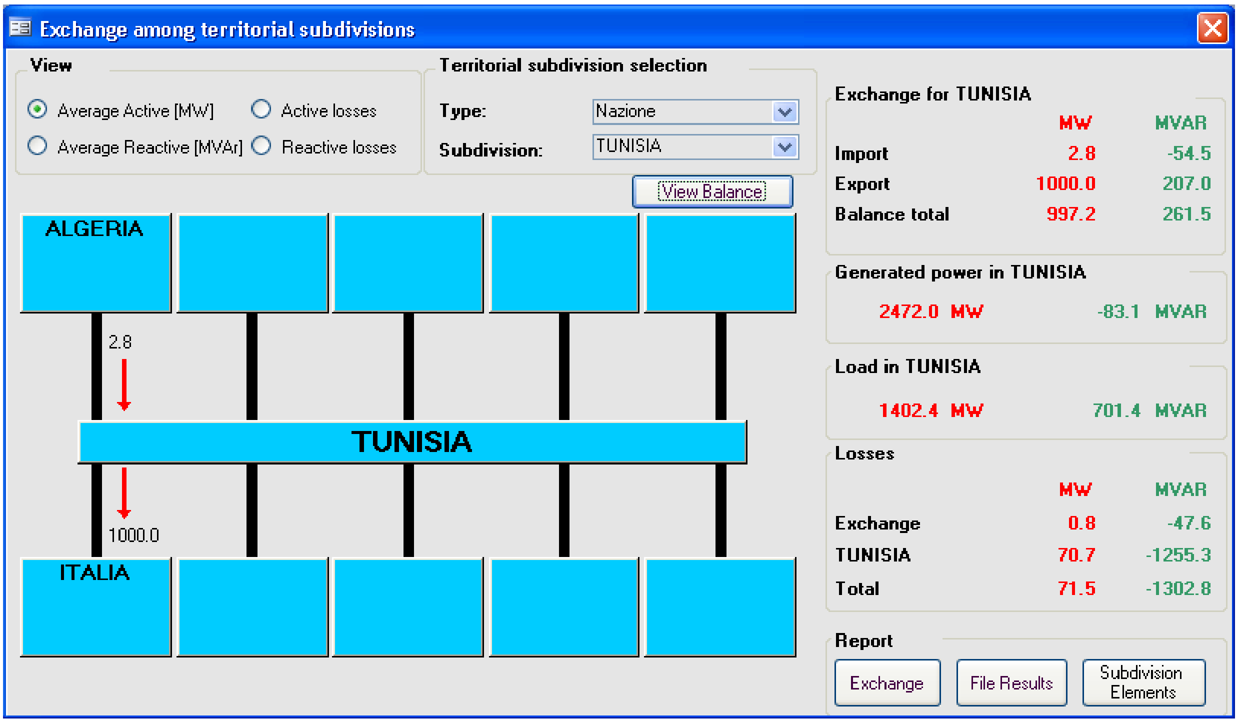


Fig.4.73 - 1000 MW case - International exchanges and power balances for the Tunisian grid.

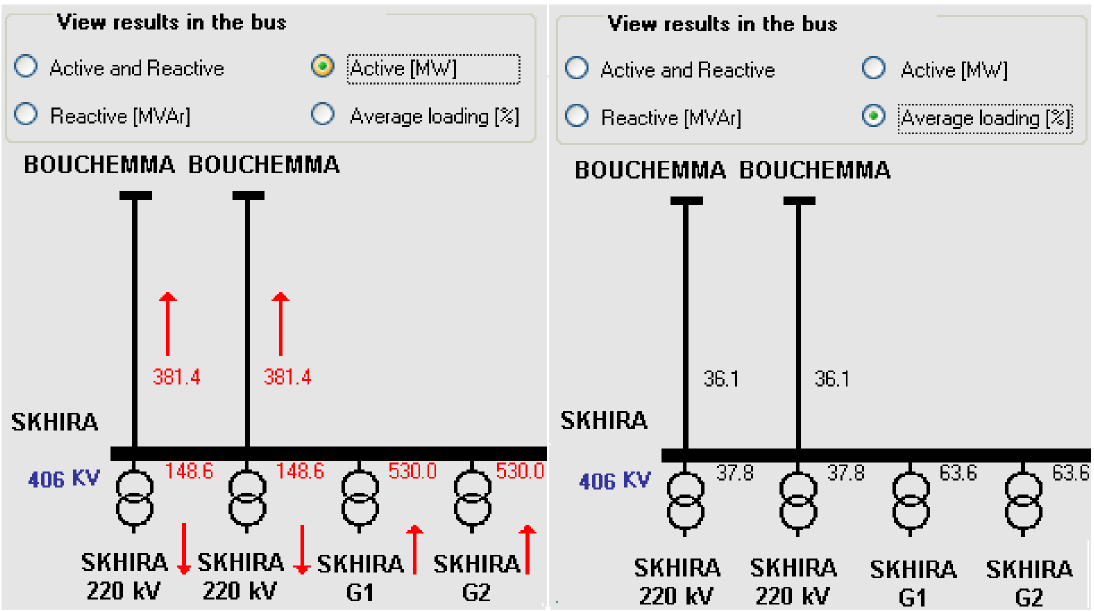


Fig.4.74 - 1000 MW case - Power flows and average loading on the two new 400kV connections.

Tab.4-35 - "N-1" security analysis results (violations and overloads).

Contingency		Vn (kV)	Violation	Vn (kV)	V_N (kV)	V_{N-1} (kV)	ΔV (%)
MORNAGUIA	**HAWARIA**	**400**	**HAWARIA**	**400**	**385**	**296.8**	**-25.7**

SOLUTION "D"

For what concern the minimum load condition analysis, this solution presents results very similar to those of Solution "A1".

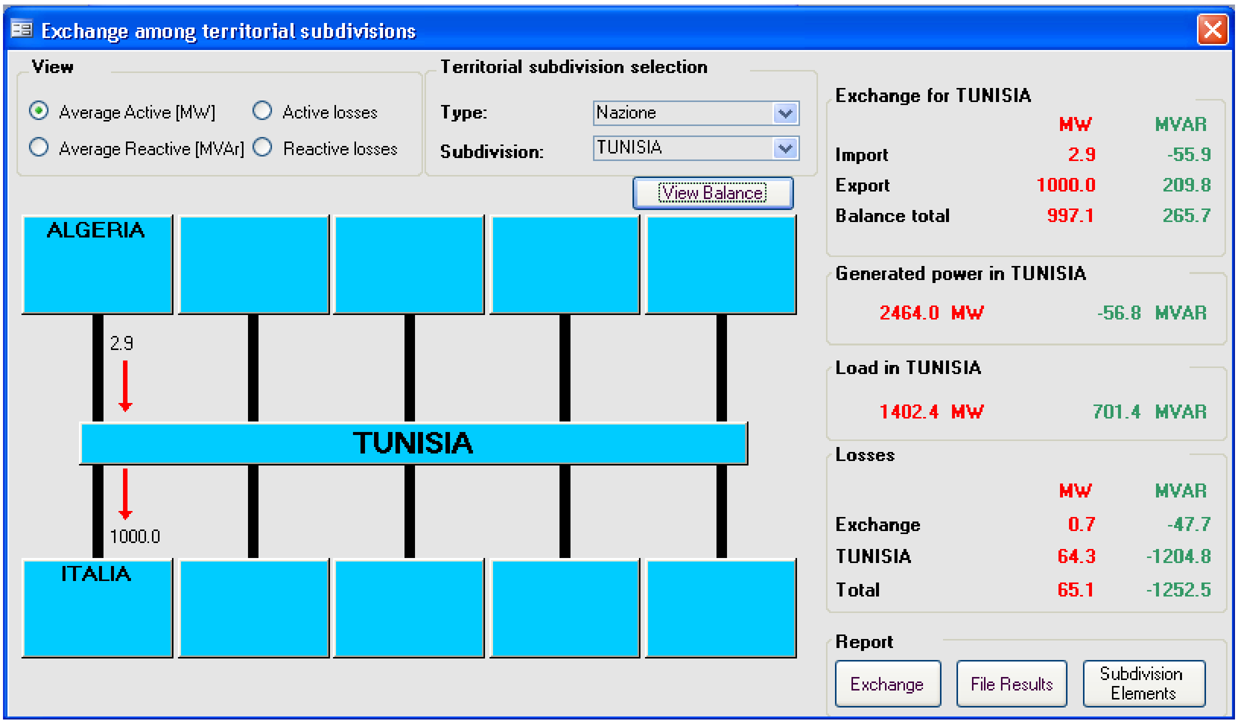


Fig.4.75 - 1000 MW case - International exchanges and power balances for the Tunisian grid.

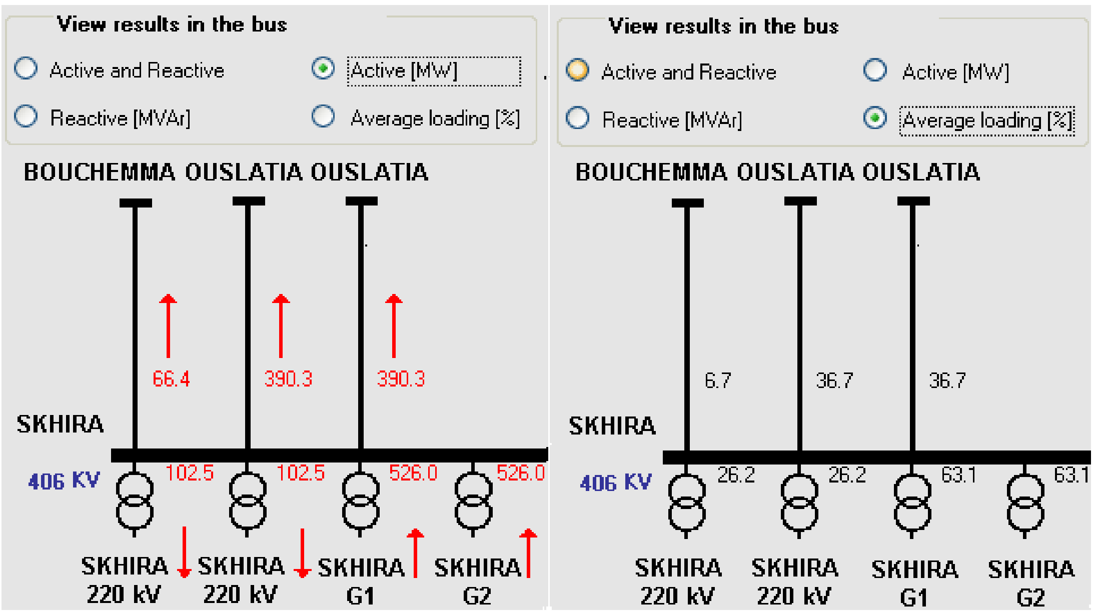


Fig.4.76 - 1000 MW case - Power flows and average loading on the two new 400 kV connections.

Tab.4-36 - "N-1" security analysis results (violations and overloads).

Contingency		Vn (kV)	Violation	Vn (kV)	V_N (kV)	V_{N-1} (kV)	ΔV (%)
MORNAGUIA	**HAWARIA**	**400**	**HAWARIA**	**400**	**383**	**295**	**-26**

4.4.3 *Skhira: solutions of network reinforcements and conclusions*

When examining the siting of the ELMED power plant in Skhira, as in the case of the previous alternatives we investigated the feasible connection schemes to supply the internal load on Tunisia only and those needed also for the power export to Sicily.

For the supply of the internal load with a power production level of 400 MW, two basic solutions are acceptable:

a) turn-in/turn-out substation on the 225 kV double circuit line Bouchemma-Sidi Mansour equipped with 2 x 400 MVA transformers[13];
b) one 400 kV line outcoming from Skhira (the shortest one being Skhira-Macknassy 70 km) and the turn-in/turn-out substation on the 225 kV double circuit line Bouchemma-Sidi Mansour equipped with one 400 MVA transformer.

Indeed, these solutions do not fulfil the security constraints when the ELMED power plant generates its rated power (1200 MW); hence, additional reinforcements shall be considered as illustrated in Tab. 4-37 here below.

With the reinforcements shown in Tab. 4-37, all solutions are feasible, except A0. The following comments are worth being highlighted:

- Solution C is characterised by poorer performances in terms of power losses. Indeed, reinforcements towards the southern direction are not favourable since both the internal load and the exporting point are located in the North. Thus, this connection solution is not recommended;
- Solutions A1, A2 and B, involving a 400 kV connection with the existing 225 kV s/s of Maknassy may be completed by the addition of a 400/225 kV at the Maknassy s/s for more flexibility in the operation. Nevertheless, this integration is not needed for the power evacuation from the ELMED power plant in compliance with the security criteria;
- Solutions A2 and B entailing the erection of very long 400 kV may be critical for the voltage control and an appropriate Var compensation scheme shall be investigated: likely dynamically controlled shunt Var compensation devices are needed. Moreover, the energisation procedure of the long 400 kV line might reveal critical, especially in low load conditions characterised by low short circuit power. If chosen, these solutions require the execution of dedicated studies and, very likely, extra costs are to be considered for the voltage control;
- All solutions, except A0, show a poor loading on the 400/225 kV transformers at the turn-in/turn-out station along the Bouchemma-Sidi Mansour line. As a matter of fact, if we consider two 400 kV lines outgoing from Skhira power plant, one might consider the connection of one autotransformer only, or, better, two autotransformers with lower rate (e.g.: 250 MVA). This latter solution warrants a better reliability and operation flexibility.

[13] This configuration ensures a better sharing of the power flows on the two circuits of the 225 kV line.

Tab. 4-37 – ELMED power plant in Skhira : network reinforcements and other ranking elements

Solution	Reinforcements	New lines total length (km) (1)	New ATR 400/225 kV	Losses in peak conditions (MW)	Notes
A0	T-in/T-out B.-S.M.*	**2x20**	**2**	**---**	Solution NOT feasible for the full capacity pf the ELMED power plant
A1	T-in/T-out B.-S.M.* Skhira-Maknassy double circuit (d.c.) Maknassy-Oueslatia Oueslatia-Mornaguia 2x El Hawaria-Mornaguia	**2x20** **2x70** **180** **130** **300**	**3****	**113.6**	ESCR within 3.28 ÷ 3.67 p.u
A2	T-in/T-out B.-S.M.* Skhira-Maknassy Shkira-El Hawaria El Hawaria-Mornaguia	**2x20** **70** **410** **150**	**3****	**112.1**	ESCR within 2.79 ÷ 3.13 p.u
B	T-in/T-out B.-S.M.* Skhira-Maknassy Skhira-Mornaguia 2x El Hawaria-Mornaguia	**2x20** **70** **350** **300**	**3****	**114.1**	ESCR within 3.28 ÷ 3.67 p.u
C	T-in/T-out B.-S.M.* Skhira-Bouchemma d.c. Bouchemma-Oueslatia Oueslatia-Mornaguia 2xEl Hawaria-Mornaguia	**2x20** **2x70** **280** **130** **300**	**2*****	**130.7**	ESCR within 3.23 ÷ 3.63 p.u
D	T-in/T-out B.-S.M.* Skhira - T-in/T-out along the line Bouchemma-Oueslatia Skhira-Oueslatia Oueslatia-Mornaguia 2xEl Hawaria-Mornaguia	**2x20** **85** **245** **130** **300**	**2*****	**119.6**	ESCR within 3.27 ÷ 3.66 p.u

(1) In the table we have split the km of new lines necessary to connect the ELMED power plant to the Tunisian grid from those necessary to connect the AC/DC substation in El Hawaria to the Tunisian grid.

** Turn-in/Turn-out substation on the 225 kV double circuit line Bouchemma-Sidi Mansour*

*** 1 ATR 400 MVA in Maknassy and 2 ATR in Skhira for the T-in/T-out along the line Bouchemma-Sidi Mansour with appropriate size (e.g.: 250 MVA). Alternatively, one can foresee 1 ATR only in Skhira with the standard rating of 400 MVA.*

**** 2 ATR in Skhira for the T-in/T-out along the line Bouchemma-Sidi Mansour with appropriate size (e.g.: 250 MVA). Alternatively, one can foresee 1 ATR only in Skhira with the standard rating of 400 MVA.*

Tab. 4-38– ELMED power plant in Skhira: reactive power compensation

Solution	Reactive power compensation [Mvar]	
	Peak Load	Minimum Load
A0	---	---
A1	400	650
A2	400	370*
B	400	650
C	400	650
D	400	650

**A dynamic Var compensation device is likely required*

Note: the shunt Var compensation shown in the above table shall be intended only as indicative, since the study didn't addressed the optimisation of this equipment.

In conclusion, the siting of the ELMED power plant in Skhira turns out to be the most binding alternative with respect to the other ones in terms of network reinforcements.

By comparing the feasible solutions, we note that the short circuit power in El Hawaria is quite similar with no big difference in the ESCR ranges. Hence, this parameter cannot be considered as a discriminating factor for the ranking of the solutions.

The most favourable solution in terms of new network reinforcements (km of new lines) is solution A2; however, this solution is not recommended due to the difficulty in the voltage control of a very long 400 kV AC line in a weak transmission system.

Solution C is not favourable both in terms of network reinforcements and losses.

Solution D shows higher losses than solutions A1 and B; moreover it requires the construction of a new substation along the line Bouchemma-Oueslatia.

Solutions A1 and B are comparable both in terms of losses and network reinforcements, but the latter connection scheme entails the need to build a long 400 kV line (Skhira-Mornaguia: 350 km). Moreover, solution A1, characterised by several shorter sections of 400 kV, offers more flexibility in the operation stage.

For the above considerations, solution A1 turns out to be the most favourable one. In summary this connection solution is selected because:

- it avoids very long transmission lines that can cause voltage problems in case of low power flows;
- it uses an already existing corridor to build most of the new reinforcements;
- it will hardly cause under-excitation problems for generators in case of restoration;
- it is one of the solution with the lowest network losses.

Thus, this solution is examined more in detail assessing the performances of the system in dynamic conditions.

Here below, we summarise the reasons why the other connection solutions are excluded.

SOLUTION "A2"

This solution consists of a line from Skhira to Maknassy and a very long line from Skhira to El Hawaria. This solution shows worst performances if compared to solution "A1" because:

- the construction of a very long 400 kV line from Skhira to El Hawaria (410 km) entails voltage problems;
- this solution is likely prone to stability problems greater than those of solution A1 in case of three phase short circuit on Skhira – Maknassy line due to the high impedance of Skhira – El Hawaria line;
- risks under-excitation for generators may exist in case of restoration;
- it requires a completely new South-North right-of-way instead of use the already planned 400 kV corridor.

SOLUTION "B"

This solution consists of a line from Skhira to Maknassy and a long line from Skhira to Mornaguia. It also shows poorer performances if compared to solution "A1" because:

- it requires a long 400 kV line from Skhira to Mornaguia that can cause voltage problems;
- the solution is likely to show stability problems greater than those expected for solutions "A1" in case of three phase short circuit on Skhira – Maknassy line due to the high impedance of Skhira – Mornaguia line;
- it may present under-excitation problems for generators in case of restoration;
- it does not use the already planned 400 kV corridor for the new reinforcements.

SOLUTION "C"

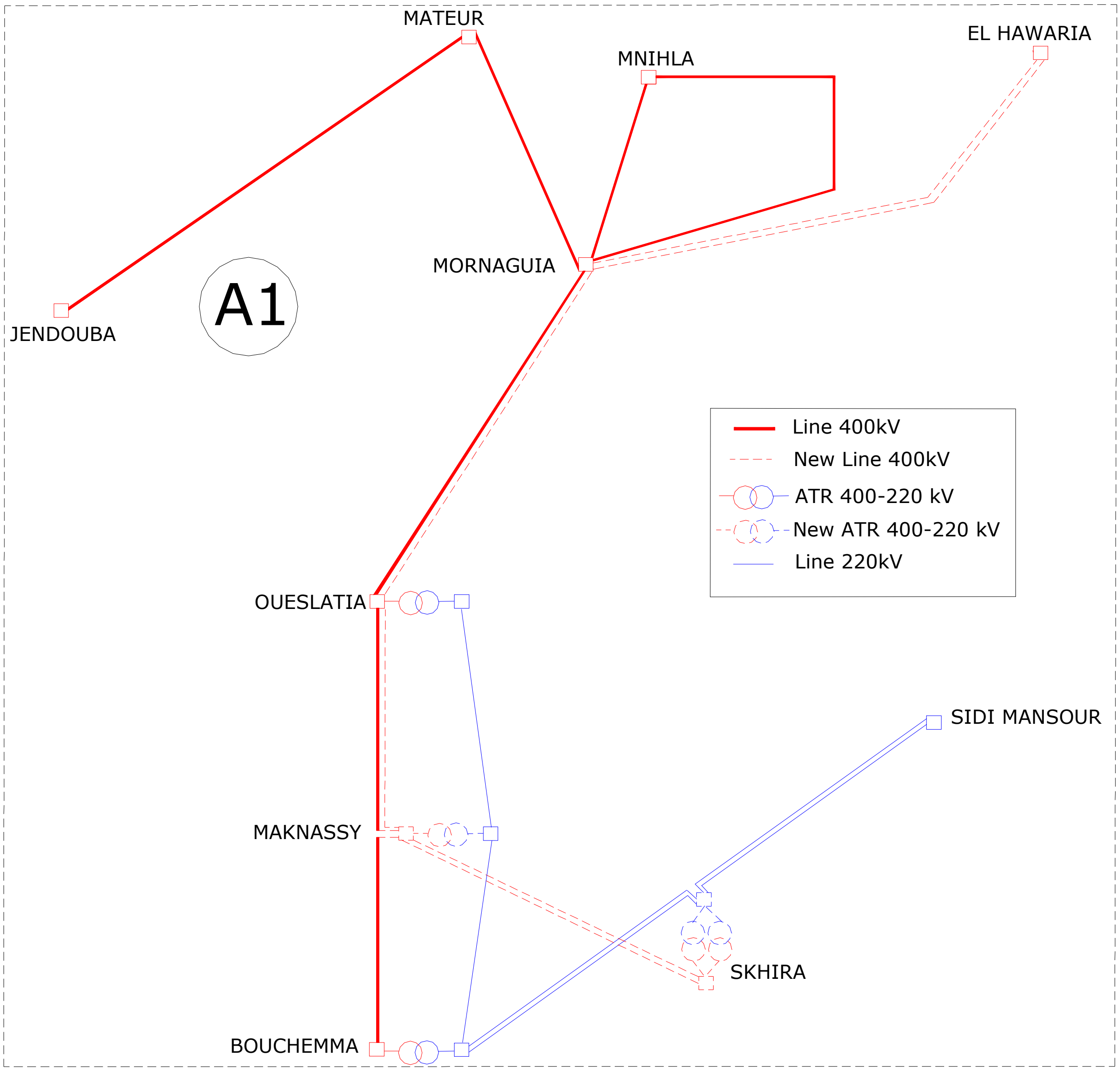
This solution foresees two single lines from Skhira to Bouchemma. It definitely shows worse performances to solution "A1" because:

- it convey the power generated in Skhira in the southern region of Tunisia (Bouchemma) and, then, the power is sent to the north of the country where the largest share of the load is concentrated;
- it is the solution with the highest active power losses;
- it is necessary to reinforce the whole south-north 400 kV corridor from Bouchemma to Mornaguia;
- it may cause grater instability phenomena than solution "A1" because in case of loss on one Skhira – Bouchemma line the equivalent impedance is high.

SOLUTION "D"

This solution foresee a line from Skhira to the already planned line Oueslatia – Bouchemma with an E/S and a line from Skhira to Oueslatia. This solution is not very different to case "A1", but:

- it causes greater losses;
- in case of fault on Skhira – E/S Oueslatia – Bouchemma it might show some stability problems due to the impedance of Skhira – Oueslatia line;
- there is the need to build a new substation along the line Bouchemma-Oueslatia;
- it requires two news corridors instead of one only, as in the case of solution "A1".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MNIHLA
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MORNAGUIA
A1
JENDOUBA
Line 400kV
New Line 400kV
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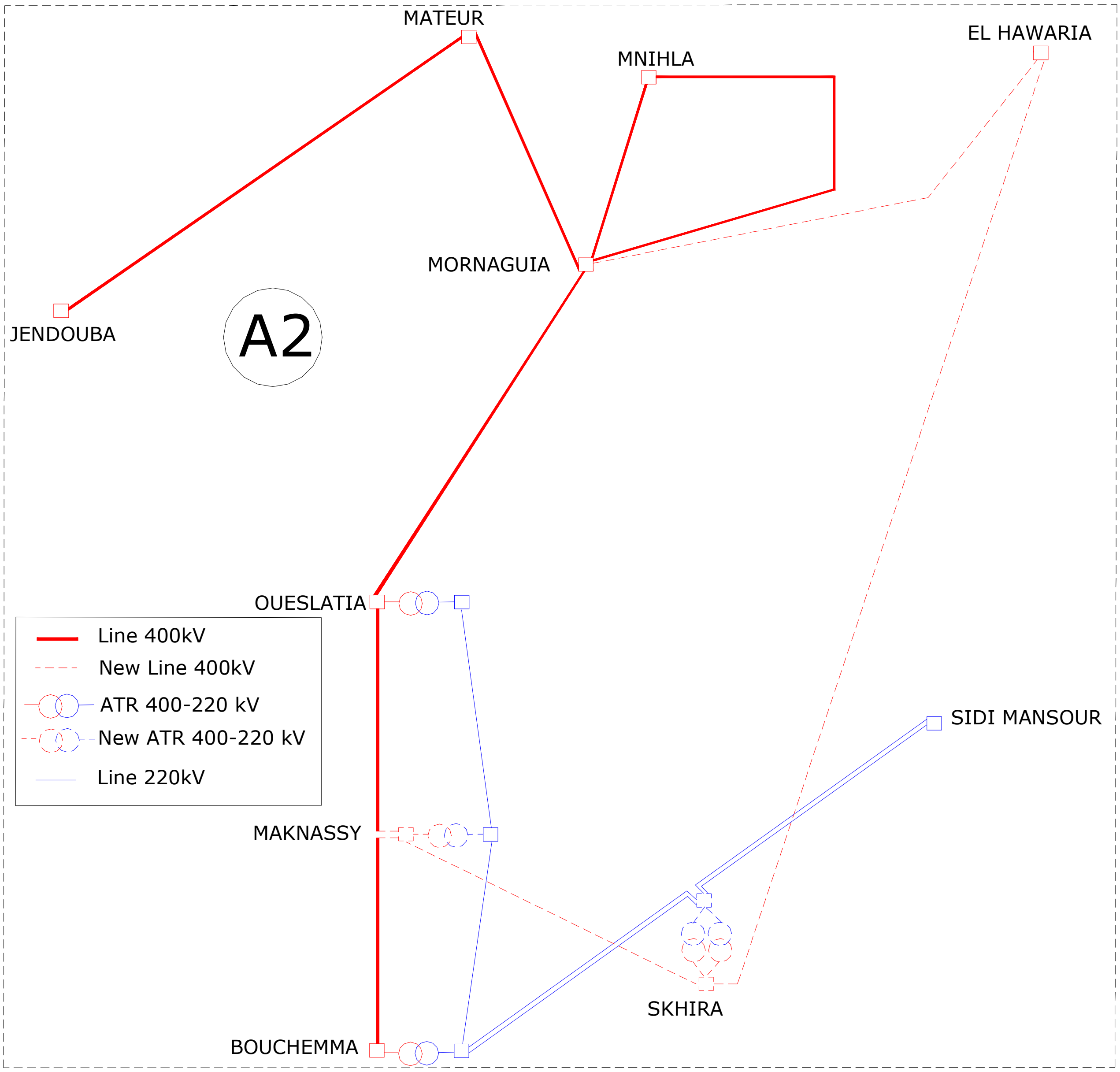
Line 220kV
OUESLATIA
SIDI MANSOUR
MAKNASSY
SKHIRA
BOUCHEMMA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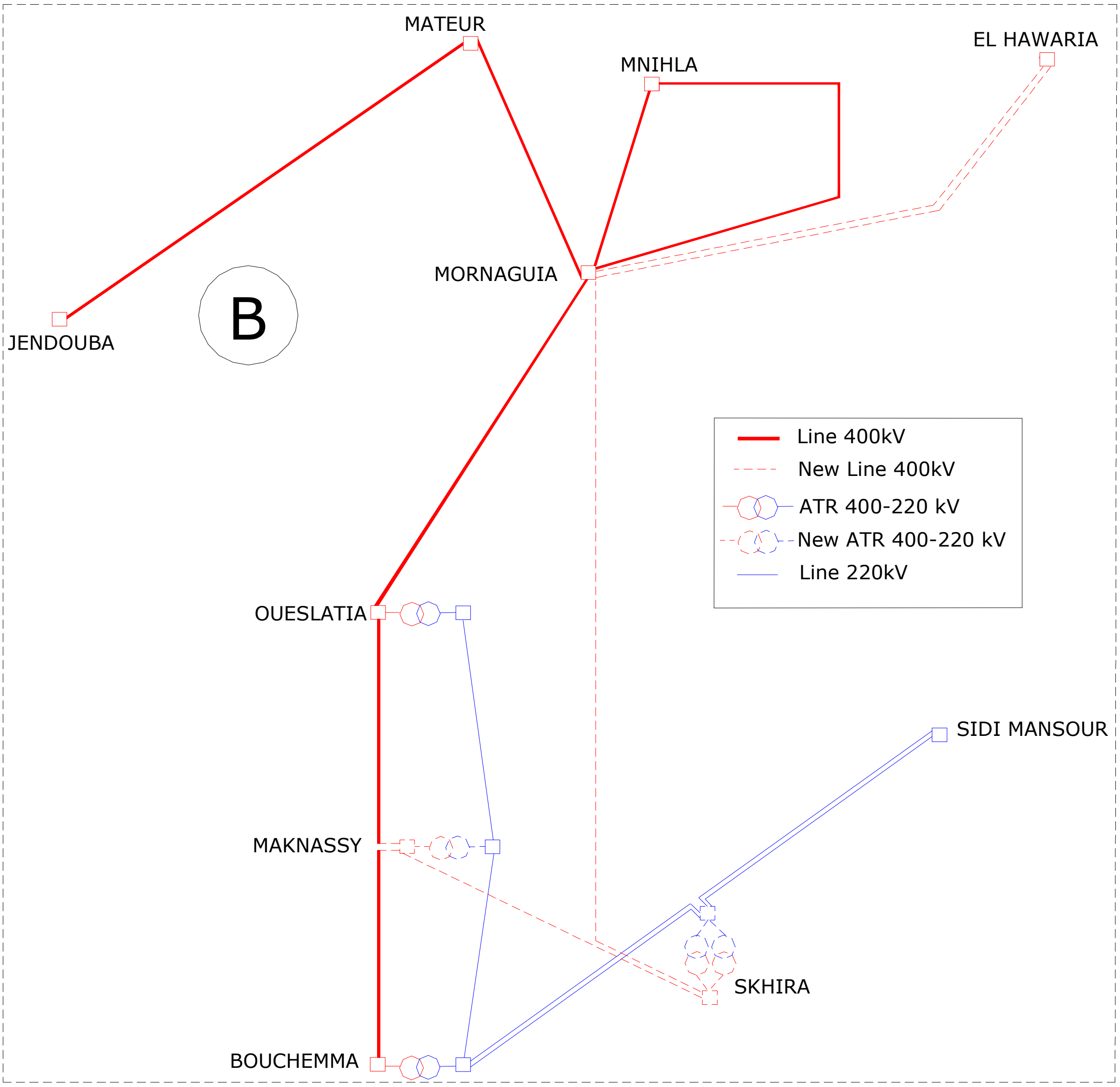
MAKNASSY
SKHIRA
BOUCHEMMA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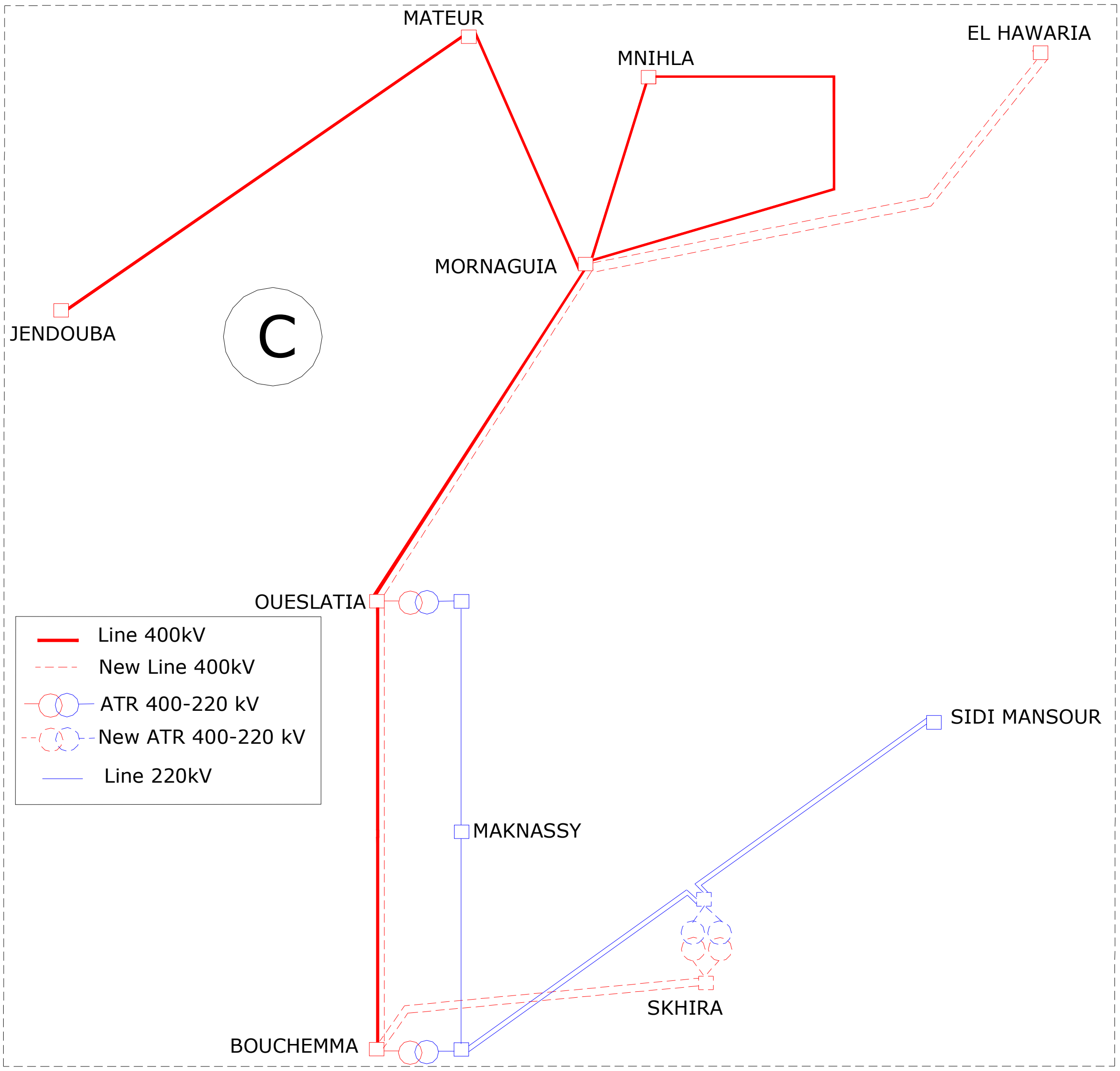
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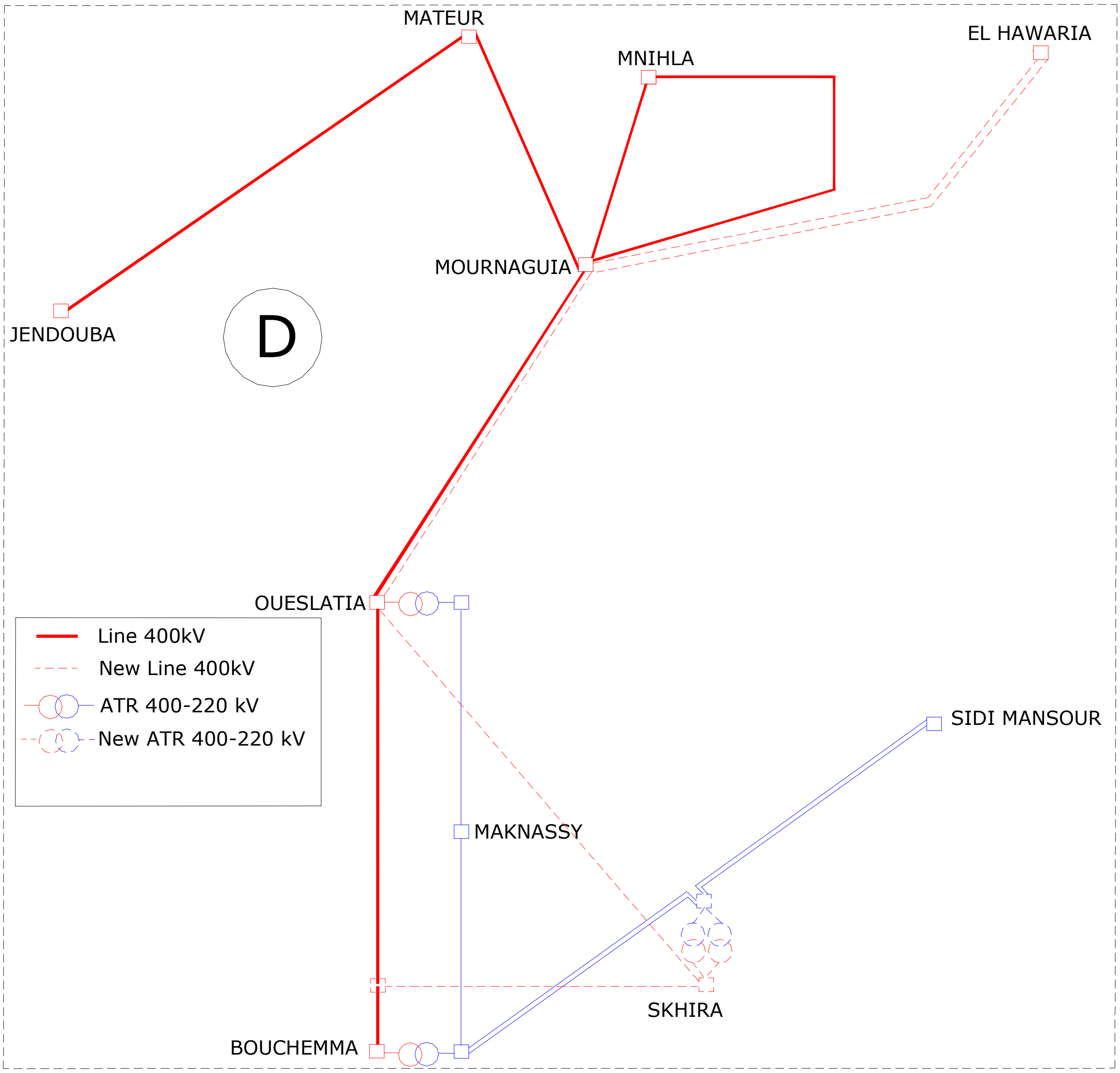
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5 IMPACT OF THE ELMED PRODUCTION CLUSTER ON THE TUNISIAN TRANSMISSION SYSTEM: DETAILED ANALYSIS APPLIED TO THE SELECTED ALTERNATIVE

This chapter addresses the detailed dynamic analyses applied to the ELMED power plant located in Skhira and the connection scheme of solutions “A1”.
The aim of these analyses is:

- to evaluate the Critical Clearing Time (CCT) of Skhira power plant in case of short circuit close to the power plant and show the effect of Fast Valving device during the transient;
- to show the importance of HVDC link to improve the performance of the Tunisian electric system in dynamic conditions;
- to evaluate the impact of the loss of one HVDC pole on Tunisian electric system.

The analyses show the system behaviour, both in peak and low load conditions, at the occurrence of the following contingencies:

1. three-phase short circuit without fault impedance on the 400 kV line Skhira – Maknassy;
2. loss of one Skhira generator in three situations:
    a. Tunisia connected to the rest of Maghreb and Europe and HVDC link to Italy in frequency regulation;
    b. Tunisia isolated and HVDC system to Italy in frequency regulation;
    c. Tunisia isolated and HVDC system to Italy out of frequency regulation.
3. loss of one pole of HVDC system.

5.1 Solution adopted for dynamic analyses

All dynamic analyses, referred both to peak and minimum load conditions, have been executed with reference to the connection solution “A1” of Skhira power plant consisting of the following network reinforcements[14]:

- two 400 kV lines from Skhira to Maknassy;
- one 400 kV line from Maknassy to Oueslatia (two 400 kV lines in total);
- one 400 kV line from Oueslatia to Mornaguia (two 400 kV lines in total);
- two 400 kV lines from Mornaguia to El Hawaria;
- two 400 MVA 400/225 kV transformers in Skhira with an E/S on Bouchemma – Sidi Mansour 225 kV lines;
- one 400 MVA 400/225 kV transformer in Maknassy station on local 225 kV voltage level.

The HVDC link is always included in the time domain simulations and it exports to Italy the following power amount:

- 800 MW in peak load scenario;
- 1000 MW in minimum load scenario.

[14] Additional reinforcements with respect to what already planned.

5.2 Hypotheses adopted for the simulations

To increase the stability margin of the Tunisian system and to have an acceptable CCT value the following devices have been considered for 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.

Obviously, these hypotheses derive from many simulations carried out by CESI and they shall be considered as a conclusion of dynamic analyses. In this report we fully report only the simulations concerning the best final solution including these devices (FV, PSS and independent excitation supply system) to show clearly the dynamic stability limits of Tunisian network. However, some additional graphs obtained without these devices for Skhira power plant are reported to show the improvements obtained installing the recommended components.

Moreover, typical values of dynamic parameters for Skhira generators (time constants, reactances, inertia, etc.) have been considered. These values have been adopted with reference to generating units of the same size in coal power plants[15].

With reference to HVDC system:

- the reactive compensation identified in static analyses has been applied also in dynamic simulations;
- a droop equal to 5% has been adopted for the control system in the converter stations;
- typical values of time constants and control parameters (with reference to SAPEI interconnection[16]) have been adopted.

Moreover; the following assumptions have been considered:

- 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 done 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.

5.3 Variables analysed in the simulations

During the simulations the behaviours of the following variables have been monitored and reported in this document:

- the electric and mechanical power of Skhira power plant;
- the rotoric angle of Skhira generators (in case of short circuit fault);

[15] In particular, reference is made to modern coal units recently commissioned in Italy.
[16] 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.

- the active power of HVDC system;
- the frequency of some important 400 kV substations of the network, such as Skhira, Bouchemma, Oueslatia and Mornaguia;
- the voltages of the same substations;
- the active power exchanges between Tunisia and Algeria, considering both the total power export / import and the flows on the single tie-lines.

5.4 Peak load scenario

Tab. 5-1 shows the values of CCT in case of three-phase short circuit without fault impedance on one 400 kV line from Skhira to Maknassy with and without Fast Valving device and with HVDC system in and out frequency regulation. In this scenario the ELMED power plant produces 1200 MW.
Comparing the values, it is possible to say that:

- Only with Fast Valving device the CCT parameter assumes acceptable values: 170 ms can be considered adequate for the network also because after a further increase of this value also Ghannouch and El Biban power plants lose the synchronism;
- The CCT is independent from HVDC frequency regulation.

Tab. 5-1 – CCT in case of Skhira – Maknassy 400 kV line short circuit

Critical Clearing Time [ms]			
HVDC in frequency regulation		**HVDC out of frequency regulation**	
Without FV	**With FV**	**Without FV**	**With FV**
120[17]	**170** *(1)*	**120**	**170** *(1)*

(1) Limited by Ghannouch and El Biban power plants

Considering that Skhira power plant has the biggest generating units of the Tunisian system and are among the biggest generators in all Maghreb area, a CCT equal to 120 ms can not be considered acceptable to have a significant dynamic security margin for Tunisian network. Moreover, 120 ms are generally insufficient to permit a reliable tele-protection action: for this manoeuvre 150 ms of CCT are generally required.

Tab. 5-2 shows the value of CCT in the same previous conditions in case of three-phase short circuit on one 400 kV line from Maknassy to Oueslatia.
In this case, moving away from the station of Skhira the CCT values increase rapidly both with and without Fast Valving. The little CCT difference with FV caused by HVDC regulation is attributable to the power oscillations caused by the interaction of Skhira power plant and HVDC controllers.

[17] The CCT showed in CESI presentation in Tunis, in June 2010, was equal to 70 ms. This value was obtained without Power System Stabilizer and without independent excitation supply system for both Skhira generators. These two additional elements increase significantly the value of this parameter.

Tab. 5-2 – CCT in case of Maknassy – Oueslatia 400 kV line short circuit

Critical Clearing Time [ms]			
HVDC in frequency regulation		**HVDC out of frequency regulation**	
Without FV	**With FV**	**Without FV**	**With FV**
180	**280** *(1)*	**180**	**290** *(1)*

(1) Limited by Ghannouch power plant

5.4.1 Short circuit on Skhira – Maknassy 400 kV line

<u>Preliminary case: fault without FV device for both Skhira generators</u>

In this paragraph the simulation results obtained without Fast Valving device for both Skhira generators are reported. The PSS and the independent excitation supply system are always in service; the duration of the fault is equal to 170 ms, the same adopted in the next paragraph (stabilized case).

From the figures reported it is possible to highlight that Skhira power plant is unstable: the electric power oscillates and the rotoric angle increases indefinitely.

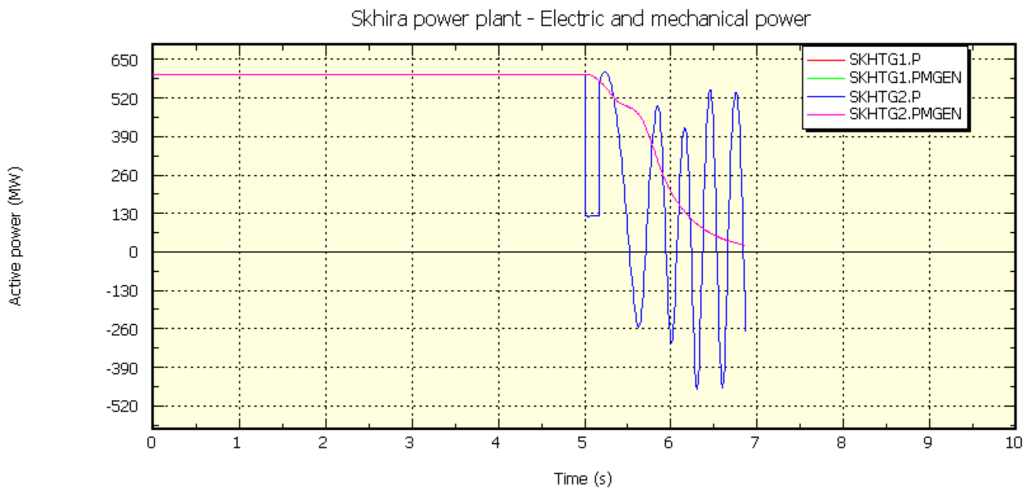

Fig. 5.1 - Peak condition, Skhira – Maknassy 400 kV short circuit, electric and mechanical power of Skhira without FV. Legend: P – Electric Power; PMGEN – Mechanical Power

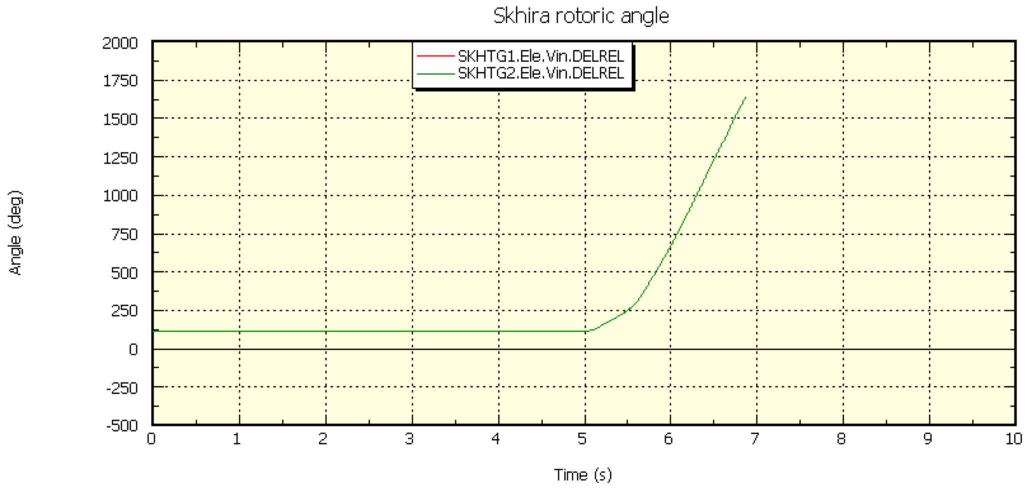

Fig. 5.2 - Peak condition, Skhira – Maknassy 400 kV short circuit, Skhira rotoric angle without FV.

Stabilized case: fault with FV device for both Skhira generators

From Fig. 5.3 to Fig. 5.9 the diagrams obtained with a three-phase short circuit on Skhira-Maknassy 400 kV line are reported. These diagrams are obtained with fault duration equal to the CCT: 170 ms and the HVDC in frequency regulation.

Fig. 5.3 shows the differences between electric and mechanical power of Skhira power plant. The effect of FV device is observable: the mechanical power decrease significantly after the fault to avoid the instability of the machine.

Fig. 5.4 shows the rotoric angle behaviours of Skhira generators. The trace reported show clearly that the power plant maintain the stability after the contingency and the angle come back to about the original value at the end of the oscillations.

Fig. 5.5 shows the active power flow on the HVDC converter station: after the oscillations caused by the effects of the fault, at the end the final value is about equal to the original one.

Fig. 5.6 shows the frequencies in four important substations of the network. From the graph it is possible to point out that the most important oscillations are present in the southern part of the network, particularly in the node of Skhira and Bouchemma; the northern part of Tunisian grid, farther from the fault and stronger than the southern one has lower frequency deviations.

Fig. 5.7 shows the voltages on the same substations. After the fault the voltages increase rapidly thanks also to the exciter of Skhira equipped with independent supply.

Fig. 5.8 and Fig. 5.9 show the active power exchanges with Algeria, respectively the total amount and the flow interesting the single tie line. From the diagrams it is possible to point out that the most important variations concern the 400 kV line Jendouba-Chefia: the highest oscillations exceed 600 MW in importation (from Algeria to Tunisia). This means that the protective relays shall be suitably tuned to avoid the risk of tie-line trippings. It is worth noting that the phenomenon of high power oscillations at the 400 kV tie-line is independent from the size of each single Shkira unit, but it is related to the total amount of power generated in Skhira.

Tab. 5-3 is the legend of Fig. 5.9.

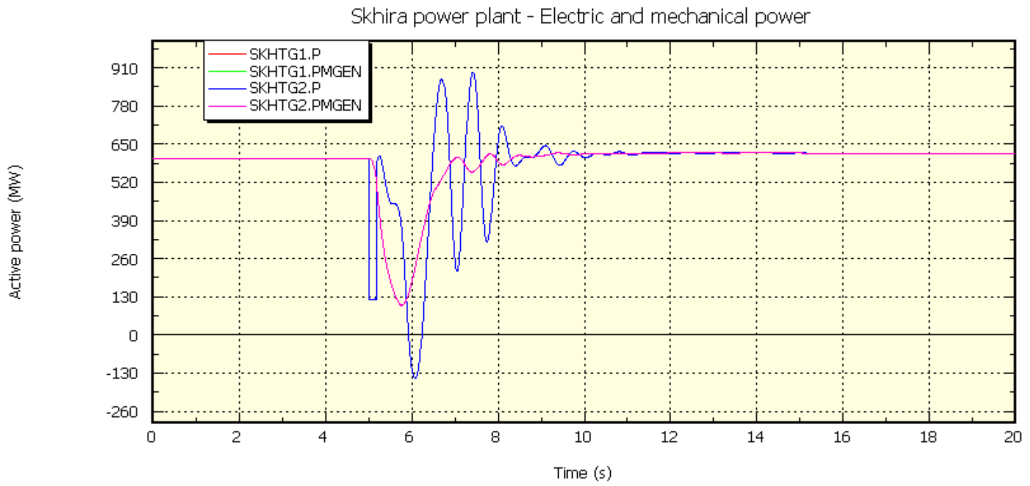

Fig. 5.3 - Peak condition, Skhira – Maknassy 400 kV short circuit, electric and mechanical power of Skhira. Legend: P – Electric Power; PMGEN – Mechanical Power

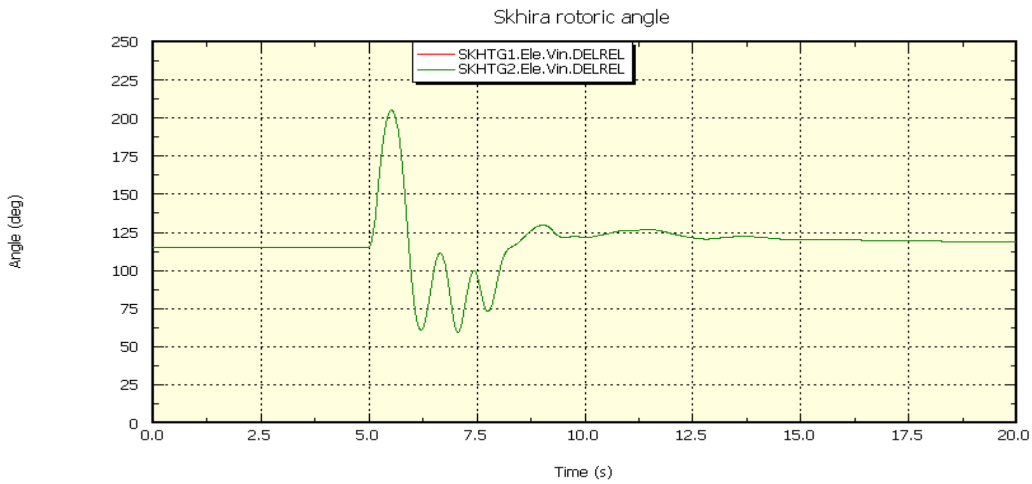

Fig. 5.4 - Peak condition, Skhira – Maknassy 400 kV short circuit, Skhira rotoric angle.

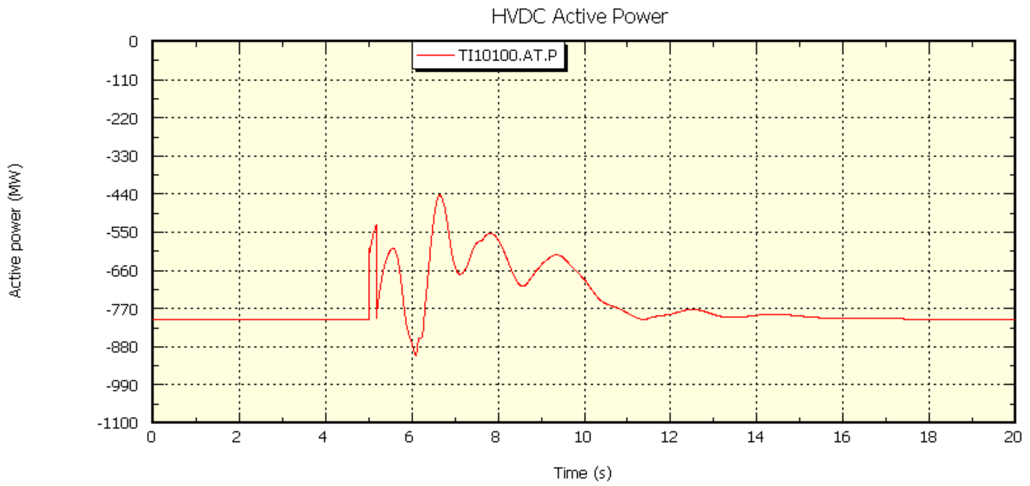

Fig. 5.5 - Peak condition, Skhira – Maknassy 400 kV short circuit, HVDC active power flow.

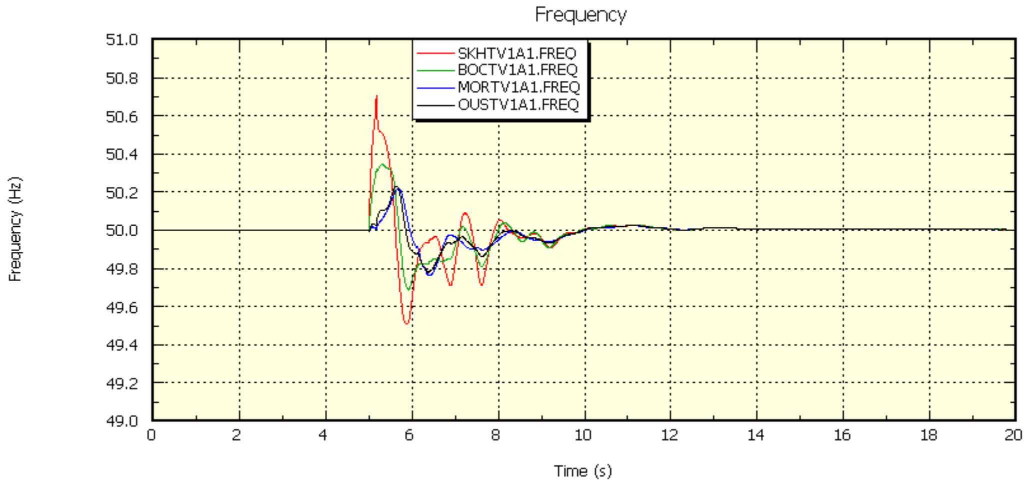

Fig. 5.6 - Peak condition, Skhira – Maknassy 400 kV short circuit, frequencies (Skhira, Bouchemma, Mornaguia, Oueslatia).

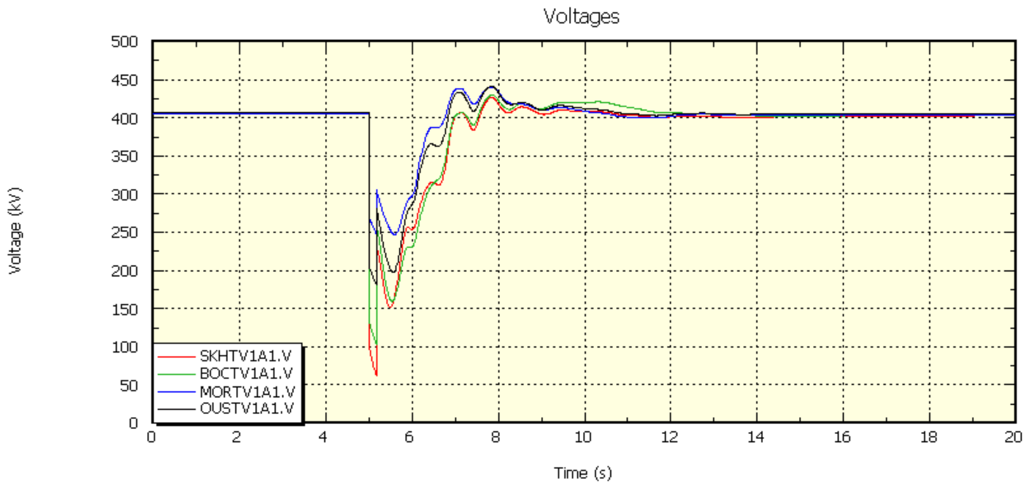

Fig. 5.7 - Peak condition, Skhira – Maknassy 400 kV short circuit, voltages (Skhira, Bouchemma, Mornaguia, Oueslatia).

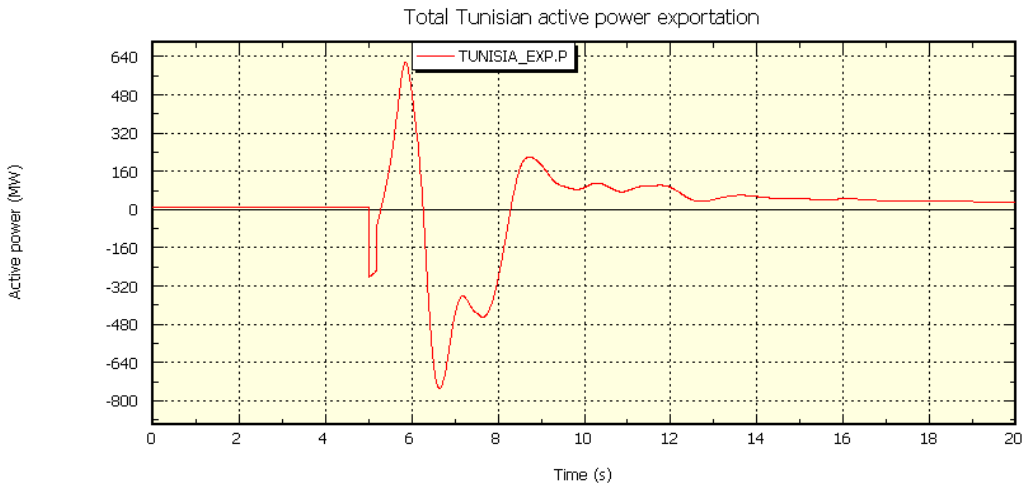

Fig. 5.8 - Peak condition, Skhira – Maknassy 400 kV short circuit, total active power exchange with Algeria only.

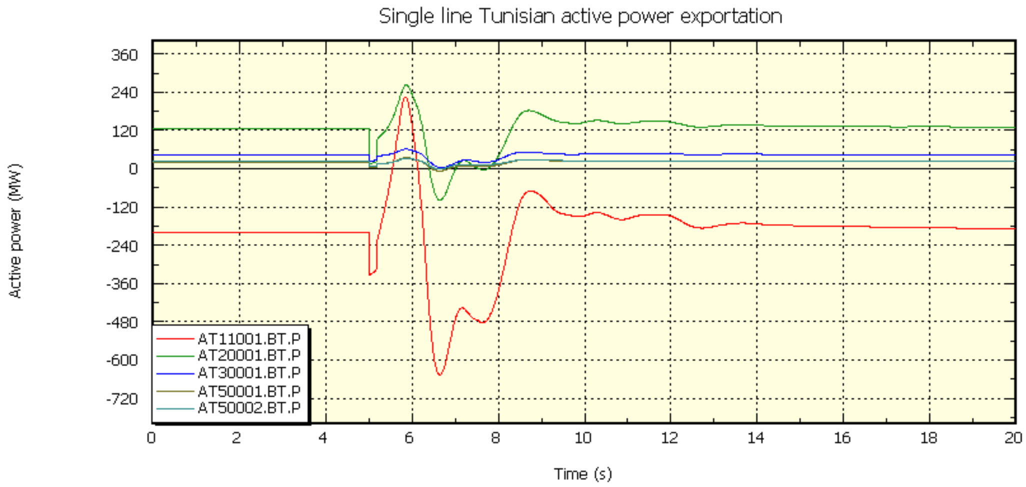

Fig. 5.9 - Peak condition, Skhira – Maknassy 400 kV short circuit, single line active power exchanges.

Tab. 5-3 – 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)

5.4.2 Skhira generator loss

In this paragraph the most important results and considerations obtained after the loss of one generator in Skhira power plant are reported.

This contingency has a very strong impact on the system: the loss of 600 MW of power (equal about to 15% of Tunisian internal load in peak load scenario) can cause very important variations in terms of power flow and frequency values.

To point out the positive effects on the Tunisian transmission system of the HVDC link, this contingency is repeated in three different situations:

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

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

Figures from Fig. 5.10 to Fig. 5.15 show the Tunisian system response after the contingency in “Case 1”. In this situation the power shortfall caused by the tripping of one Skhira generator (600 MW) is partially covered by the other Tunisian generators according to their droops but mainly by the decreasing of exportation to Italy (Fig. 5.11 shows that the HVDC converter station reduces its exportation of about 320 MW) and importing from Algeria (Fig. 5.14) about 200 MW. Only about 80 MW are provided by other Tunisian generators. In this case there aren’t any particular oscillations

and the final value of the frequency (reported in Fig. 5.12) equal to about 49.95 Hz can be considered as a good result. The exchanges from Algeria also in this case concern particularly the 400 kV line Jendouba-Chefia (with a peak in importation greater than 500 MW).
Tab. 5-4 is the legend of Fig. 5.15.

Figures from Fig. 5.16 to Fig. 5.19 show the Tunisian network response after the same contingency in “Case 2”. In this situation the power shortfall due to the tripping of one Skhira generator (600 MW) is partially provided by the other Tunisian generators according to their droops (about 120 MW), but mainly by the HVDC link that decreases its exportation of about 480 MW. Also in this situation there are not particular problems in terms of dynamic oscillations and final values: for example the minimum value of the frequency is about 49.70 Hz during the transient and about 49.93 Hz as a final value; only the voltages, particularly in Mornaguia and Oueslatia stations have transient values equal to 441 kV, but they came back to their limits at the end of the transient: the lower power flows on the 400 kV transmission level cause the increase of voltages (see Fig. 5.13).

Figures from Fig. 5.20 to Fig. 5.23 show the Tunisian network response after the same contingency in “Case 3”. This is a critical situation: the loss of 600 MW and the HVDC link without frequency regulation cause problems for the network because in peak load scenario the Tunisian generators cannot cover the lost power. In this case the load shedding intervention is necessary.

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

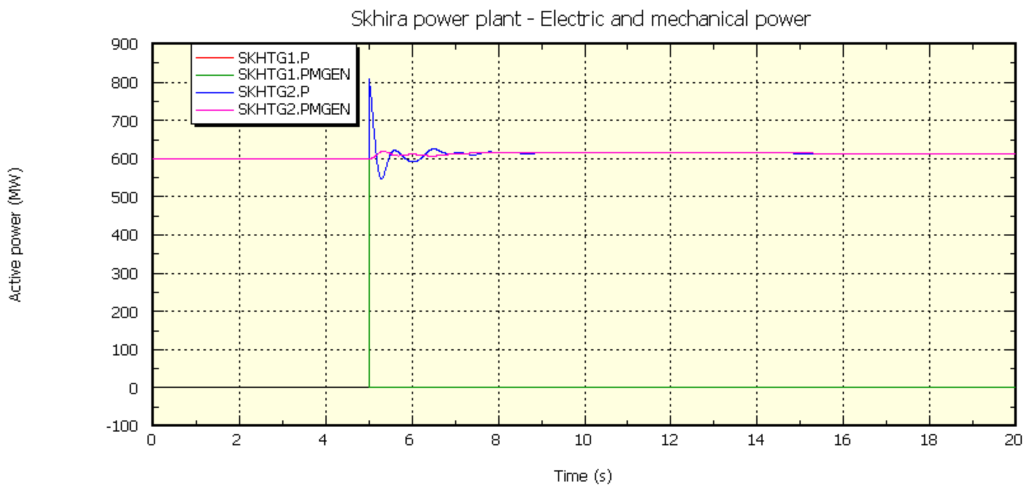

Fig. 5.10 - Peak condition, Skhira generator loss, electric and mechanical power of Skhira (Case 1). Legend: P – Electric Power; PMGEN – Mechanical Power

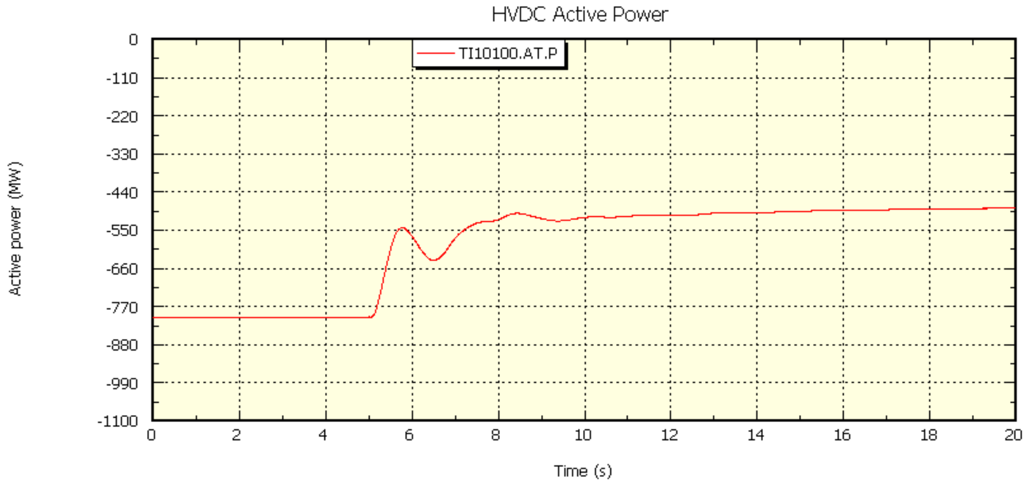

Fig. 5.11 - Peak condition, Skhira generator loss, HVDC active power flow (Case 1).

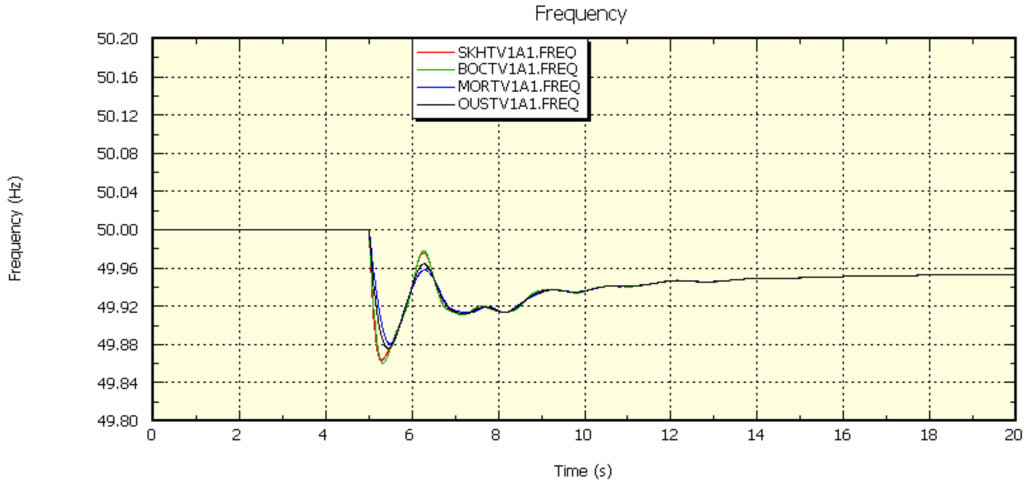

Fig. 5.12 - Peak condition, Skhira generator loss, frequencies (Skhira, Bouchemma, Mornaguia, Oueslatia)(Case 1).

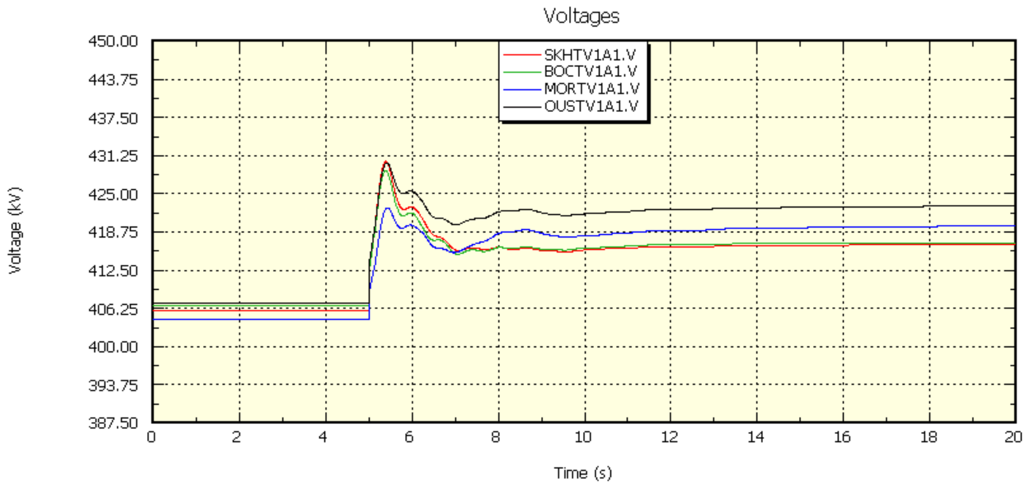

Fig. 5.13 - Peak condition, Skhira generator loss, voltages (Skhira, Bouchemma, Mornaguia, Oueslatia) (Case 1).

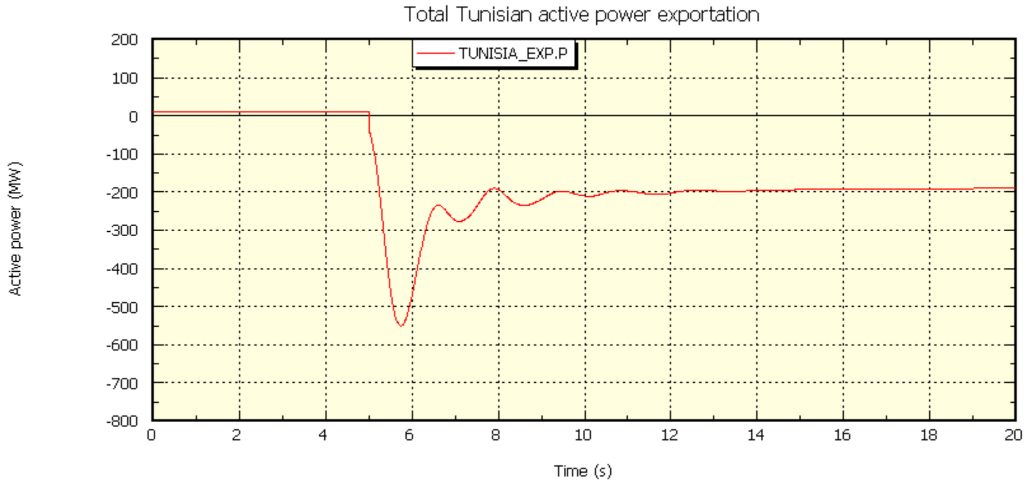

Fig. 5.14 - Peak condition, Skhira generator loss, total active power exchange with Algeria only (Case 1).

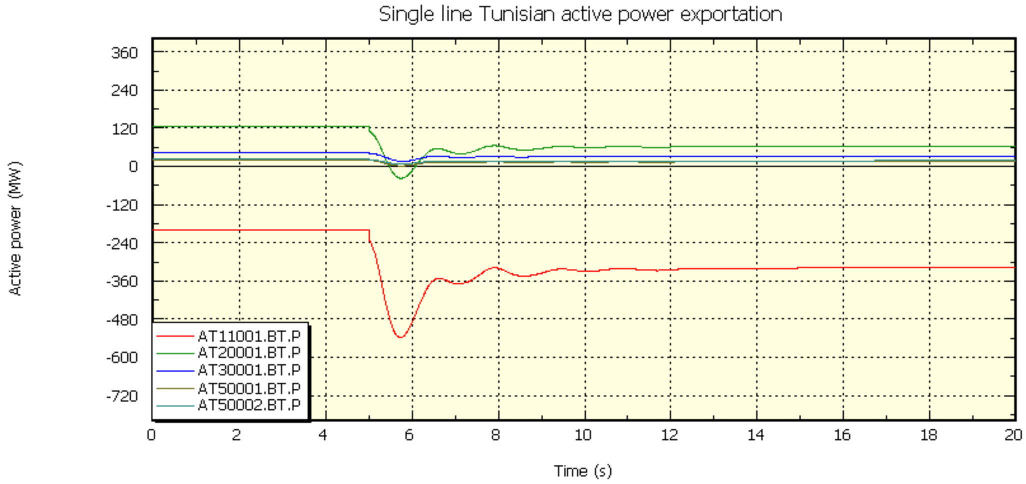

Fig. 5.15 - Peak condition, Skhira generator loss, single line active power exchanges (Case 1).

Tab. 5-4 – 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)

5.4.2.2 Case 2: Tunisia isolated and HVDC system in frequency regulation

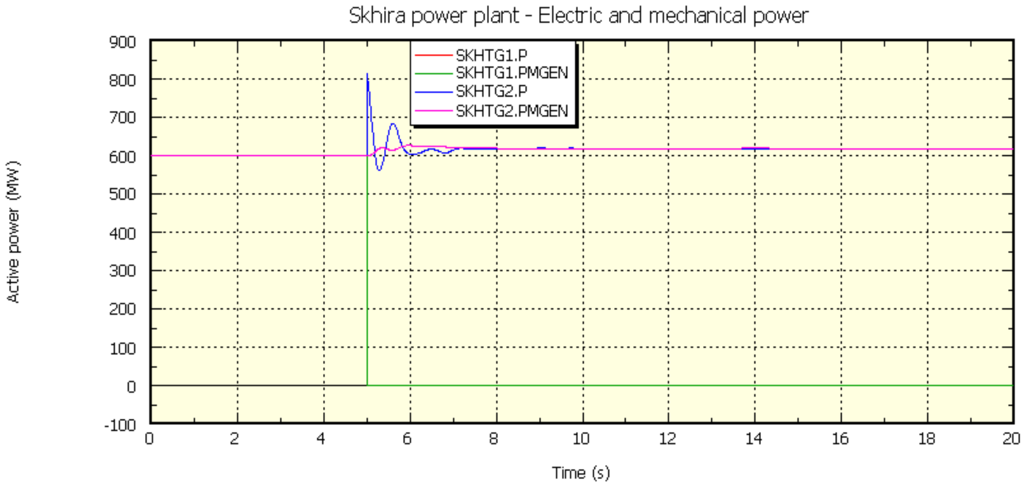

Fig. 5.16 - Peak condition, Skhira generator loss, electric and mechanical power of Skhira (Case 2). Legend: P – Electric Power; PMGEN – Mechanical Power

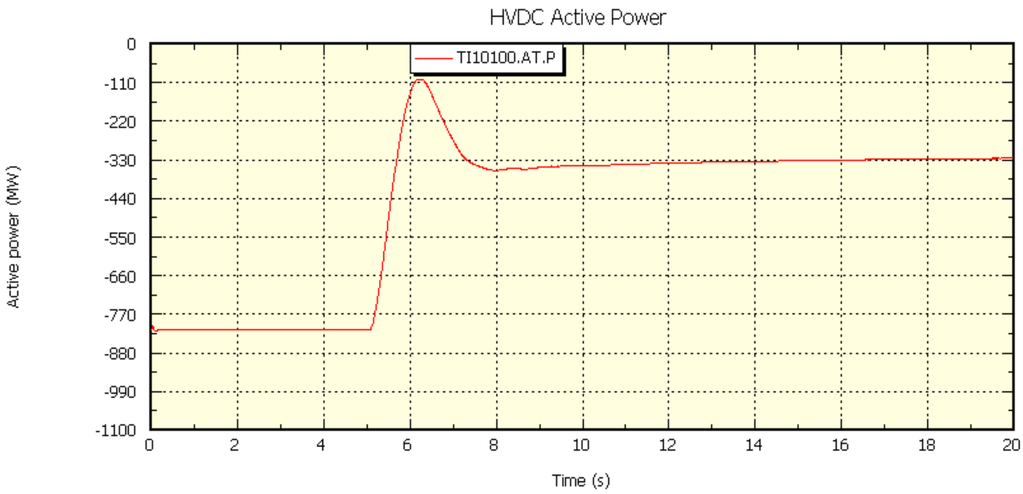

Fig. 5.17 - Peak condition, Skhira generator loss, HVDC active power flow (Case 2).

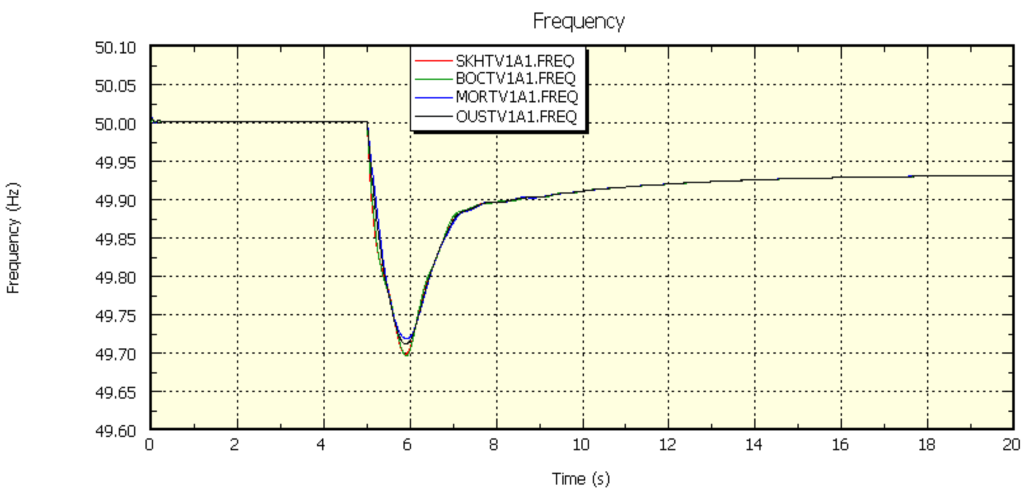

Fig. 5.18 - Peak condition, Skhira generator loss, frequencies (Skhira, Bouchemma, Mornaguia, Oueslatia) (Case 2).

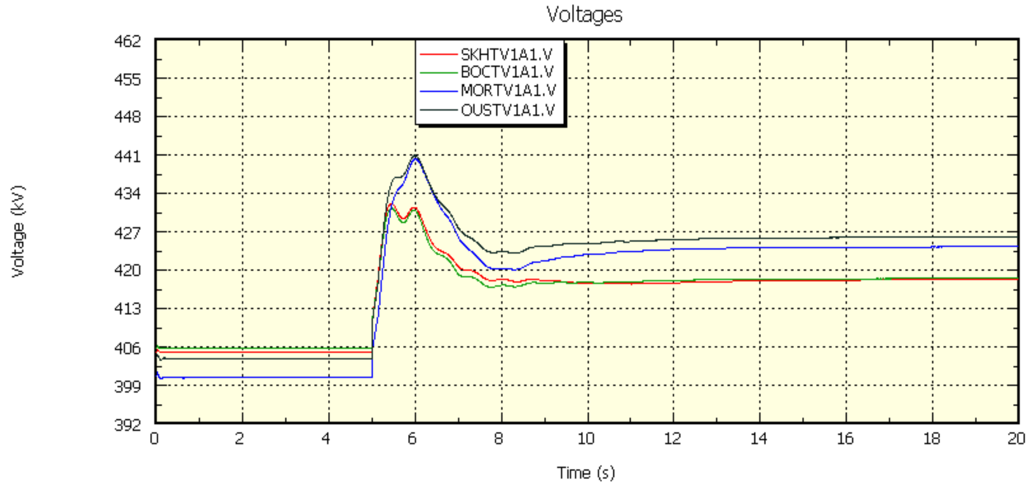

Fig. 5.19 - Peak condition, Skhira generator loss, voltages (Skhira, Bouchemma, Mornaguia, Oueslatia) (Case 2).

5.4.2.3 Case 3: Tunisia isolated and HVDC system without frequency regulation

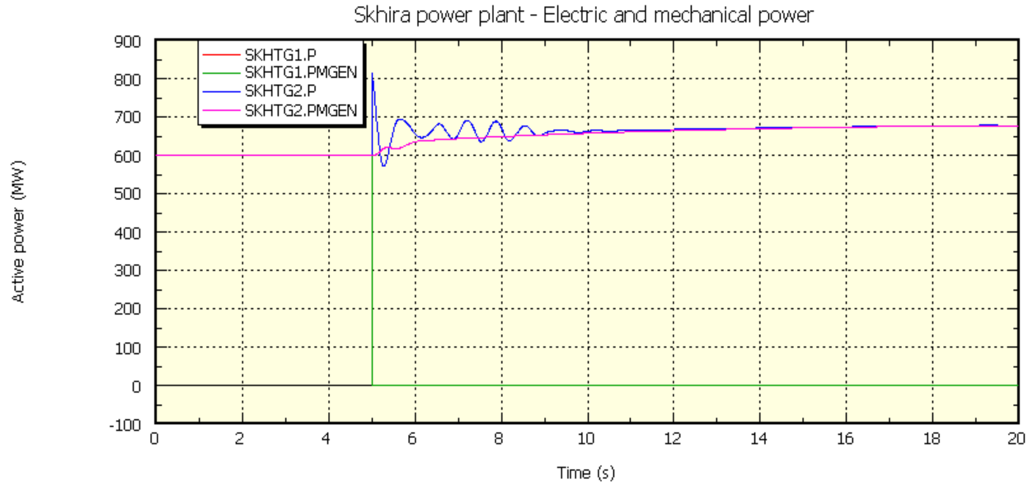

Fig. 5.20 - Peak condition, Skhira generator loss, electric and mechanical power of Skhira (Case 3).
Legend: P – Electric Power; PMGEN – Mechanical Power

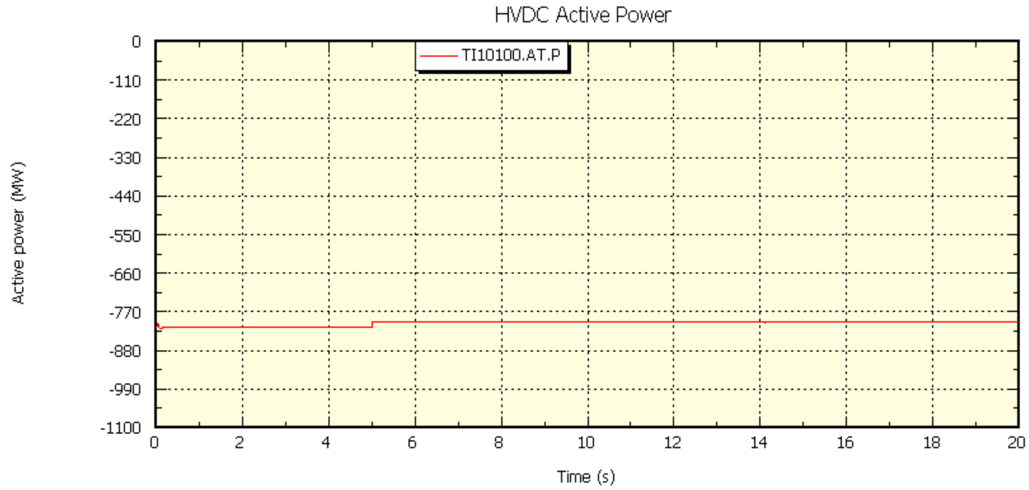

Fig. 5.21 - Peak condition, Skhira generator loss, HVDC active power flow (Case 3).

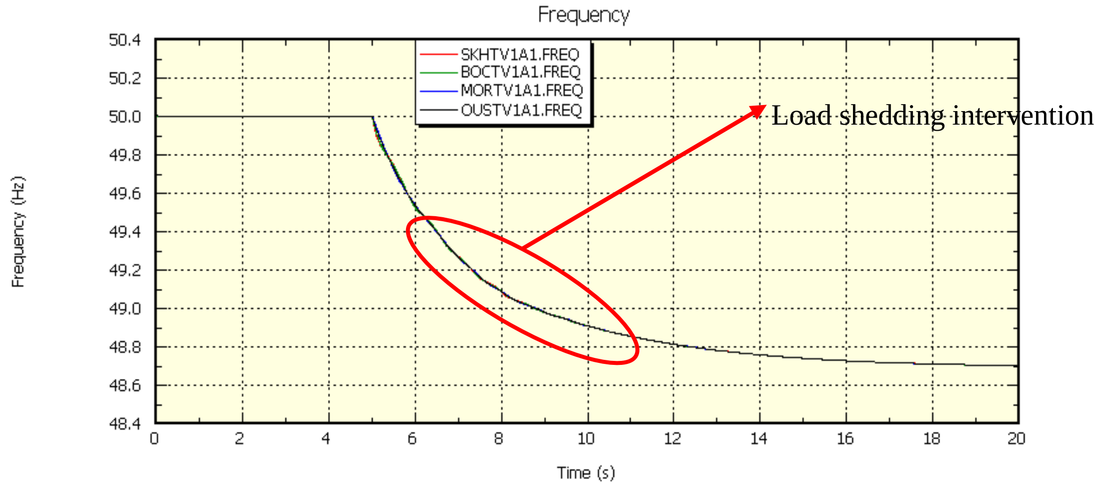

Fig. 5.22 - Peak condition, Skhira generator loss, frequencies (Skhira, Bouchemma, Mornaguia, Oueslatia) (Case 3).

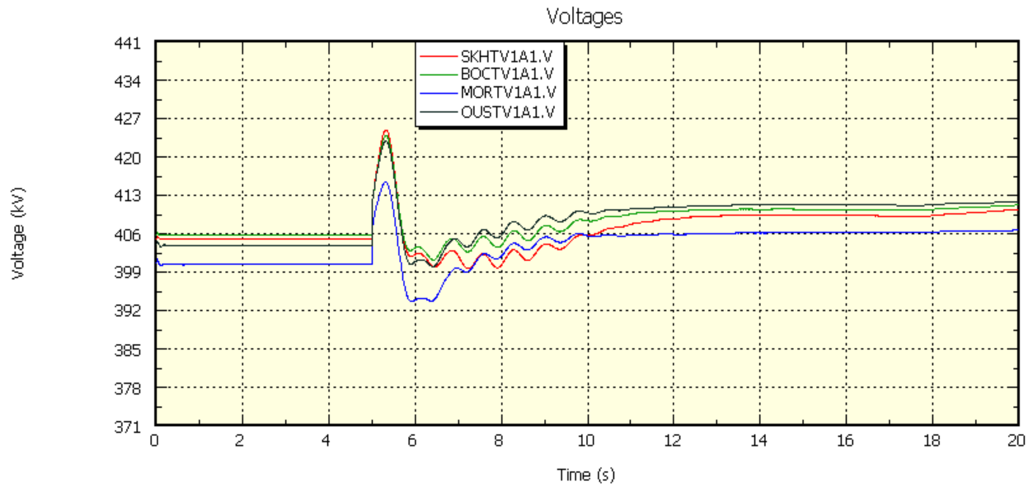

Fig. 5.23 - Peak condition, Skhira generator loss, voltages (Skhira, Bouchemma, Mornaguia, Oueslatia) (Case 3).

5.4.3 HVDC pole loss

In this paragraph the most important results and considerations obtained after the loss of one pole of the HVDC link are described.

Assuming that the HVDC link with Sicily will have a bipolar configuration, we consider the loss of only one pole since the loss of the whole converter station is considered very improbable.

This contingency, equivalent to a sudden load decrease, is repeated in two different situations:

- Case 1: Tunisian grid connected to the rest of Maghreb (and Europe) leaving the other pole of the HVDC system in frequency regulation;
- Case 2: Tunisian grid isolated and leaving the other pole of the HVDC system in frequency regulation.

The case with Tunisian grid isolated and the other pole of HVDC without frequency regulation is not significant because of the moderate margin of frequency regulation.[18]

5.4.3.1 Case 1: Tunisia interconnected with the rest of Maghreb

From Fig. 5.24 to Fig. 5.29 we note that there are not particular problems for the power system. The most important effect that it is possible to highlight, is the increase of the power export from Tunisia to Algeria: Fig. 5.28 shows that after the transient Tunisia exports to Algeria more than 200 MW; Fig. 5.29 shows that in this case the line that most increases its power flow (in absolute value) is the 225 kV line Tajerouine-El Aouinet.

Tab. 5-5 is the legend of Fig. 5.29.

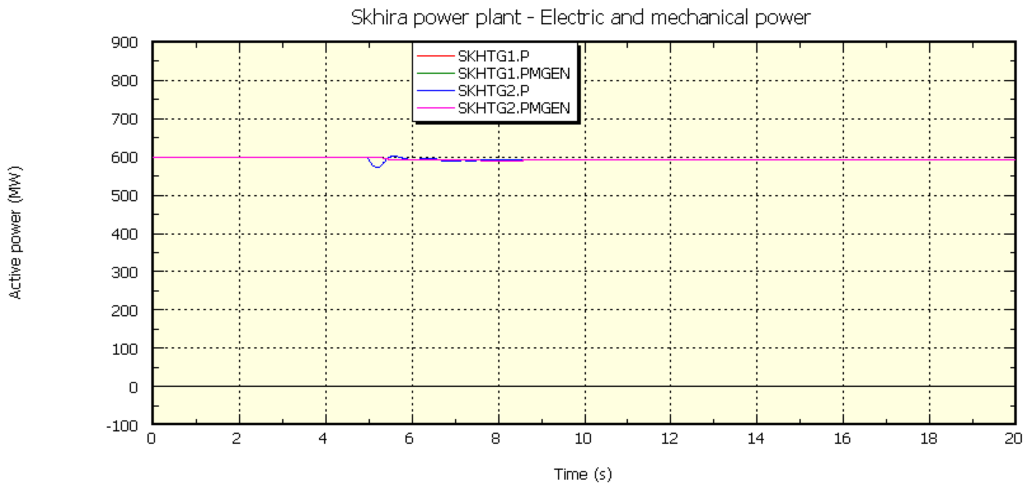

Fig. 5.24 - Peak condition, HVDC pole loss, electric and mechanical power of Skhira (Case 1). Legend: P – Electric Power; PMGEN – Mechanical Power

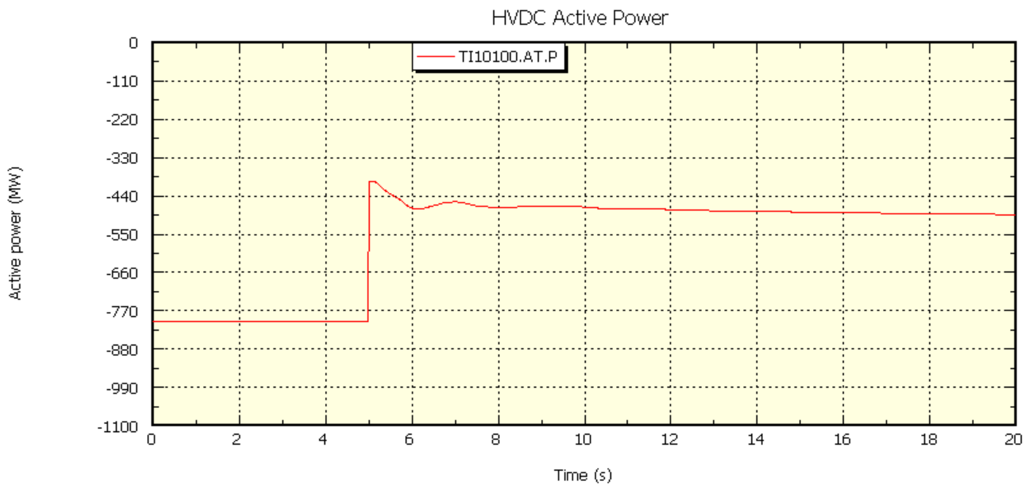

Fig. 5.25 - Peak condition, HVDC pole loss, HVDC active power flow (Case 1).

[18] In this case after the contingency the HVDC pole in service increases the exportation to Italy to reduce the frequency error: this margin of regulation is not particularly wide due to the high value of active power exported in starting conditions (100 MW is the margin in peak load conditions for each pole).

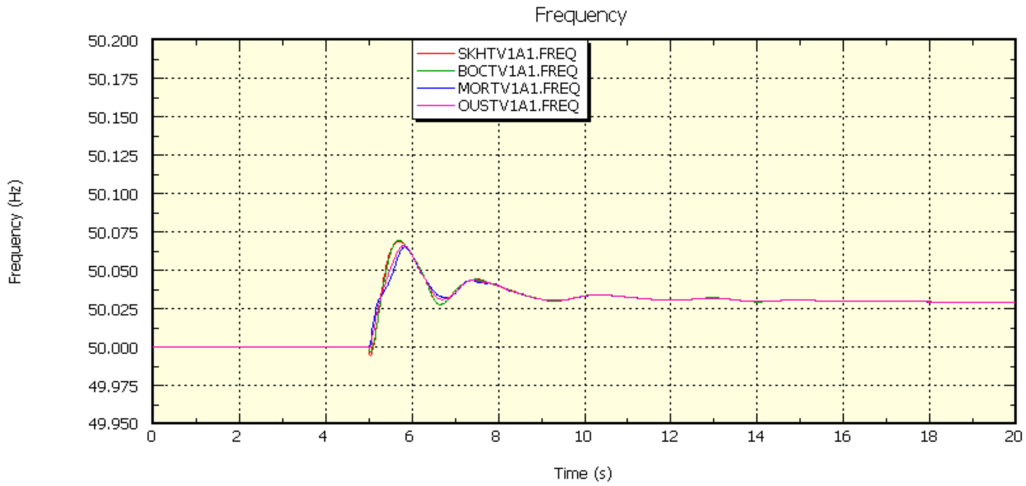

Fig. 5.26 - Peak condition, HVDC pole loss, frequencies (Skhira, Bouchemma, Mornaguia, Oueslatia) (Case 1).

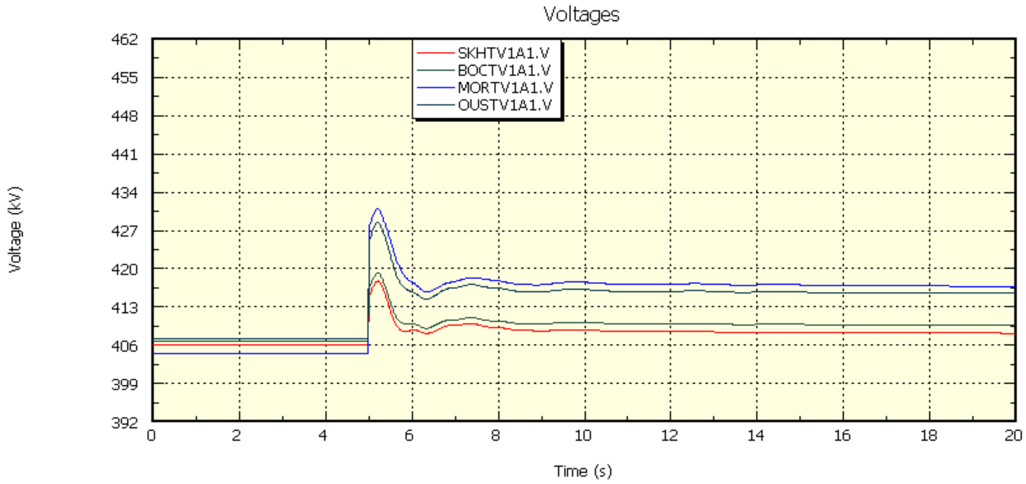

Fig. 5.27 - Peak condition, HVDC pole loss, voltages (Skhira, Bouchemma, Mornaguia, Oueslatia) (Case 1).

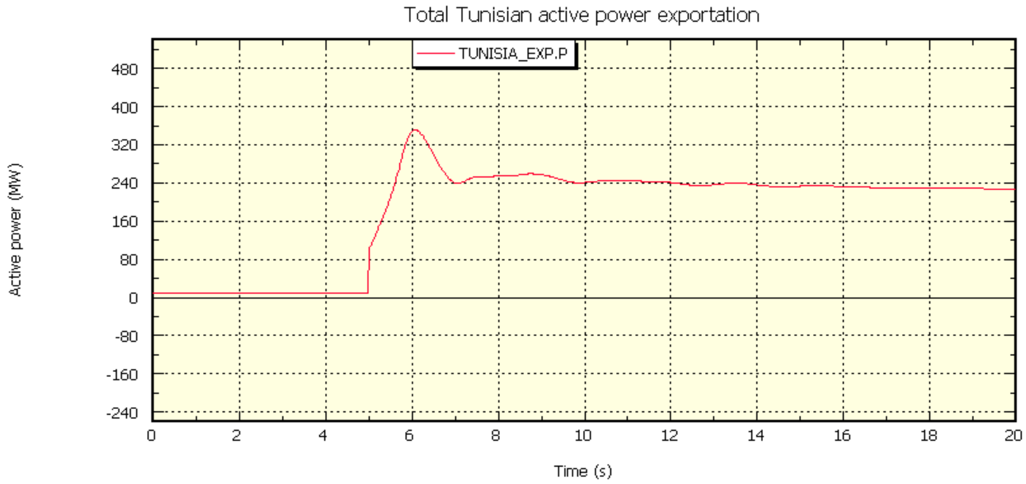

Fig. 5.28 - Peak condition, HVDC pole loss, total active power exchange with Algeria only (Case 1).

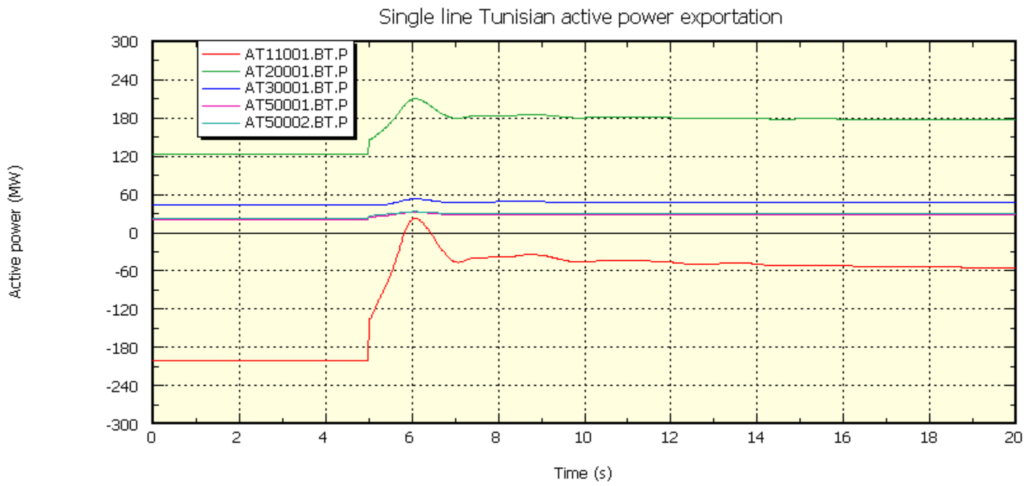

Fig. 5.29 - Peak condition, HVDC pole loss, tie-line active power exchanges (Case 1).

Tab. 5-5 – 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)

5.4.3.2 Case 2: Tunisia isolated

From Fig. 5.30 to Fig. 5.33 we note that in this case after the contingency the frequency increases significantly until about 50.25 Hz. In fact, the contingency is equal to a load shedding and the frequency goes up. After the fault the generators (Fig. 5.30 reports Skhira machines) decrease their productions and the other pole of HVDC exports 500 MW to Sicily (it exported 400 MW at the beginning). In this case the effect of the other pole of HVDC system is limited to only 100 MW and it is the most important case of frequency increase, particularly at the beginning of the transitory.

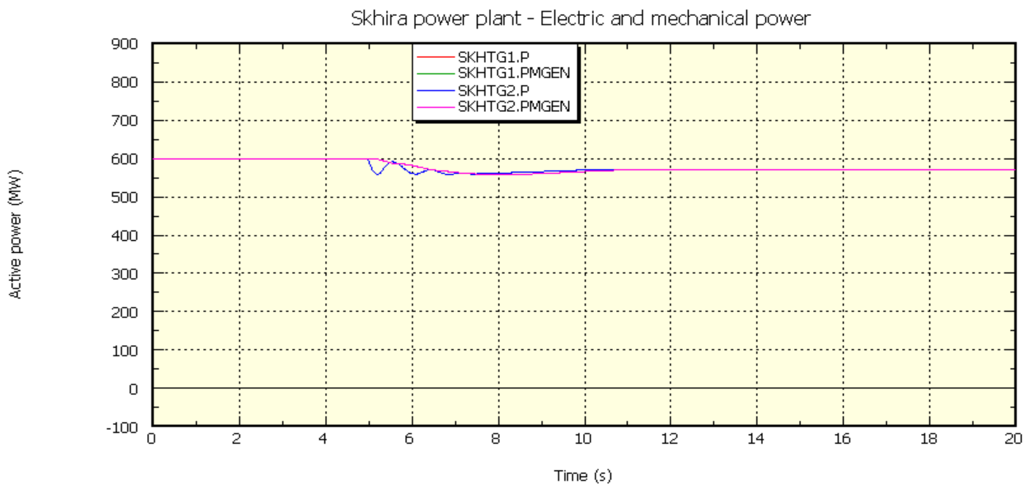

Fig. 5.30 - Peak condition, HVDC pole loss, electric and mechanical power of Skhira (Case 2).
Legend: P – Electric Power; PMGEN – Mechanical Power

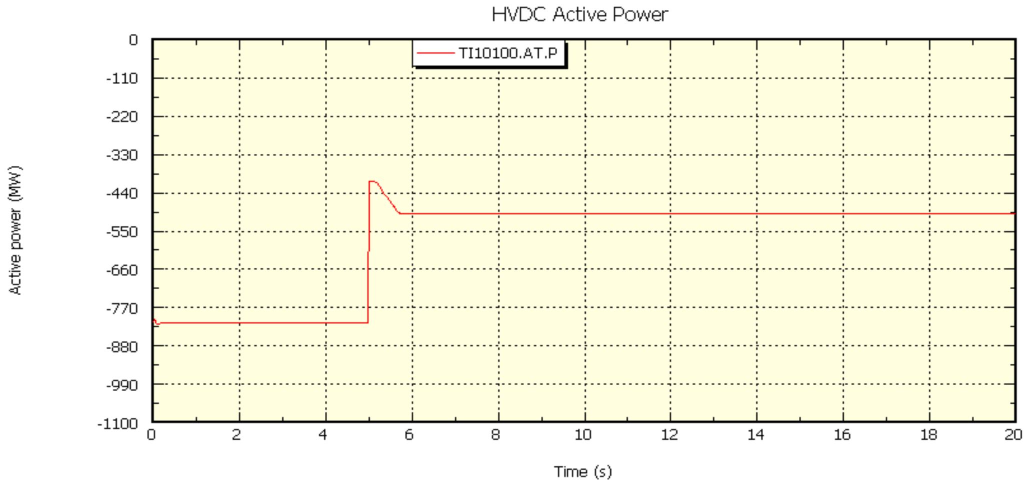

Fig. 5.31 - Peak condition, HVDC pole loss, HVDC active power flow (Case 2).

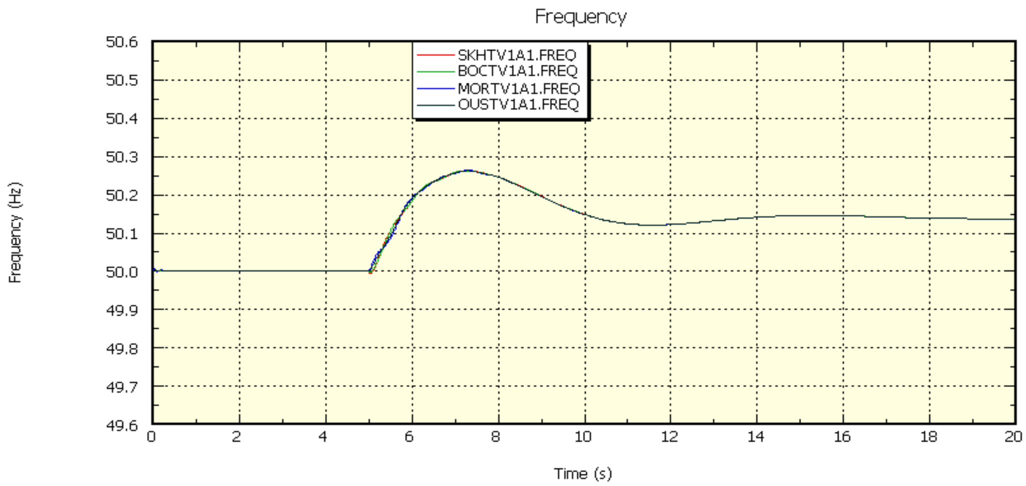

Fig. 5.32 - Peak condition, HVDC pole loss, frequencies (Skhira, Bouchemma, Mornaguia, Oueslatia) (Case 2).

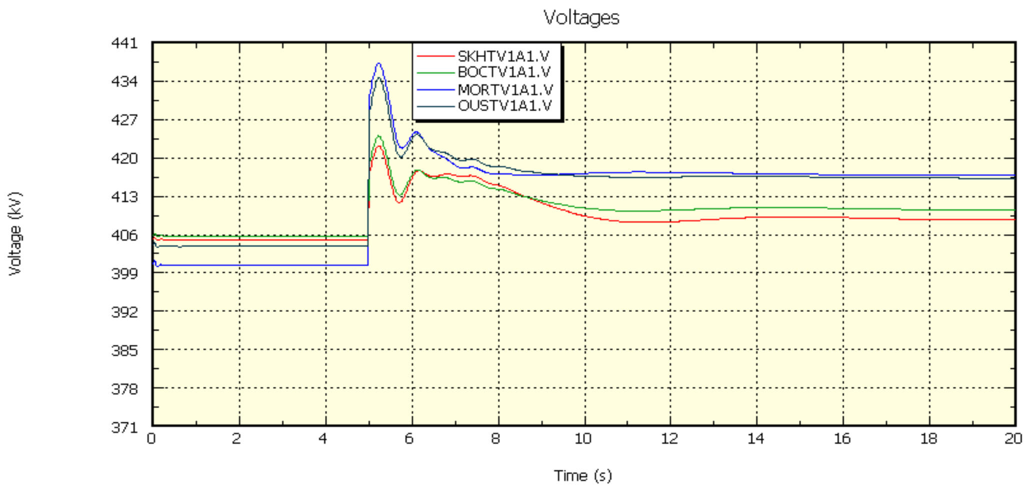

Fig. 5.33 - Peak condition, HVDC pole loss, voltages (Skhira, Bouchemma, Mornaguia, Oueslatia) (Case 2).

5.5 Minimum load scenario

Tab. 5-6 shows the values of CCT in case of three-phase short circuit without fault impedance (solid short circuit) on one 400 kV line from Skhira to Maknassy with and without Fast Valving device and with the HVDC link in and out frequency regulation (same conditions of peak load scenario). In this scenario the ELMED power plant produces 1048 MW.

From the value reported it is possible to point out that also in absence of FV device the CCT is already acceptable (equal to 200 ms). The increasing of CCT parameter in this case is mainly due to the lower production of ELMED power plant (1048 MW rather than 1200 MW) with respect to peak load conditions. To have acceptable values of CCT also with a production of 1200 MW (like in peak load scenario), the FV is necessary.

Tab. 5-6 – CCT in case of Skhira – Maknassy 400 kV line short circuit

Critical Clearing Time [ms]			
HVDC in frequency regulation		**HVDC out of frequency regulation**	
Without FV	**With FV**	**Without FV**	**With FV**
200	**270** *(1)*	**200**	**280** *(1)*

(1) Limited by Ghannouch power plant

Tab. 5-7 shows the value of CCT in the same previous conditions in case of three-phase short circuit on one 400 kV line from Maknassy to Oueslatia.

In this case, moving away from the substation of Skhira, the CCT values increase a lot both with and without Fast Valving. The little difference with FV caused by HVDC regulation is attributable to the power oscillations caused by the interaction of Skhira power plant and HVDC controllers[19].

Tab. 5-7 – CCT in case of Maknassy – Oueslatia 400 kV line short circuit

Critical Clearing Time [ms]			
HVDC in frequency regulation		**HVDC out of frequency regulation**	
Without FV	**With FV**	**Without FV**	**With FV**
310	**730** *(1)*	**310**	**760** *(1)*

(1) Limited by Ghannouch power plant

[19] The interaction of HVDC and generator dynamic controllers, particularly in situations with very stressed network (in this case the short circuit duration is very long) can cause little differences in the grid stability margin. These differences, like in this case, are emphasized also by the difference between time constants (HVDC controller is faster than generator controller).

5.5.1 Short circuit on Skhira – Maknassy 400 kV line

Preliminary case: fault without FV device for both Skhira generators

In this paragraph the simulation results obtained without Fast Valving device for both Skhira generators are reported. The PSS and the independent excitation supply system are always in service; the duration of the fault is equal to 270 ms, the same adopted in the next paragraph (stabilized case).
Like in peak load conditions, from the figures reported it is possible to highlight that Skhira power plant is unstable: the electric power oscillates and the rotoric angle increases indefinitely.

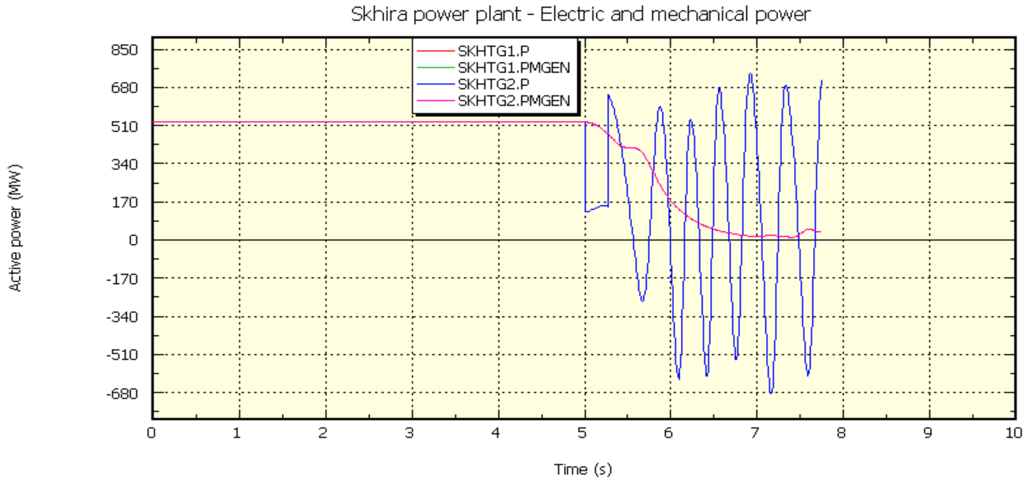

Fig. 5.34 - Minimum condition, Skhira – Maknassy 400 kV short circuit, electric and mechanical power of Skhira without FV. Legend: P – Electric Power; PMGEN – Mechanical Power

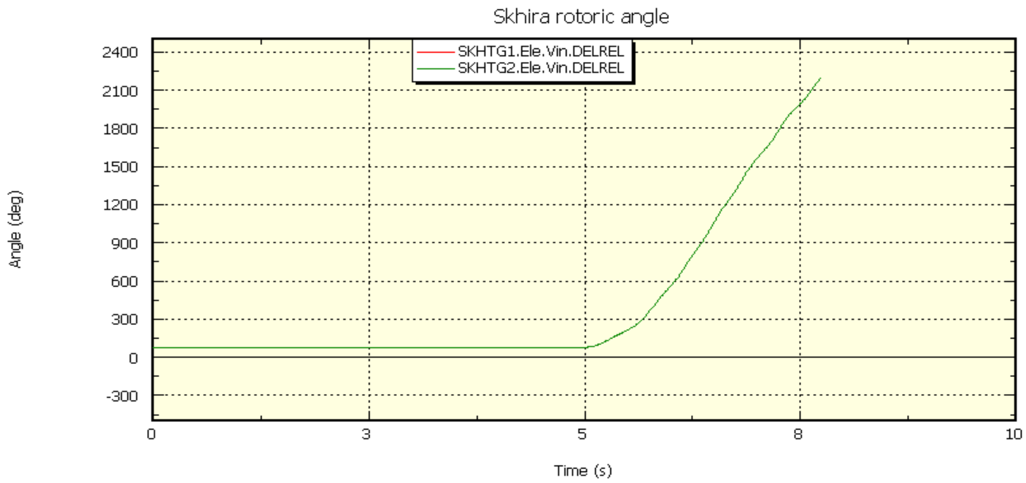

Fig. 5.35 - Minimum condition, Skhira – Maknassy 400 kV short circuit, Skhira rotoric angle without FV.

Stabilized case: fault with FV device for both Skhira generators

The diagrams obtained with a three-phase short circuit on Skhira-Maknassy 400 kV line are shown from Fig. 5.36 to Fig. 5.42. These traces are obtained with a fault duration equal to the CCT: 270 ms and the HVDC in frequency regulation.

Fig. 5.36 shows the differences between electric and mechanical power of Skhira power plant. The effect of FV device is observable: the mechanical power decreases significantly after the fault to avoid the instability of the machine.
Fig. 5.37 shows the rotoric angle behaviours of Skhira generators. The trace reported show clearly that, like in peak load conditions, the power plant maintain the stability after the contingency and the angle come back to about the original value at the end of the oscillations.
Fig. 5.38 shows the active power flow on HVDC device: after the oscillations caused by the effects of the fault, at the end the final value is about equal to the original value In this scenario it is important to underline that the HVDC interconnection does not increase its exportation because it exports already 1000 MW to Italy in base conditions.
Fig. 5.39 shows the frequencies in four important substations of the network. From the graph it is possible to note that the most important oscillations are present also in this scenario in the southern part of the network, particularly in the node of Skhira and Bouchemma; in this case the amplitude of these oscillations is greater that those in peak load conditions due to a lower inertia of the system.
Fig. 5.40 shows the voltages on the same substations where the frequency was displayed. After the fault they increase rapidly thank to the exciter of Skhira with independent power supply. In this scenario, mainly in the station of Mornaguia and Oueslatia, the transient values increase up to 455 kV: these values are high, but their duration is low and the final values are inside allowed limits. However, the possibility of accepting such high transient voltages shall be carefully checked referring to the BIL[20] of the planned 400 kV lines.
Fig. 5.41 and Fig. 5.42 show the active power exchanges with Algeria, respectively the total amount and the active power flowing in the single tie lines. From the diagrams we see that the most important variations concern the 400 kV line Jendouba-Chefia: <u>the highest oscillations exceed 780 MW in importation (from Algeria to Tunisia)</u>. Hence, <u>an appropriate tuning of the protective relays on the 400 kV tie-line has to be implemented</u>. Furthermore, we underline that <u>the protection setting shall be coordinated with the other 400 kV lines in Algeria and Morocco along the east-west corridor</u>.

Tab. 5-8 is the legend of Fig. 5.42.

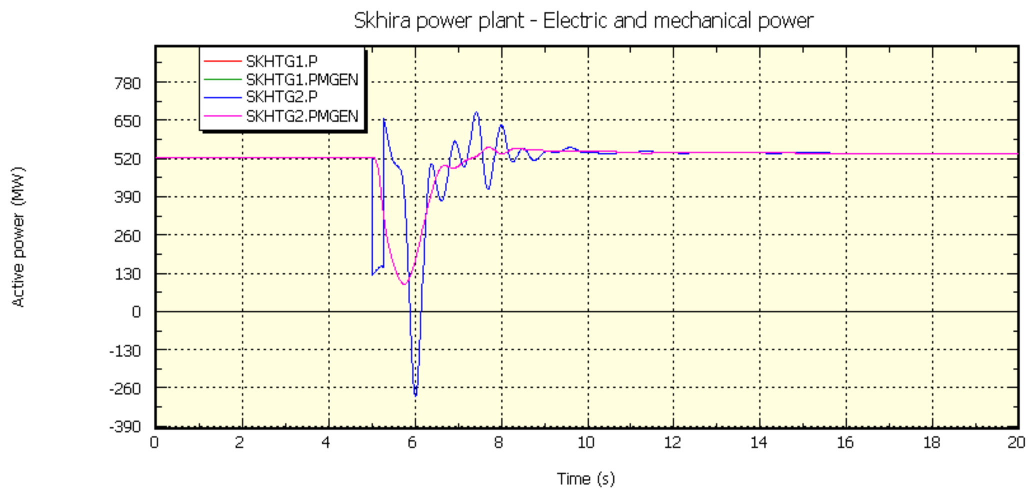

Fig. 5.36 - Minimum condition, Skhira – Maknassy 400 kV short circuit, electric and mechanical power of Skhira. Legend: P – Electric Power; PMGEN – Mechanical Power

[20] BIL: Basic Insulation Level

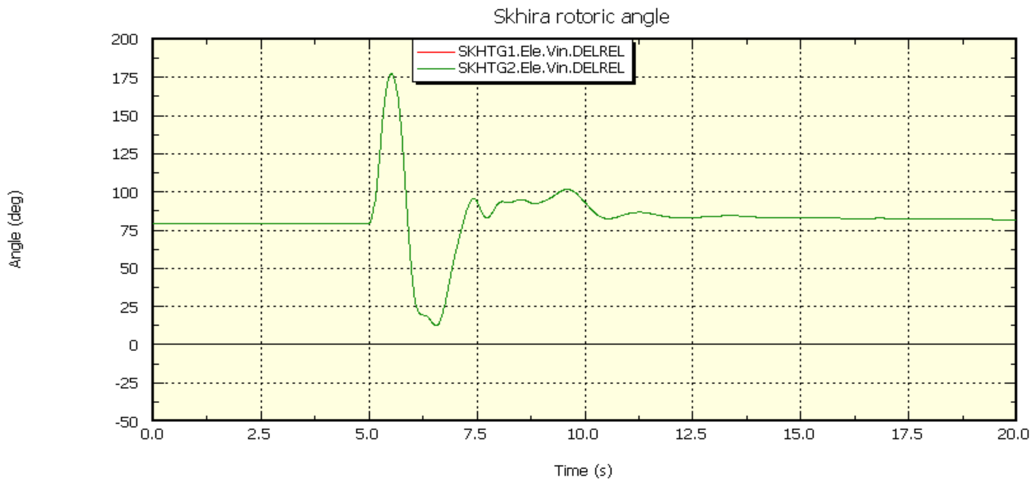

Fig. 5.37 - Minimum condition, Skhira – Maknassy 400 kV short circuit, Skhira rotoric angle.

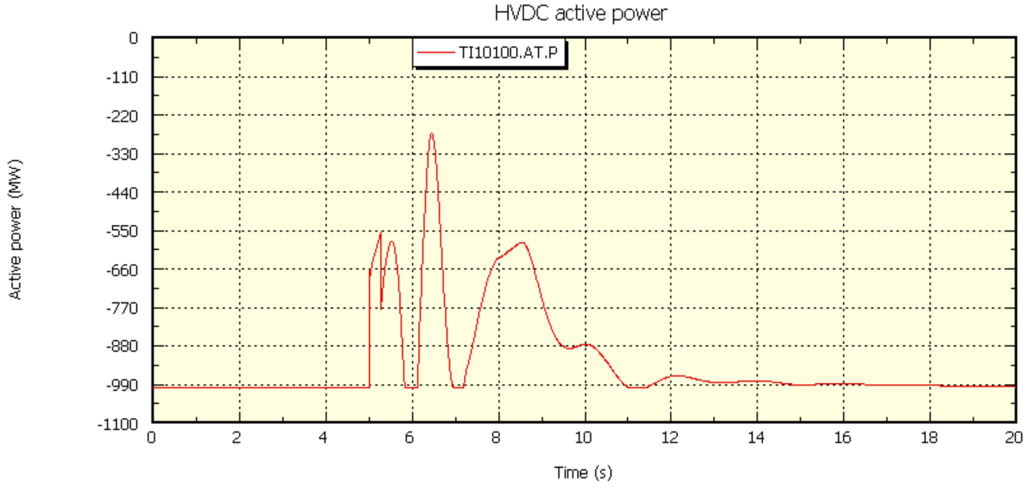

Fig. 5.38 - Minimum condition, Skhira – Maknassy 400 kV short circuit, HVDC active power flow.

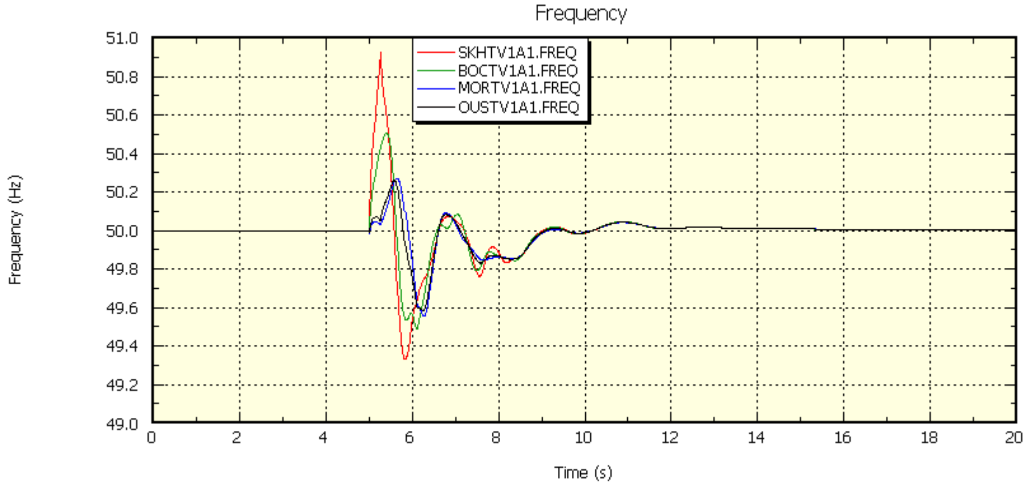

Fig. 5.39 - Minimum condition, Skhira – Maknassy 400 kV short circuit, frequencies (Skhira, Bouchemma, Mornaguia, Oueslatia).

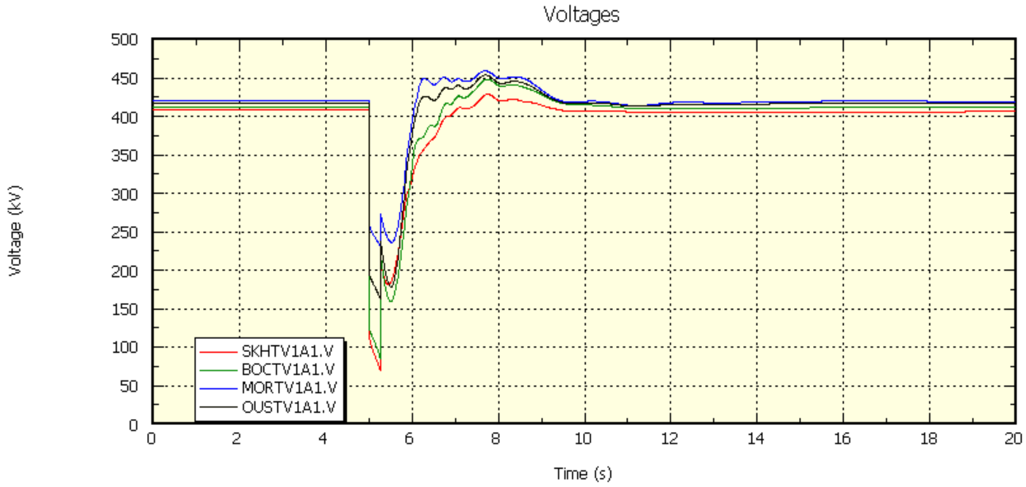

Fig. 5.40 - Minimum condition, Skhira – Maknassy 400 kV short circuit, voltages (Skhira, Bouchemma, Mornaguia, Oueslatia).

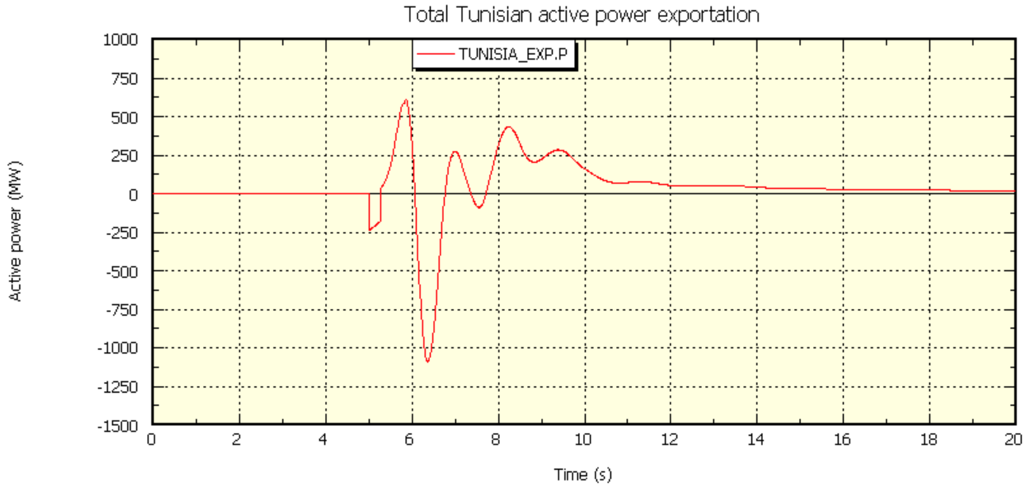

Fig. 5.41 - Minimum condition, Skhira – Maknassy 400 kV short circuit, total active power exchange with Algeria only.

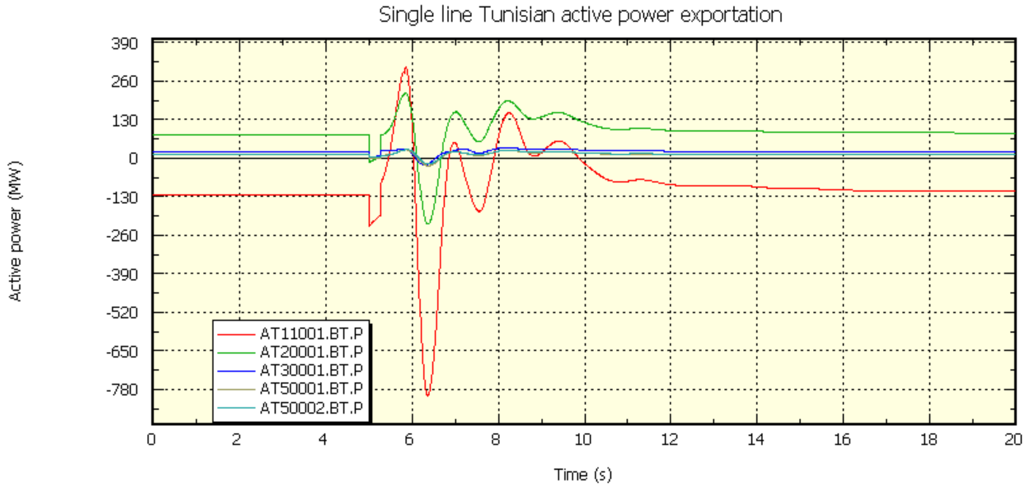

Fig. 5.42 - Minimum condition, Skhira – Maknassy 400 kV short circuit, single line active power exchanges.

Tab. 5-8 – 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)

5.5.2 Skhira generator loss

In this paragraph the most important results and considerations obtained after the loss of one generator in Skhira power plant are described.

This is a very strong contingency: the loss of 524 MW of power (equal about to 37% of Tunisian internal load in minimum load scenario) can cause very important variations in terms of power flow and frequency values.

To highlight the positive effects on the Tunisian transmission system of HVDC link we examined the following three cases, similarly to what done in peak conditions:

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

Figures from Fig. 5.43 to Fig. 5.48 show the Tunisian network response after the contingency in “Case 1”. In this situation the loss of Skhira generation (524 MW) is partially covered by the other Tunisian generators according to their droops but mainly with the decreasing of exportation to Italy (Fig. 5.44 show that HVDC reduces its exportation of about 320 MW) and importing from Algeria (Fig. 5.47) of about 130 MW. Only about 70 MW are provided by other Tunisian generators. Also in this case there aren’t any particular oscillations and the final value of the frequency (reported in Fig. 5.45) equal to about 49.95 Hz can be considered as a good result. The exchanges from Algeria also in this case concern particularly the 400 kV line Jendouba-Chefia (with a peak in importation equal about to 400 MW). In this scenario the voltages (Fig. 5.46) are quite high after the contingency due to the low power flow on 400 kV transmission line.

Tab. 5-9 is the legend of Fig. 5.48.

Figures from Fig. 5.49 to Fig. 5.52 show the Tunisian network response after the same contingency in “Case 2”. In this situation the loss of Skhira generation (524 MW) is partially covered by the other Tunisian generators according to their droops (about 120 MW) but mainly by the HVDC system that decreases its exportation of about 450 MW. In this situation it is important to highlight that during transient the voltages can have peak values also greater than 470 kV and greater than 450 kV at the end on the dynamic, particularly in Mornaguia and Oueslatia stations. Hence, an appropriate Var compensation shall be defined, identified the possible need for a dynamically controlled Var compensation.

Also in this situation there are not particular problems in terms of dynamic oscillations and final values for the frequency: its minimum value is about 49.67 Hz during the transient and about 49.93 Hz as final value.

Figures from Fig. 5.53 to Fig. 5.56 show the Tunisian network response after the same contingency in “Case 3”. This contingency is less critical than the same one in peak load conditions because in this case the Tunisian generators have enough reserve to supply the internal load. In fact, even if HVDC system exports always 1000 MW to Italy, the frequency achieves a stable final value equal to 49.53 Hz and also the minimum value during the transient (equal to 49.20 Hz) is not so low (obviously this behaviour can cause problems for the network like first step load shedding intervention). In this case, as shown in Fig. 5.56, the voltages are lower than in the previous case with HVDC in frequency regulation because the converter station keeps its power export at full load (1000 MW) with consequent higher power flows on the Tunisian system, which helps to contain voltages.

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

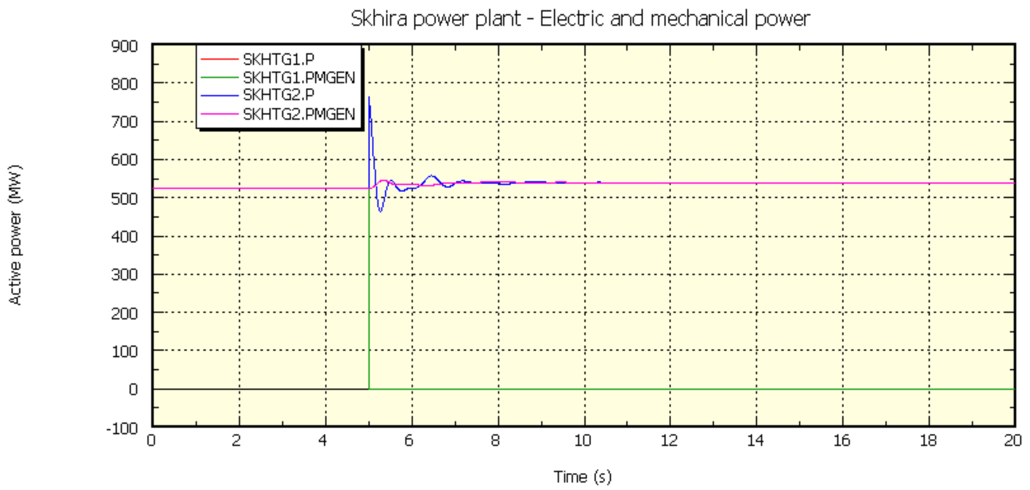

Fig. 5.43 - Minimum condition, Skhira generator loss, electric and mechanical power of Skhira (Case 1). Legend: P – Electric Power; PMGEN – Mechanical Power

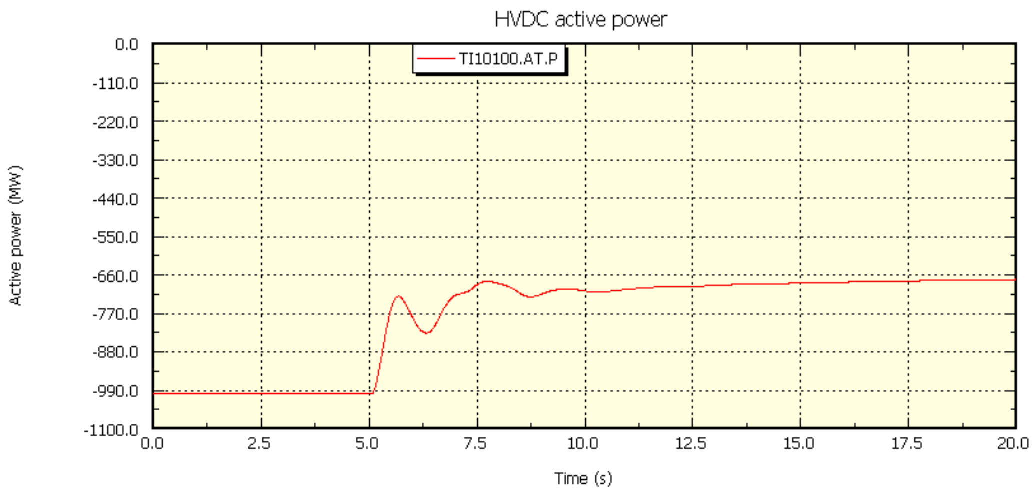

Fig. 5.44 - Minimum condition, Skhira generator loss, HVDC active power flow (Case 1).

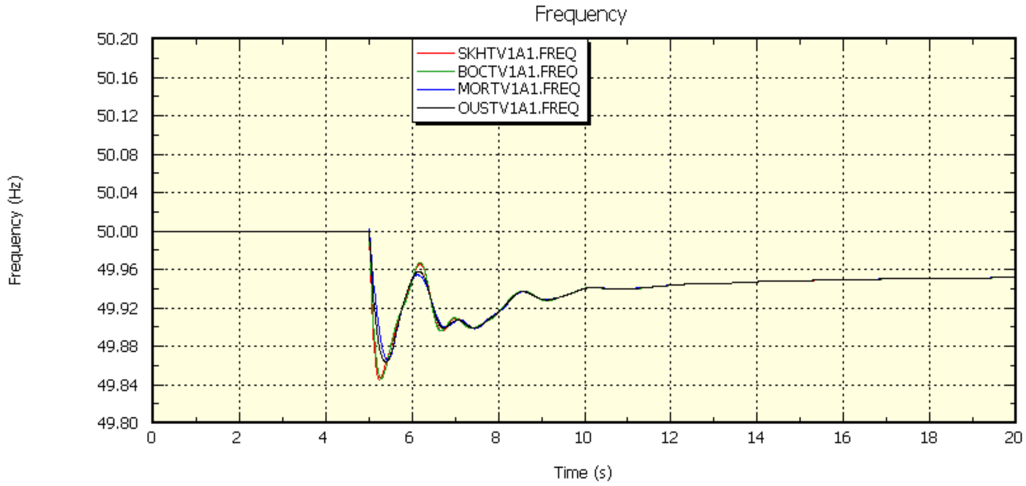

Fig. 5.45 - Minimum condition, Skhira generator loss, frequencies (Skhira, Bouchemma, Mornaguia, Oueslatia) (Case 1).

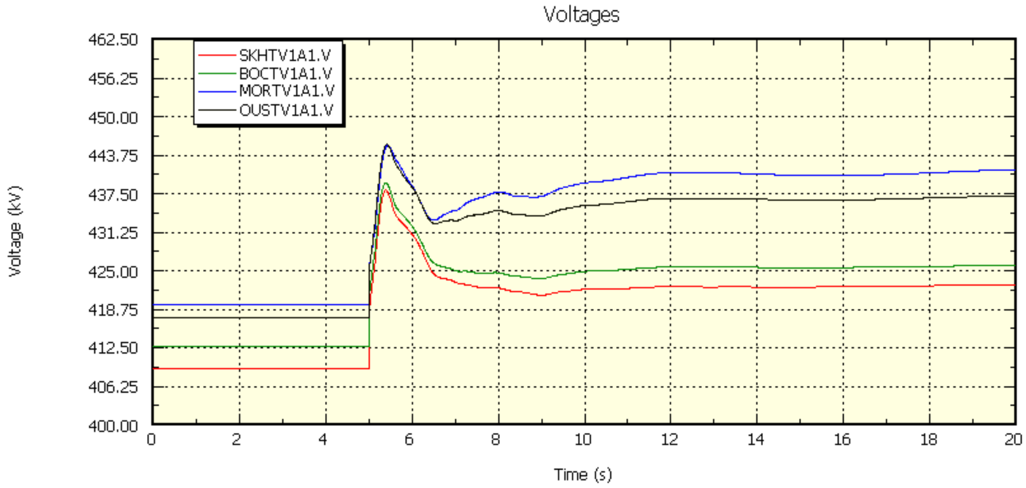

Fig. 5.46 - Minimum condition, Skhira generator loss, voltages (Skhira, Bouchemma, Mornaguia, Oueslatia) (Case 1).

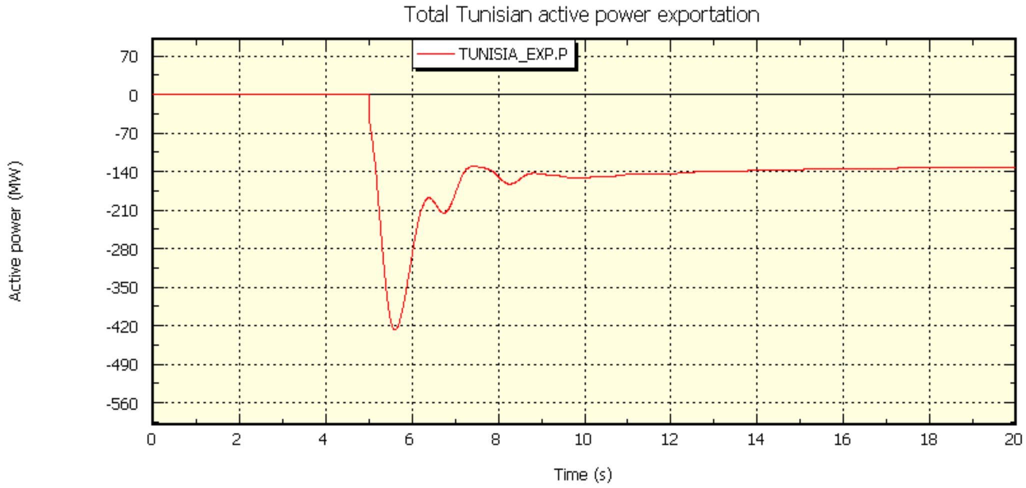

Fig. 5.47 - Minimum condition, Skhira generator loss, total active power exchange with Algeria only (Case 1).

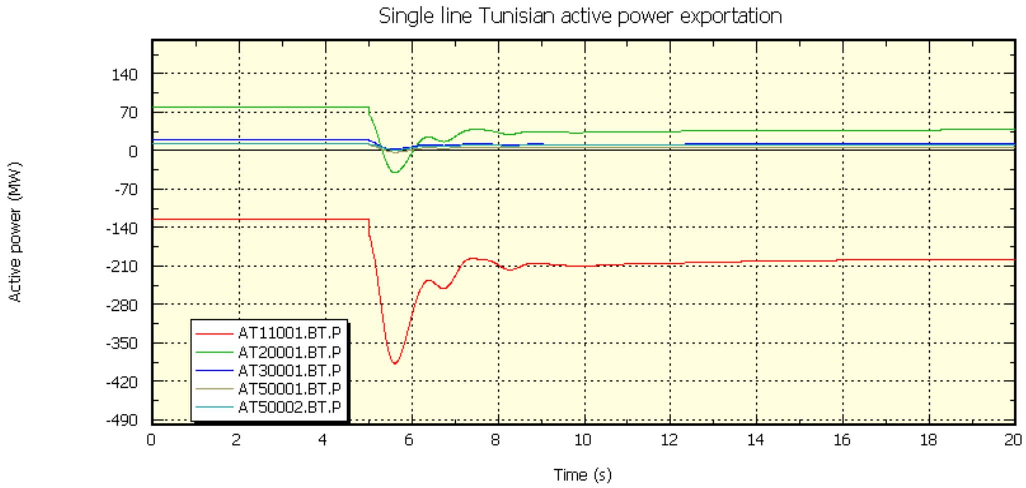

Fig. 5.48 - Minimum condition, Skhira generator loss, single line active power exchanges (Case 1).

Tab. 5-9 – 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)

5.5.2.2 Case 2: Tunisia isolated and HVDC system in frequency regulation

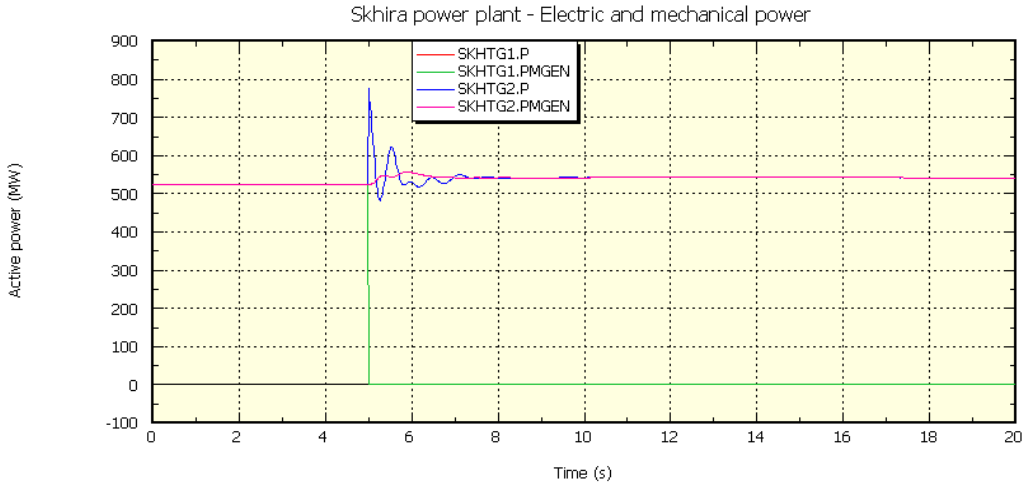

Fig. 5.49 - Minimum condition, Skhira generator loss, electric and mechanical power of Skhira (Case 2). Legend: P – Electric Power; PMGEN – Mechanical Power

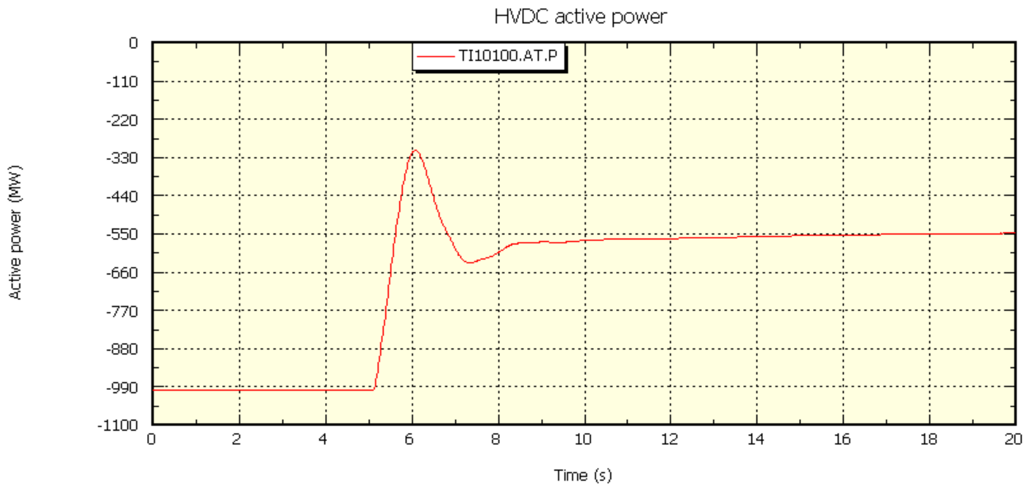

Fig. 5.50 - Minimum condition, Skhira generator loss, HVDC active power flow (Case 2).

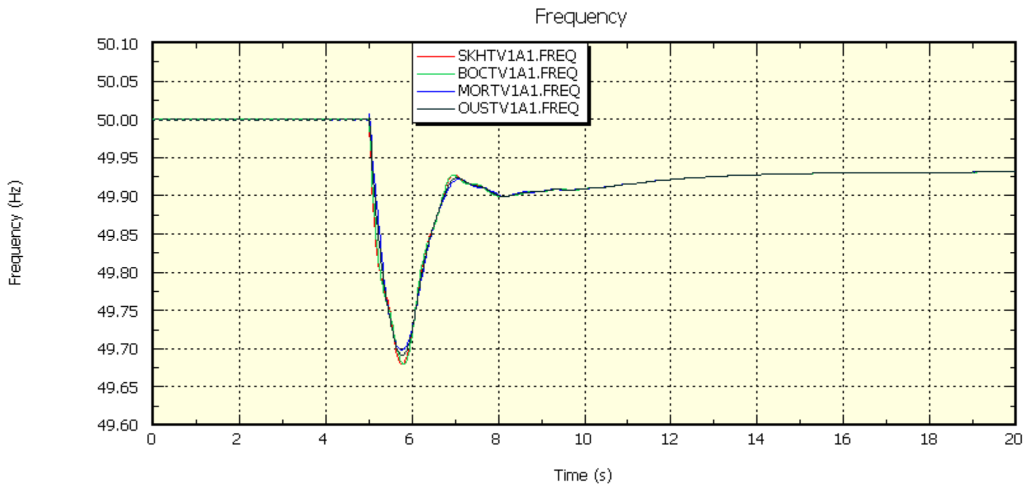

Fig. 5.51 - Minimum condition, Skhira generator loss, frequencies (Skhira, Bouchemma, Mornaguia, Oueslatia) (Case 2).

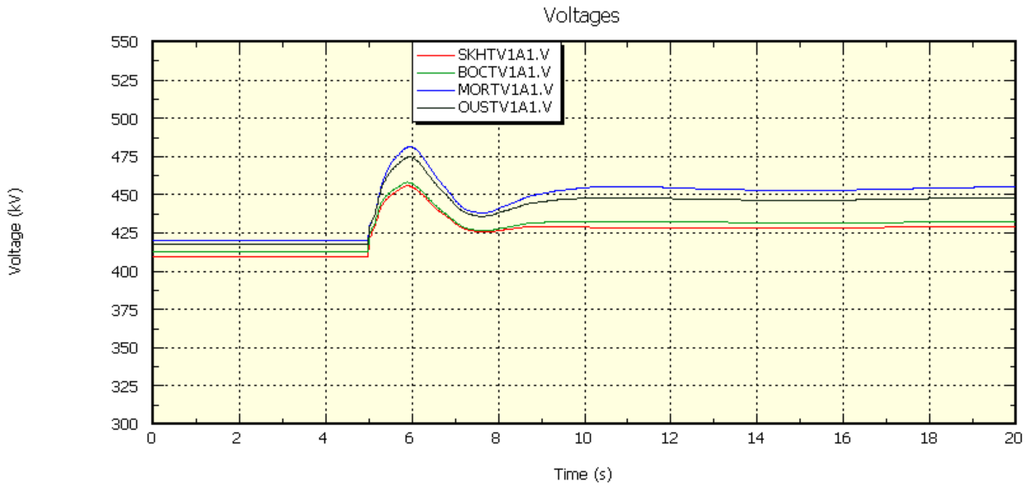

Fig. 5.52 - Minimum condition, Skhira generator loss, voltages (Skhira, Bouchemma, Mornaguia, Oueslatia) (Case 2).

5.5.2.3 *Case 3: Tunisia isolated and HVDC system without frequency regulation*

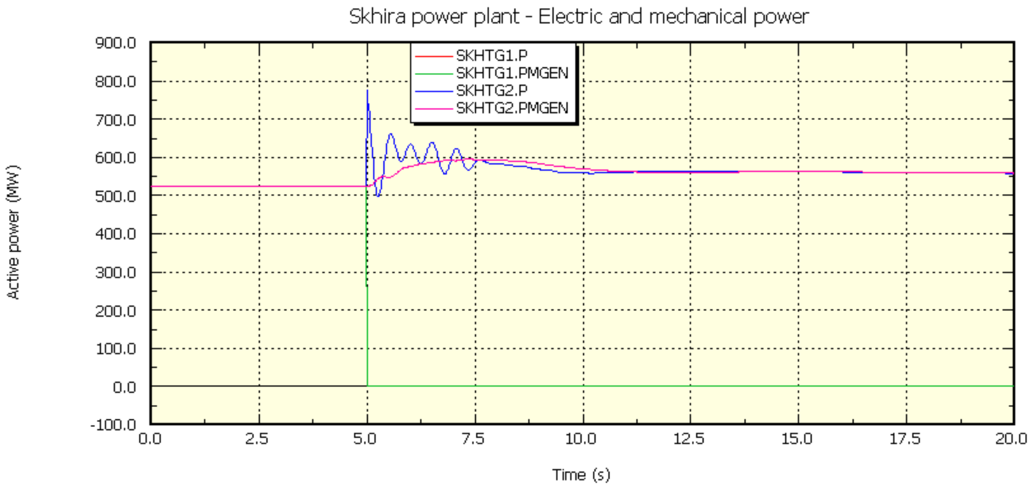

Fig. 5.53 - Minimum condition, Skhira generator loss, electric and mechanical power of Skhira (Case 3). Legend: P – Electric Power; PMGEN – Mechanical Power

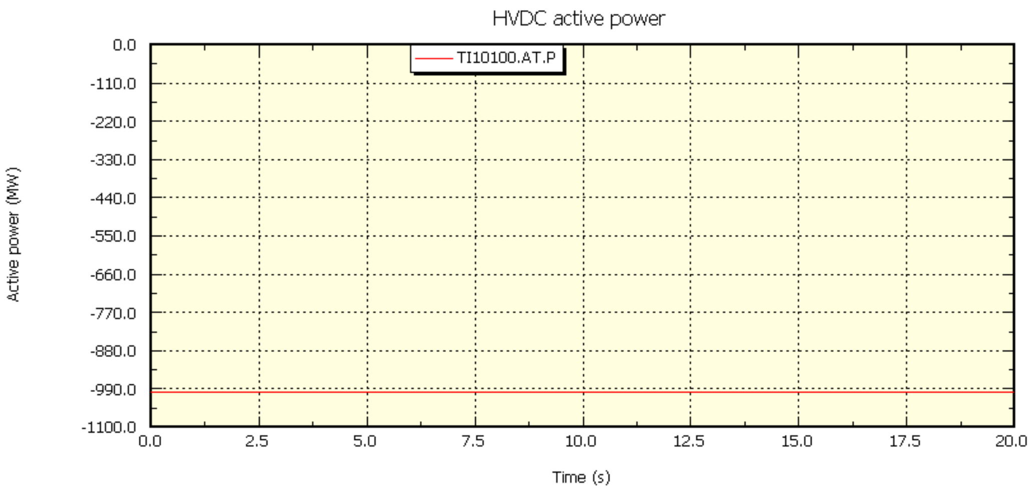

Fig. 5.54 - Minimum condition, Skhira generator loss, HVDC active power flow (Case 3).

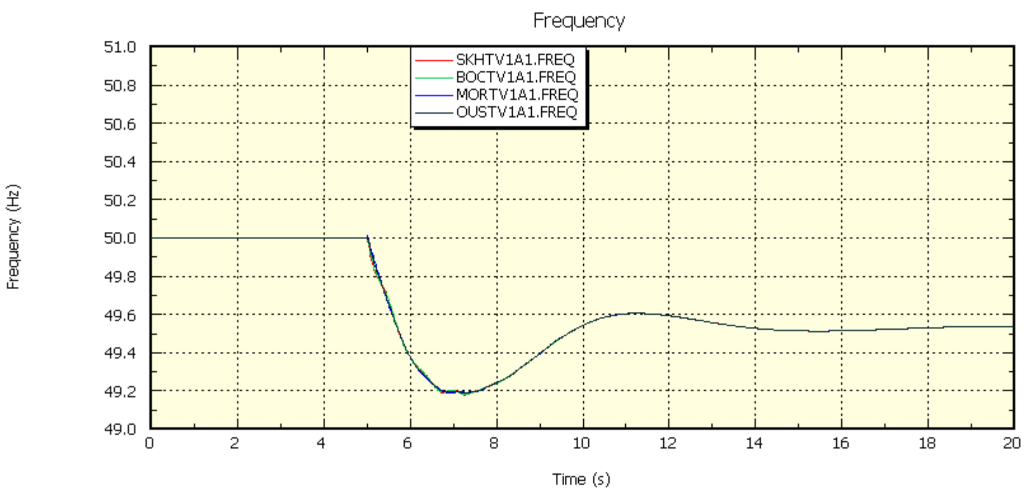

Fig. 5.55 - Minimum condition, Skhira generator loss, frequencies (Skhira, Bouchemma, Mornaguia, Oueslatia) (Case 3).

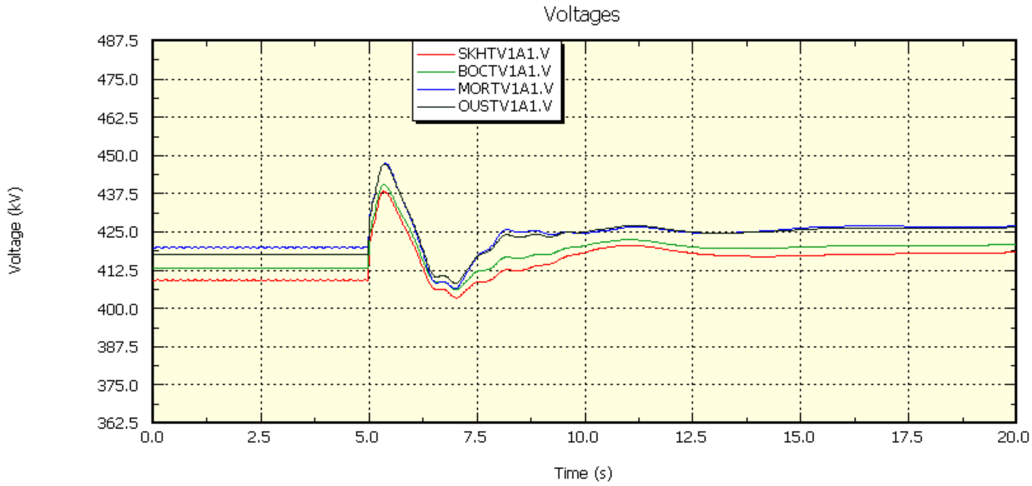

Fig. 5.56 - Minimum condition, Skhira generator loss, voltages (Skhira, Bouchemma, Mornaguia, Oueslatia) (Case 3).

5.5.3 HVDC pole loss

In this paragraph the most important results and considerations obtained after the loss of one pole of HVDC system are summarized.

Assuming that the future HVDC link will have a bipolar configuration, the contingency reported below considers the loss of only one pole since the loss of the whole converter station is considered very improbable.

Also in this scenario this contingency, equivalent to a sudden load decrease, is repeated in two different situations:

- Case 1: Tunisian grid connected to the rest of Maghreb (and Europe) leaving the other pole of the HVDC system in frequency regulation;
- Case 2: Tunisian grid isolated and leaving the other pole of the HVDC system in frequency regulation.

The case with Tunisian grid isolated and the other pole of HVDC without frequency regulation is not significant because of the nul margin of frequency regulation.[21]

5.5.3.1 Case 1: Tunisia interconnected with the rest of Maghreb

From the figures reported below there are not particular problems for the network even if, like reported in Fig. 5.60, the voltage are quite high, particularly during the transient. We underline again the need for an accurate optimisation of the Var shunt compensation.

Another important effect that it is possible to underline consists of the increasing in Tunisian exportations: Fig. 5.61 shows that after the transient Tunisia exports to Algeria about 350 MW; Fig. 5.62 shows that also in this case the line that most increases its power flow (in absolute value) is the 225 kV line Tajerouine-El Aouinet.

Tab. 5-10 is the legend of Fig. 5.62.

[21] In this case, because of the initial exportation to Sicily equal to 1000 MW, the margin for frequency regulation is equal to zero: this means that the cases with the HVDC pole in service with and without frequency regulation are equal.

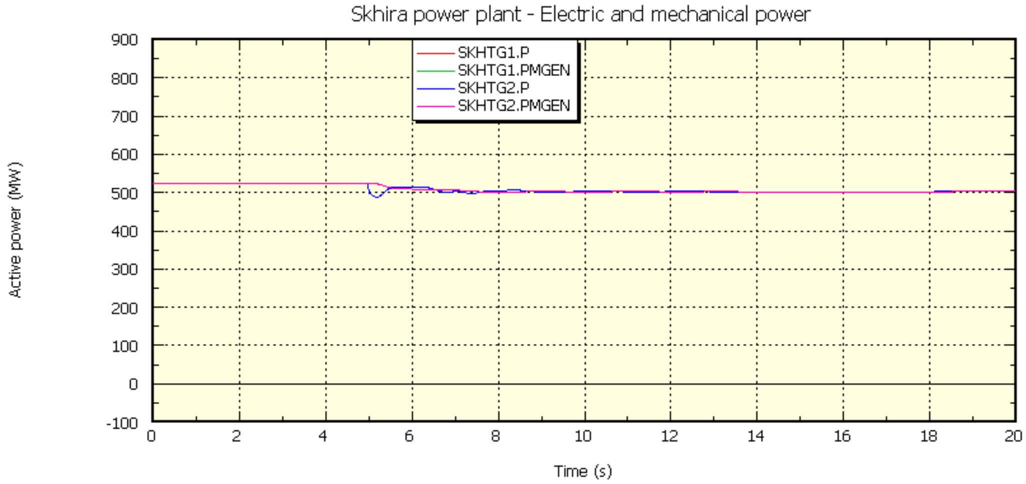

Fig. 5.57 - Minimum condition, HVDC pole loss, electric and mechanical power of Skhira. Legend: P – Electric Power; PMGEN – Mechanical Power (Case 1)

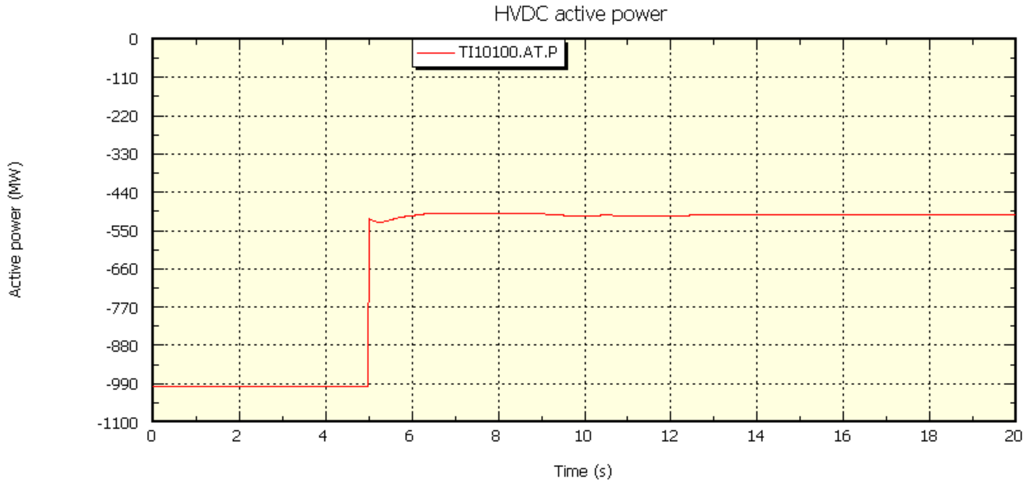

Fig. 5.58 - Minimum condition, HVDC pole loss, HVDC active power flow (Case 1).

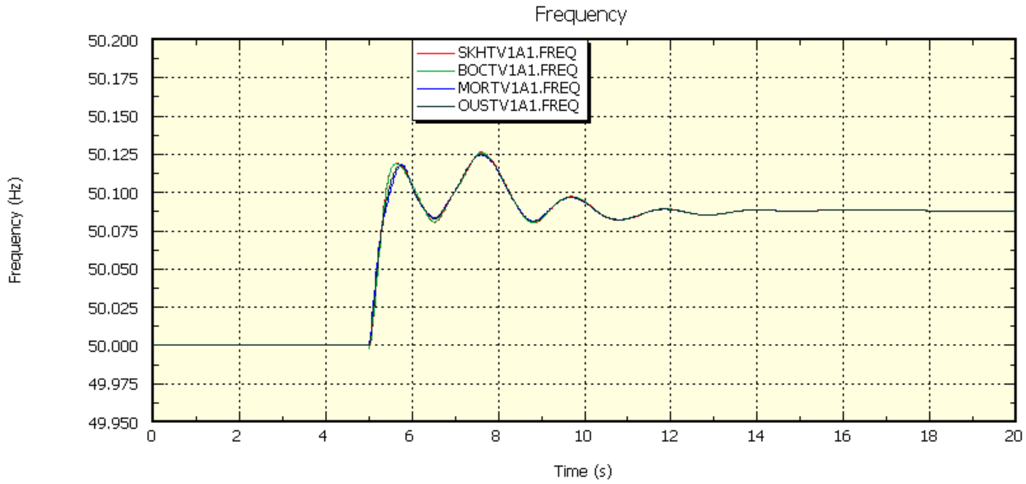

Fig. 5.59 - Minimum condition, HVDC pole loss, frequencies (Skhira, Bouchemma, Mornaguia, Oueslatia) (Case 1).

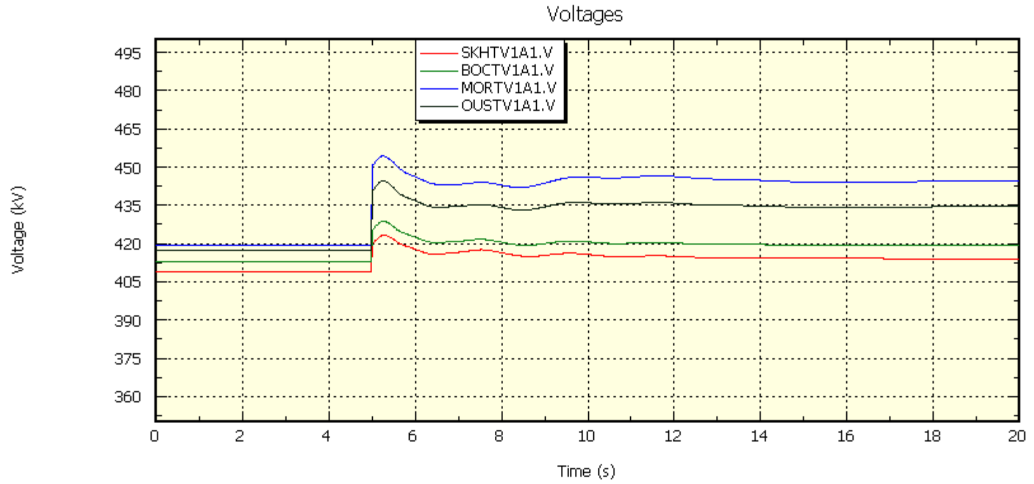

Fig. 5.60 - Minimum condition, HVDC pole loss, voltages (Skhira, Bouchemma, Mornaguia, Oueslatia) (Case 1).

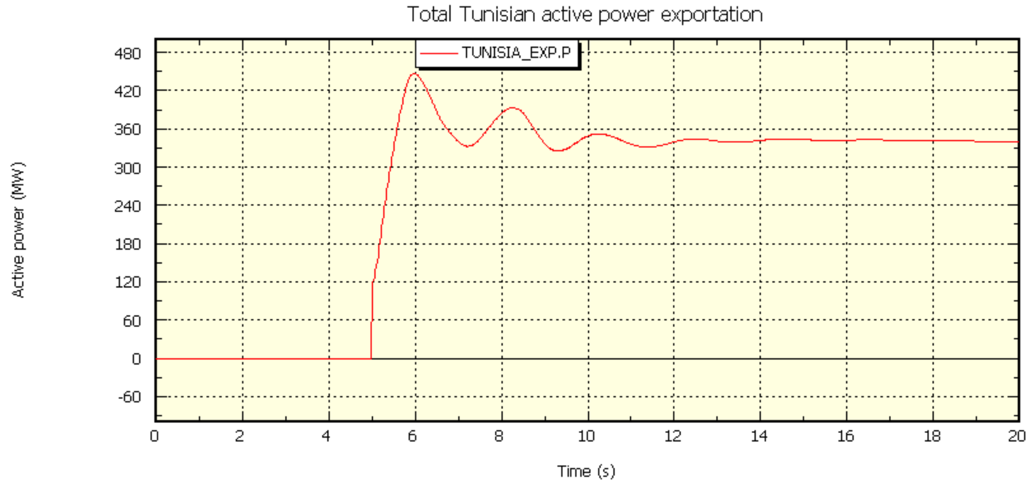

Fig. 5.61 - Minimum condition, HVDC pole loss, total active power exchange with Algeria only (Case 1).

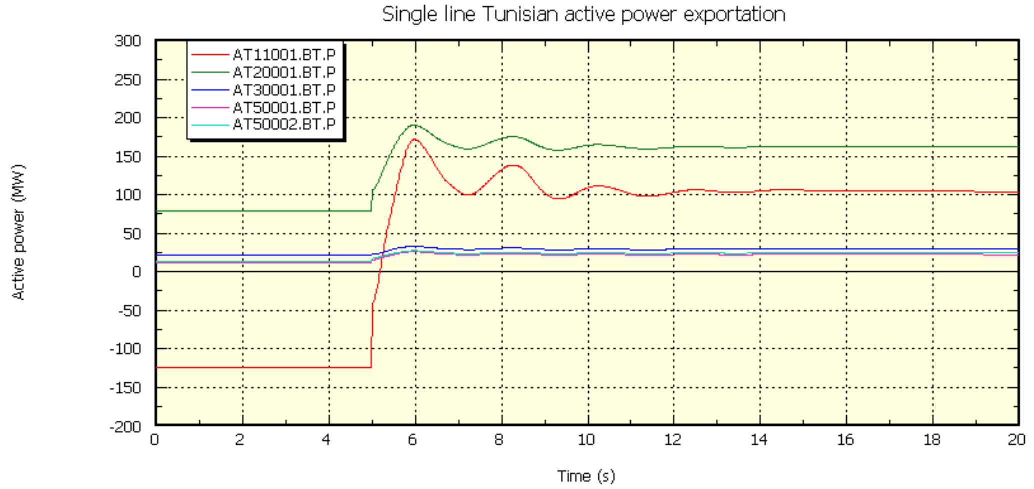

Fig. 5.62 - Minimum condition, HVDC pole loss, single line active power exchanges (Case 1).

Tab. 5-10 – 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)

5.5.3.2 Case 2: Tunisia isolated

From Fig. 5.63 to Fig. 5.66 we note that in this case after the contingency the frequency increases a lot until about 50.53 Hz. In fact, the contingency is equal to a load shedding equal to 500 MW and the frequency goes up. After the fault the generators (Fig. 5.30 reports Skhira machines) decrease their productions and the other pole of HVDC exports can not regulate due to the lack of power margin: the combined effects of significant loss of exportation, a reduced number of active power plants in service and a null margin for the HVDC pole in service cause these problems of over-frequency

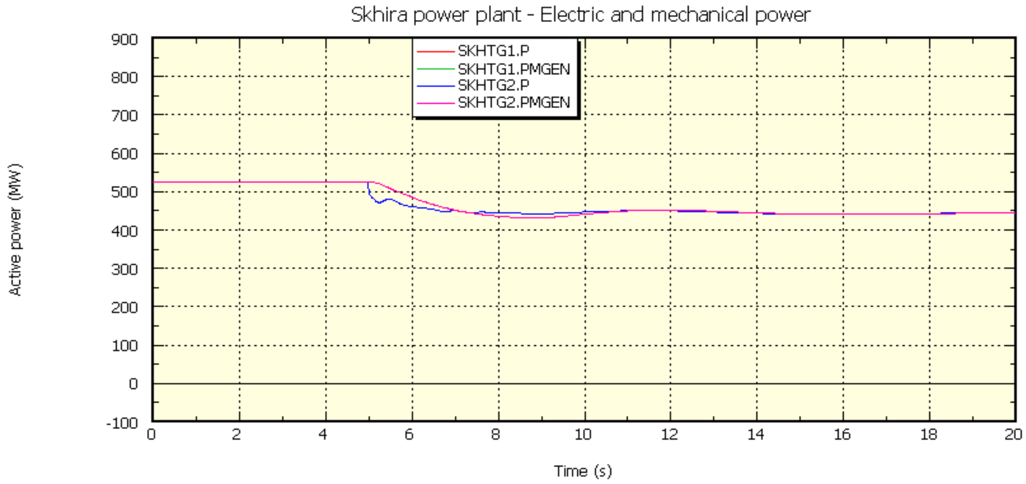

Fig. 5.63 - Minimum condition, HVDC pole loss, electric and mechanical power of Skhira.
Legend: P – Electric Power; PMGEN – Mechanical Power (Case 2)

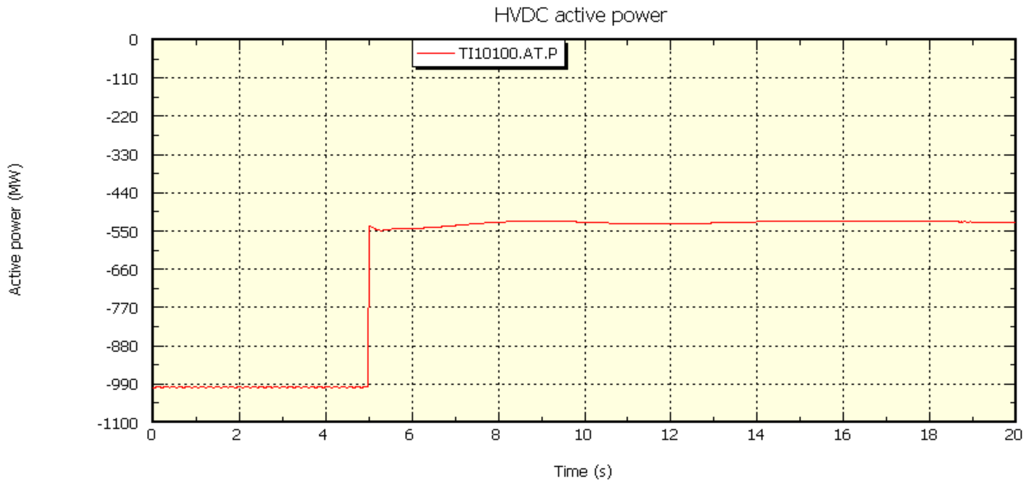

Fig. 5.64 - Minimum condition, HVDC pole loss, HVDC active power flow (Case 2).

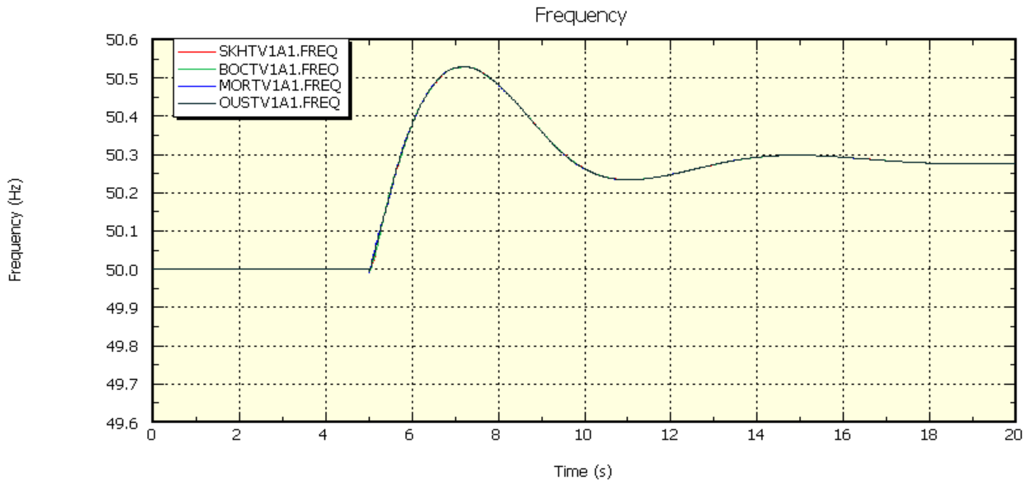

Fig. 5.65 - Minimum condition, HVDC pole loss, frequencies (Skhira, Bouchemma, Mornaguia, Oueslatia) (Case 2).

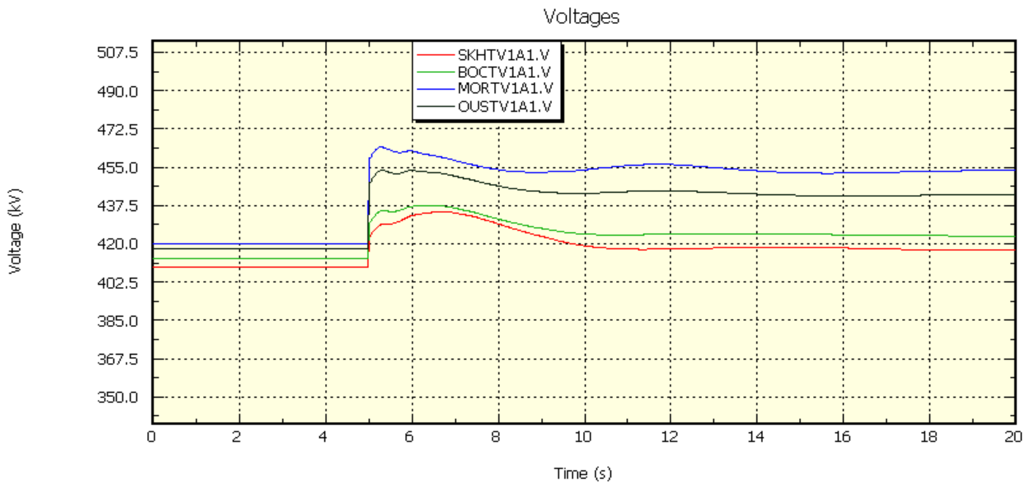

Fig. 5.66 - Minimum condition, HVDC pole loss, voltages (Skhira, Bouchemma, Mornaguia, Oueslatia) (Case 2).

5.6 Considerations about further network reinforcements

In this paragraph we summarized the results obtained adopting different network reinforcement schemes.

As a matter of fact, as explained in the previous paragraphs, one of the most binding problems detected in our analyses for Skhira power plant is the low CCT value at full power production in Skhira (see the peak load conditions) in case of three phase short circuit without fault impedance on the Skhira-Maknassy 400 kV line.

To increase this value both Skhira generators have been provided with the following devices:

1. Power System Stabilizer;
2. Fast Valving for both high and medium pressure valves;
3. independent supply excitation system.

Particularly the second and the third device help a lot to increase the CCT.

Another way to increase this parameter and to help the machines to maintain the synchronism to the rest of the grid is to reduce the equivalent reactance seen by the machines.

This aspect has been verified adopting, from Skhira to Maknassy stations, two double circuits instead two single circuits line. Unfortunately, these additional reinforcements do not help in a significant way to increase the stability margin of Skhira power plant (the CCT parameter does not increase): in fact, the instability phenomena of Skhira power plant are strongly influenced by the voltages on 400 kV system.

Indeed, if a fault occurs on the Skhira – Maknassy 400 kV transmission line, the voltages on all 400 kV stations (particularly from Bouchemma to Mornaguia) decrease a lot. This phenomenon is due to the fact that generators are mostly connected to voltage levels others than the 400 kV and, as such, the voltage control in transient conditions is poor. This fact implies that after the line fault the voltage behaviour on Skhira power plant is quite independent from the structure of the rest of 400 kV transmission system and for this reason the CCT of the ELMED power plant does not change remarkably if further network reinforcements are added.

For the above reason, considering the structure of the Tunisian power system without devices directly connected to the 400 kV voltage level able to control voltages (generators or SVCs), to increase the stability margin of the generators in Skhira is much more important an independent supply excitation system rather than two double circuits from Skhira to Maknassy substations.

The same results have been obtained considering two double circuits from Maknassy to Oueslatia and from Oueslatia to Mornaguia (this is obviously a theoretical solution), but also in this case the stability margin has not been increased: this confirms that the voltage recovery affects a lot the stability margin of Skhira power plant. The faster is the voltage recovery, the higher is the stability margin

In conclusion, no additional network reinforcements other than those identified in static analyses are recommended, but for dynamic stability it is strongly recommended to equip both Skhira generators with:

- Power System Stabilizer
- Fast Valving device for both high and medium pressure valves
- Independent supply excitation system

6 CONCLUSIONS

The scope of this phase of the study addresses the impact on the Tunisian transmission system of the new ELMED power plant (or “ELMED Production Cluster”). More specifically, the analyses are aimed at identifying the reinforcements needed on the Tunisian grid in terms of new lines and interconnecting transformers in order to fulfil the static and dynamic criteria established by the Tunisian system operator, STEG.

The study has been split in two phases:

a) *screening phase* where we investigated the needed reinforcements following the commissioning of the new ELMED Production Cluster. Four different alternatives for the location of this new power plant are examined:
   - El Hawaria with a CCGT rated 3x400 MW ;
   - Bizerte with coal fuelled units rated 2x660 MW ;
   - Skhira with coal fuelled units rated 2x660 MW ;
   - Enfidha with coal fuelled units rated 2x660 MW.

   At this stage, static analyses only are carried out.

   Two generation levels of the ELMED power plant are examined:
   - 400 MW to supply the *internal demand in Tunisia*. The possible reinforcements necessary for the evacuation of this power generation are dictated by the expected load growth in Tunisia;
   - 1200 MW to supply the *internal demand in Tunisia* and to *export the surplus to Sicily*. The additional reinforcements with respect to the previous case are closely linked to the commissioning of the HVDC interconnection towards Sicily. These additional reinforcements shall warrant a power exchange with Sicily up to 1000 MW, which is the target rating of the submarine interconnection in bipolar configuration.

   The reinforcement possibilities for the four ELMED power plant locations have been supplied by STEG through ELMED Etudes and integrated with further alternatives proposed by CESI and agreed with ELMED Etudes and STEG.

   At the end of this screening phase the more binding solution has been chosen for the subsequent detailed analyses.

b) *Detailed analysis phase* where we examined the performance of the Tunisian production and transmission system in dynamic conditions. This set of analyses helped to highlight the minimum conditions to comply with the dynamic constraints of the Tunisian system interconnected with the rest of Maghreb and in presence of the HVDC interconnection to Sicily.

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

- yearly peak load: 3960 MW;
- yearly minimum load: 1400 MW.

In addition to the HVDC link with Sicily, the Tunisian system is linked with Algeria through five tie-lines, while the lines with Libya have always been considered out of service.

Results of the screening phase

To comply with the N-1 security criteria, two 400 kV lines are required for the connection of the ELMED power plant as well as the HVDC converter station to the backbone of the Tunisian power system. With the exception of the ELMED power plant located in El Hawaria, the 400 kV lines outgoing from the ELMED power plant are used both for the supply of the internal load in Tunisia and for power export.

For the ranking of the connection alternatives between the ELMED power plant and the Tunisian power system, the following elements were considered:

- length of new lines;
- losses;
- strength of the grid at the HVDC converter station (ESCR parameter);
- other environmental oriented elements such as the number of new right-of-ways.

ELMED power plant located in El Hawaria: The most favourable location for the new ELMED production cluster is in El Hawaria. This alternative doesn't require any network reinforcement for the power export to Sicily. Network reinforcements are needed only to supply power to cover the internal load in Tunisia or, in general, in the Maghreb. Two 400 kV lines are required connecting El Hawaria to Mornaguia ensuring a capability of 1000 MW. This solution is also very favourable since it ensures a high short circuit power at the HVDC converter station and doesn't cause any additional losses in the Tunisian system for the power export to Sicily. Moreover, thanks to the 2x400 kV lines El Hawaria-Mornaguia, there aren't any restrictions for the power import from Sicily in emergency situation.

ELMED power plant located in Bizerte: three technically feasible solutions have been retained:

<table>
<tr><th>Solution</th><th>Reinforcements</th><th>New lines total length (km)</th><th>Losses in peak conditions (MW)</th><th>Notes</th></tr>
<tr><td rowspan="2">A</td><td>Bizerte-Mateur
Bizerte-Mornaguia</td><td>170</td><td rowspan="2">67.7</td><td rowspan="2">ESCR within
1.99 ÷ 3.55 p.u.</td></tr>
<tr><td>2x El Hawaria-Mornaguia</td><td>300</td></tr>
<tr><td rowspan="2">B</td><td>Bizerte-Mateur
Bizerte- Mnihla</td><td>170</td><td rowspan="2">67.4</td><td rowspan="2">ESCR within
1.95 ÷ 3.47 p.u.:</td></tr>
<tr><td>2x El Hawaria-Mornaguia</td><td>300</td></tr>
<tr><td rowspan="2">C</td><td>Bizerte-Mateur
Bizerte-El Hawaria</td><td>310</td><td rowspan="2">68.4</td><td rowspan="2">ESCR within
0.69÷2.88 p.u.</td></tr>
<tr><td>El Hawaria-Mornaguia</td><td>150</td></tr>
</table>

As for the ranking among the solutions, we note that solutions “A” and “B” are practically equivalent even considering all ranking criteria. A possible discriminating element may be related to the environmental impact, e.g.: difficulty in selection the right-of-ways, number of expropriations, etc. Solution “C” shows a poor short circuit power at the HVDC converter station and higher losses.

ELMED power plant located in Enfidha: four solutions are technically possible (see table here below), but the performances of solution “A” are more favourable both from the technical (no critical problems detected in N-1 conditions) and environmental point of view (only two right-of-ways for the new lines).

As for the power losses, solution "C" is the most favourable one when considering the power export to Italy, even if power losses difference with solution "A" is not remarkable.

Solution	Reinforcements	New lines total length (km)	Losses in peak conditions (MW)	Notes
A	2x Enfidha-Mornaguia	200	68.3	Only two right-of-way necessary ESCR within 3.53 ÷ 3.99 p.u.
	2x El Hawaria-Mornaguia	300		
B	Enfidha-Mornaguia Enfidha-Oueslatia	210	76.4	ESCR within 3.41 ÷ 3.88 p.u
	2x El Hawaria-Mornaguia	300		
C	Enfidha-Mornaguia Enfidha-El Hawaria	250	64.3	ESCR within 3.74 ÷ 4.15 p.u
	El Hawaria-Mornaguia (2)	150		
D	2x Enfidha-El Hawaria	300	70.8	ESCR within 4.83 ÷ 5.05 p.u
	El Hawaria-Mornaguia	150		

ELMED power plant located in Skhira: the location of the ELMED power plant in Skhira has the heaviest impact on the Tunisian power system since it requires the doubling of the south-north 400 kV corridor up to Mornaguia.

For the supply of the internal load with a power production level of 400 MW, two basic solutions are acceptable:

c) turn-in/turn-out substation on the 225 kV double circuit line Bouchemma-Sidi Mansour equipped with 2 x 400 MVA transformers;

d) one 400 kV line outcoming from Skhira (the shortest one being Skhira-Macknassy 70 km) and the turn-in/turn-out substation on the 225 kV double circuit line Bouchemma-Sidi Mansour equipped with one 400 MVA transformer.

Indeed, these solutions do not fulfil the security constraints when the ELMED power plant generates its rated power (1200 MW). Hence, additional reinforcements shall be considered as illustrated in the table here below.

The following comments are worth being highlighted:

- Solution C is characterised by the poorer performances in terms of power losses;
- Solutions A1, A2 and B, involving a 400 kV connection with the existing 225 kV s/s of Maknassy may be completed by the addition of a 400/225 kV at the Maknassy s/s for more flexibility in the operation. Nevertheless, this integration is not needed for the power evacuation from the ELMED power plant in compliance with the security criteria;
- Solutions A2 and B entailing the erection of very long 400 kV may be critical for the voltage control and an appropriate Var compensation scheme shall be investigated: likely dynamically controlled shunt Var compensation devices are needed. Moreover, the energisation procedure of the long 400 kV line might reveal critical, especially in low load conditions characterised by low short circuit power. If chosen, these solutions require the execution of dedicated studies and, very likely, extra costs are to be considered for the voltage control;
- All solutions, except A0, show a poor loading on the 400/225 kV transformers at the turn-in/turn-out

station along the Bouchemma-Sidi Mansour line. As a matter of fact, if we consider two 400 kV lines outgoing from Skhira power plant, one might consider the connection of one autotransformer only, or, better, two autotransformers with lower rate (e.g.: 250 MVA). This latter solution warrants a better reliability and operation flexibility.

Solution	Reinforcements	New lines total length (km)	New ATR 400/225 kV	Losses in peak conditions (MW)	Notes
A0	T-in/T-out B.-S.M.*	**2x20**	**2**	**---**	Solution NOT feasible for the full capacity pf the ELMED power plant
A1	T-in/T-out B.-S.M.* Skhira-Maknassy double circuit (d.c.) Maknassy-Oueslatia Oueslatia-Mornaguia 2x El Hawaria-Mornaguia	**2x20** **2x70** **180** **130** **300**	**3****	**113.6**	ESCR within 3.28 ÷ 3.67 p.u
A2	T-in/T-out B.-S.M.* Skhira-Maknassy Shkira-El Hawaria El Hawaria-Mornaguia	**2x20** **70** **410** **150**	**3****	**112.1**	ESCR within 2.79 ÷ 3.13 p.u
B	T-in/T-out B.-S.M.* Skhira-Maknassy Skhira-Mornaguia 2x El Hawaria-Mornaguia	**2x20** **70** **350** **300**	**3****	**114.1**	ESCR within 3.28 ÷ 3.67 p.u
C	T-in/T-out B.-S.M.* Skhira-Bouchemma d.c. Bouchemma-Oueslatia Oueslatia-Mornaguia 2xEl Hawaria-Mornaguia	**2x20** **2x70** **280** **130** **300**	**2*****	**130.7**	ESCR within 3.23 ÷ 3.63 p.u
D	T-in/T-out B.-S.M.* Skhira - T-in/T-out along the line Bouchemma-Oueslatia Skhira-Oueslatia Oueslatia-Mornaguia 2xEl Hawaria-Mornaguia	**2x20** **85** **245** **130** **300**	**2*****	**119.6**	ESCR within 3.27 ÷ 3.66 p.u

* *Turn-in/Turn-out substation on the 225 kV double circuit line Bouchemma-Sidi Mansour*

** *1 ATR 400 MVA in Maknassy and 2 ATR in Skhira for the T-in/T-out along the line Bouchemma-Sidi Mansour with appropriate size (e.g.: 250 MVA). Alternatively, one can foresee 1 ATR only in Skhira with the standard rating of 400 MVA.*

*** *2 ATR in Skhira for the T-in/T-out along the line Bouchemma-Sidi Mansour with appropriate size (e.g.: 250 MVA). Alternatively, one can foresee 1 ATR only in Skhira with the standard rating of 400 MVA.*

In conclusion, <u>the siting of the ELMED power plant in Skhira turns out to be the most binding alternative with respect to the other ones in terms of network reinforcements</u>. By considering the technical performances <u>solution "A1" is the most favourable</u> since:

- it avoids very long transmission lines that can cause voltage problems in case of low power flows;

- it uses an already existing corridor to build most of the new reinforcements;
- it will hardly cause under-excitation problems for generators in case of restoration;
- it is one of the solution with the lowest network losses.

Thus, this solution is examined more in detail assessing the performances of the system in dynamic conditions.

Results of the detailed analysis phase

The dynamic analyses focused on examining the system stability at the occurrence of large credible perturbations, namely:

1. three-phase short circuit without fault impedance on the 400 kV line Skhira – Maknassy;
2. loss of one Skhira generator in three situations:
   a. Tunisia connected to the rest of Maghreb and Europe and HVDC link to Italy in frequency regulation;
   b. Tunisia isolated and HVDC system to Italy in frequency regulation;
   c. Tunisia isolated and HVDC system to Italy out of frequency regulation.
3. loss of one pole of HVDC system in two situations:
   a. Tunisia connected to the rest of Maghreb;
   b. Tunisia isolated.

The occurrence of a three-phase short circuit on the 400 kV is a very critical perturbation for the transient stability of the Shkira units. Indeed, to ensure an adequate CCT we recommend that both Skhira generators shall be equipped with:

- Power System Stabilizer
- Fast Valving device for both high and medium pressure valves
- Independent supply excitation system.

By adopting the above measures, the CCT with Skhira at full generation level (1200 MW) attains 170 ms, independently from the control system installed at the HVDC converter station. The CCT is strongly affected by the generation level of the Skhira units (e.g.: CCT = 280 ms when the power plant generates 1050 MW). For short circuits occurring farther from the ELMED power plant in Skhira, the CCT are larger and warrant the stability also in case of intervention of the distance protections in second steps.

The loss of one unit in Skhira has a moderate impact on the Tunisian power system when it is interconnected with Algeria and the HVDC link is equipped with a frequency regulator; in peak load conditions, the loss of 600 MW in Skhira is recovered by reducing the power export to Sicily by about 320 MW, increasing the import from Algeria of about 200 MW, whilst the remaining amount of power is generated inside Tunisia. In case of Tunisia operated in isolated mode from the rest of Maghreb, to avoid the intervention of load shedding the HVDC converter station must be equipped with a frequency regulator having an appropriate droop.

Finally, the loss of one pole in the HVDC converter station (500 MW), which is equivalent to the sudden disconnection of a load, doesn't show any transient stability problems; the surplus of power is conveyed towards Algeria with a consequent increase of cross-border power flows. Only in case of Tunisia isolated the frequency, particularly in minimum load scenario, increases in a significant way. This fact is mainly due to the reduced frequency regulation margin (equal to zero in minimum load scenario) for the other HVDC pole in service. In this case a high value of power exported to Italy in starting point conditions exposes Tunisian grid to a possible over-frequency problems in case of the loss of one HVDC pole if the tie-lines with Algeria are out of service.

Three additional recommendations are formulated:

- considering the large size of the Skhira units (660 MW each) and the impact on the cross-border power flows when tripping a unit, an appropriate tuning of the protective relays on the 400 kV tie-line has to be implemented. Furthermore, we underline that the protection setting shall be coordinated with the other 400 kV lines in Algeria and Morocco along the east-west corridor;
- the defence plans of the Tunisian power system shall also be revised to cope with possible extreme contingencies taking into account the presence of the new ELMED production cluster and the HVDC link with Sicily;
- an optimisation of the shunt Var compensation devices shall be carried on, since in some cases we have detected too high voltage profiles both in transient and post-contingency situations (e.g.: loss of a Skhira units in minimum load conditions and the HVDC converter in frequency regulation).

7 REFERENCES

[1] CESI, "*Etude pour l' « Évaluation, dans le cadre du Projet ELMED, de la capacité maximale de production d'électricité de sources d'énergie renouvelables (« RES ») non programmables, connectables au réseau transport de la Tunisie conformément aux prescriptions de sécurité et de qualità - Tâche A : méthodologie, scénarios de l'étude, hypothèses et collecte des données*", CESI report n° B0016311, June 2010, Milan

ANNEXE 1. VALIDATION OF THE BASIC MODELS

Before starting the simulations, several tests were carried out to check the consistency of the results obtained with SPIRA package and SICRE simulator with respect to the original results supplied by STEG and obtained by PSS/E.
In particular, the static results were verified by crosschecking the load flows outputs between SPIRA and PSS/E.
Dynamic results were verified by crosschecking the time domain diagrams obtained by SICRE simulator and PSS/E applying the same perturbations
All the above analyses were carried out with Tunisia operated in isolated mode, since the original data base was referring to this operating condition. Later on, the Tunisian system has been interconnected with Algeria, Morocco and the ENTSO-E/SCR system; after having verified that the overall model showed the same results inside Tunisia, we have started the study.

A1.1 Tests in static conditions: coherency checks in basic configuration

Peak load conditions

The tripping of the 90 kV double circuit line Grombalia – Korba gives origin to the low - voltage level on 90 kV substation showed in the following tables. The same outage creates an overload (26%) in the parallel 90 kV line Grombalia - M. Temime. These results are coherent with those of the original PSS/E load flows.

Post-contingency voltage violations – Base case

Contingency		Vn (kV)	Violation	Vn (kV)	V_N (kV)	V_{N-1} (kV)	ΔV (%)
GROMBALI	**KORBA**	**90**	**M.TEMIME**	**90**	**89.9**	**77.1**	**-14**
GROMBALI	**KORBA**	**90**					
GROMBALI	**KORBA**	**90**	**KORBA**	**90**	**92.1**	**75.0**	**-17**
GROMBALI	**KORBA**	**90**					
GROMBALI	**KORBA**	**90**	**HAMMAMET**	**90**	**91.0**	**78.1**	**-13**
GROMBALI	**KORBA**	**90**					
GROMBALI	**KORBA**	**90**	**A.KMICHA**	**90**	**90.5**	**75.9**	**-16**
GROMBALI	**KORBA**	**90**					
KAS.NORD	**KASSERIN**	**150**	**TAJEROUI**	**150**	**159.6**	**165.8**	**11**
KAS.NORD	**KASSERIN**	**150**	**KAS.NORD**	**150**	**155.2**	**166.3**	**11**
HAMMAMET	**RADES**	**150**	**RADES**	**150**	**159.3**	**167.3**	**12**

Overloads in N-1. Base case

Contingency		Vn (kV)	Overload		Vn (kV)	I_{N-1} (kA)	I_{N-1} (p.u.)
GROMBALI	**KORBA**	**90**	**GROMBALI**	**M.TEMIME**	**90**	**0.66**	**1.26**
GROMBALI	**KORBA**	**90**					

A1.2 Tests for the dynamic model validation

In this section the comparison between the time domain diagrams obtained by CESI and those provided

by STEG is shown. This test is necessary because dynamic analyses provided by STEG are executed with PSS/E software tool; instead dynamic analyses executed by CESI are executed with SICRE simulator.
All these simulations have been obtained considering the Tunisian grid isolated.

Peak load conditions

Fig.0.1 and Fig.0.2 show the frequency behaviour after the loss of Aousdja 400 MW generator. Comparing the two diagrams, respectively provided by STEG (obtained with PSS/E software) and obtained by CESI with SICRE simulator, we note that they are very similar, both in term of dynamic oscillations and in term of final value after the contingency.

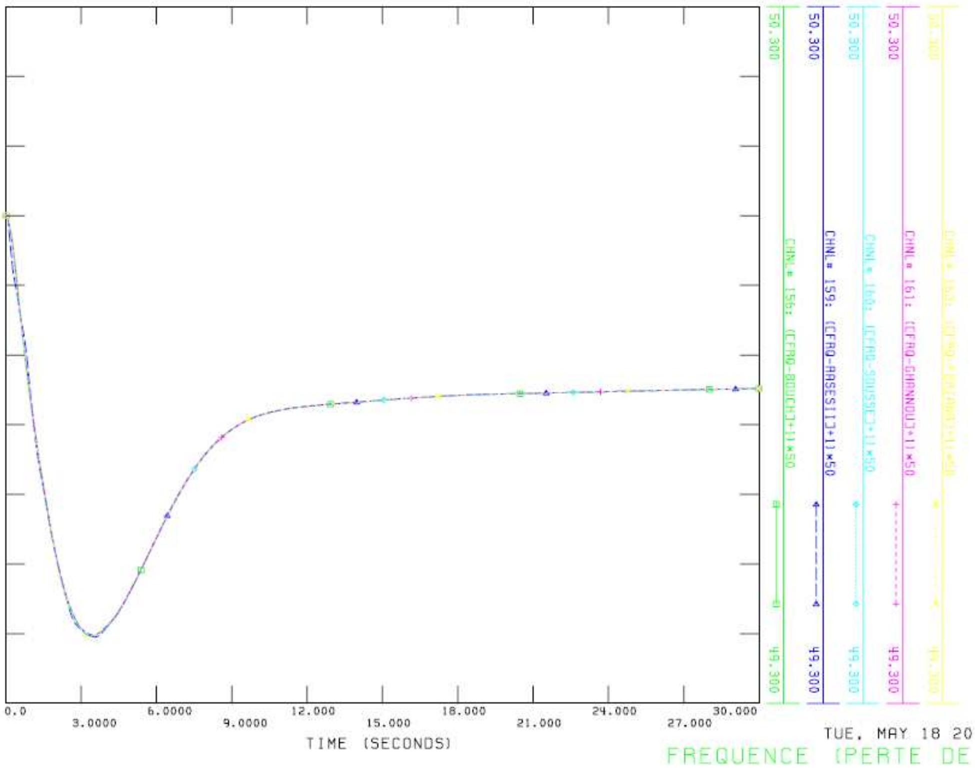

Fig.0.1 – Peak load scenario – Tunisia isolated – PSS/E trace – frequency after Aousdja 400 MW loss

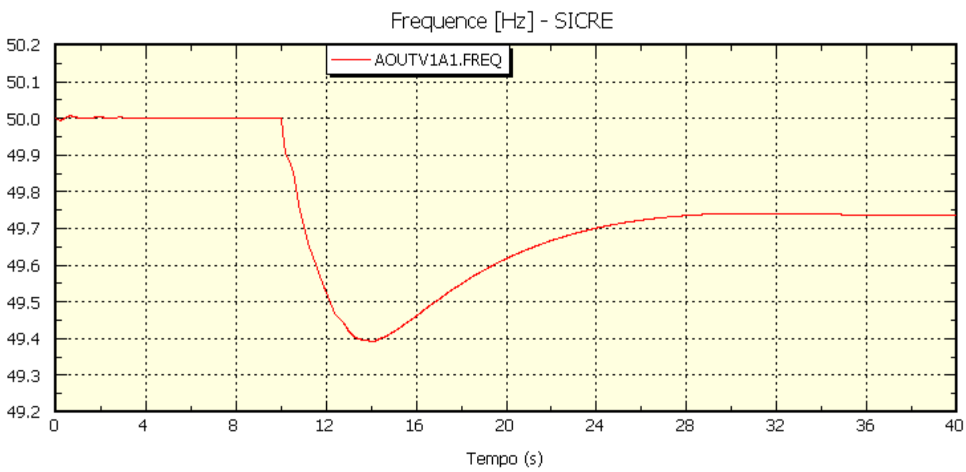

Fig.0.2 – Peak load scenario – Tunisia isolated – SICRE trace – frequency after Aousdja 400 MW loss

The same considerations apply by comparing Fig.0.3 with Fig.0.4: in this case the voltage behaviour of Aousdja station after the same previous contingency is reported. Also in this case the two diagrams are very similar, both in terms of dynamic oscillation and in terms of final value and duration of the transient.

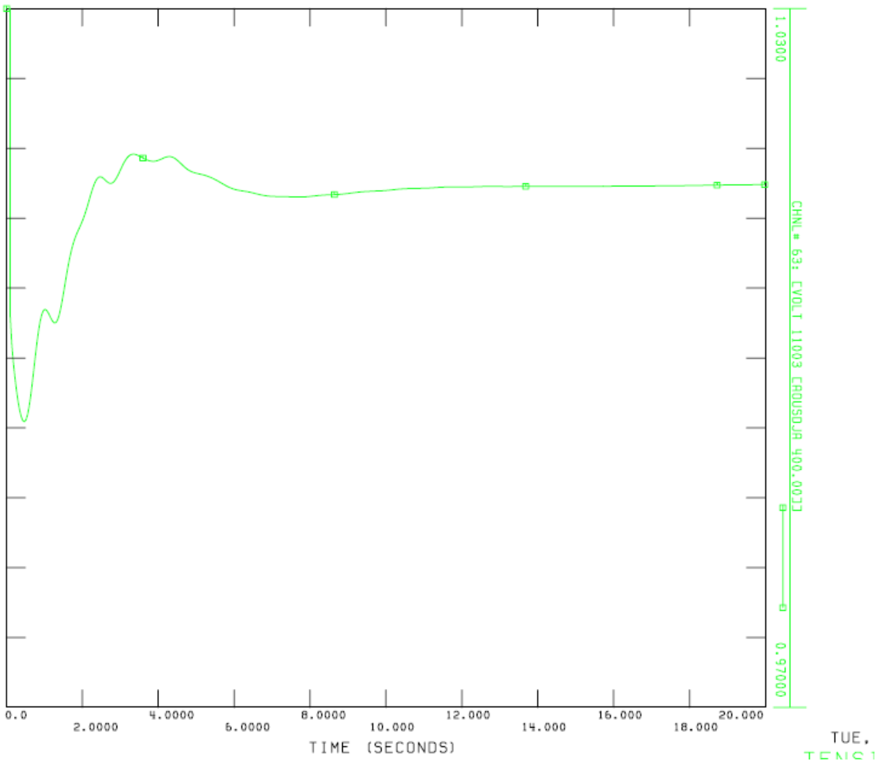

Fig.0.3 – Peak load scenario – Tunisia isolated – PSS/E trace – Aousdja voltage after Aousdja 400 MW loss

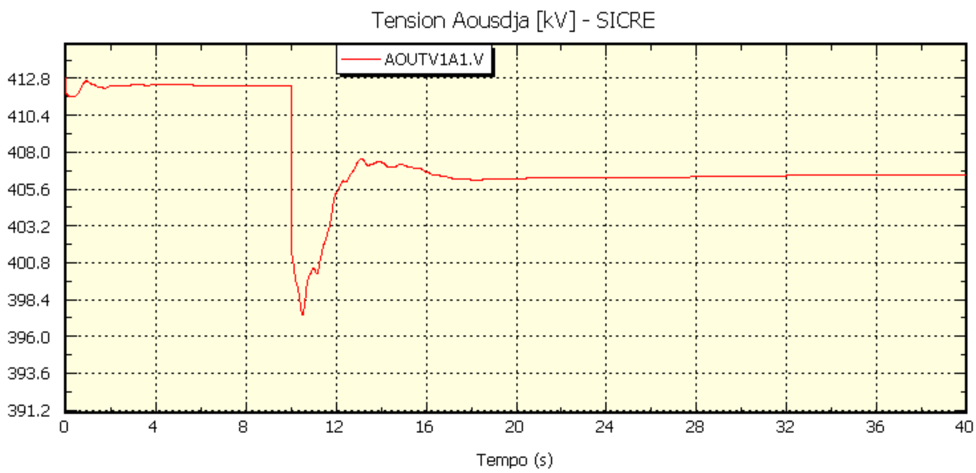

Fig.0.4 – Peak load scenario – Tunisia isolated – SICRE trace – Aousdja voltage after Aousdja 400 MW loss

Minimum load conditions

For this scenario little differences among SICRE and PSS/E behaviours are present because dynamic simulations are referred to two different minimum load conditions: in fact, diagrams provided by STEG

are referred to the first minimum load scenario provided on May 20th, 2010; instead SICRE diagrans are referred to the second and the official minimum load scenario provided on June 11th, 2010.
Fig.0.5 and Fig.0.6 show the frequency behaviour after the loss of Aousdja 200 MW generator. Comparing the two diagrams, respectively provided by STEG and obtained by CESI with SICRE simulator, we note that they are very similar, except some little dynamic oscillations caused by the different configuration between the two scenarios.

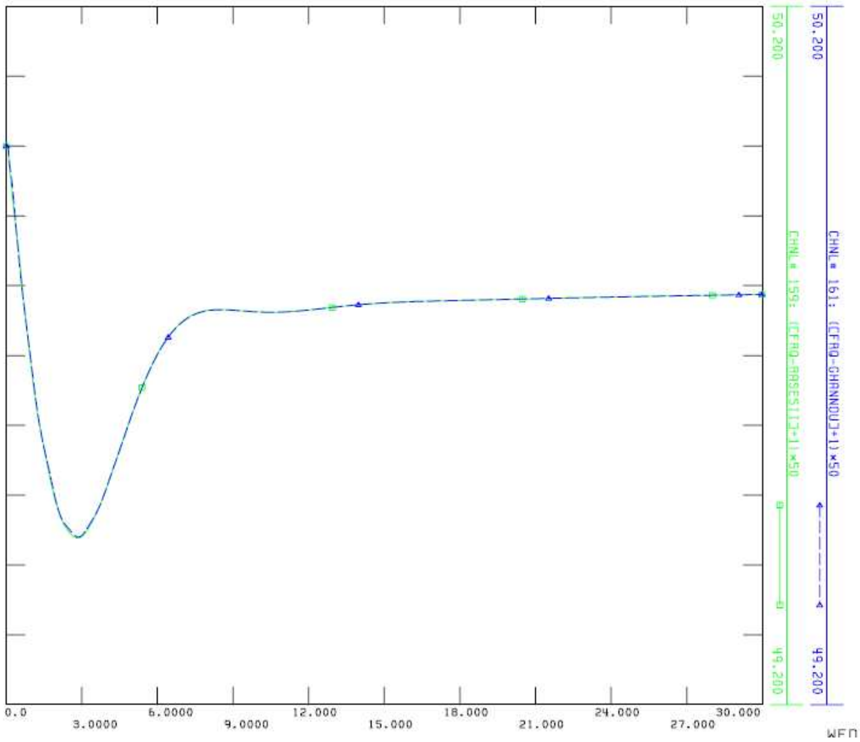

Fig.0.5 – Minimum load scenario – Tunisia isolated – PSS/E trace – frequency after Aousdja 200 MW loss

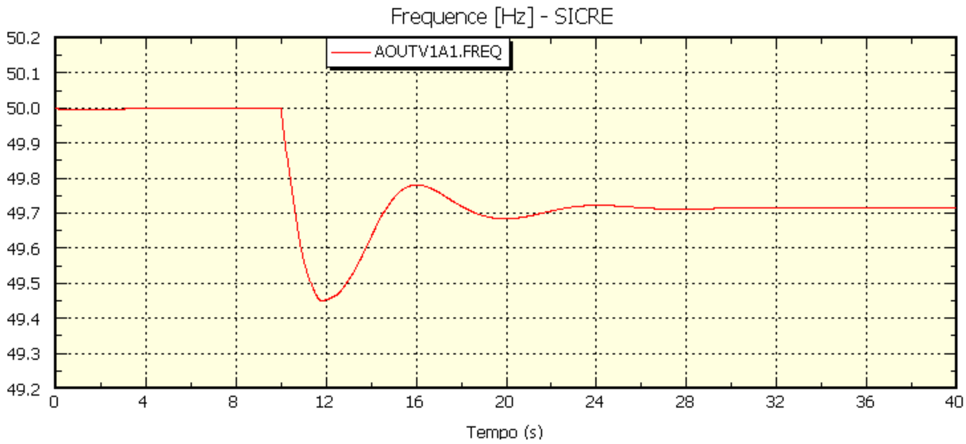

Fig.0.6 – Minimum load scenario – Tunisia isolated – SICRE trace – frequency after Aousdja 200 MW loss

The same considerations can be done comparing Fig.0.7 and Fig.0.8: in this case the voltage behaviour of Aousdja station after the same previous contingency is reported. Also in this case the two diagrams are very similar, both in terms of dynamic oscillations and in terms of the duration of the transient; the final values show some differences because Aousdja configuration is different in the two scenarios.

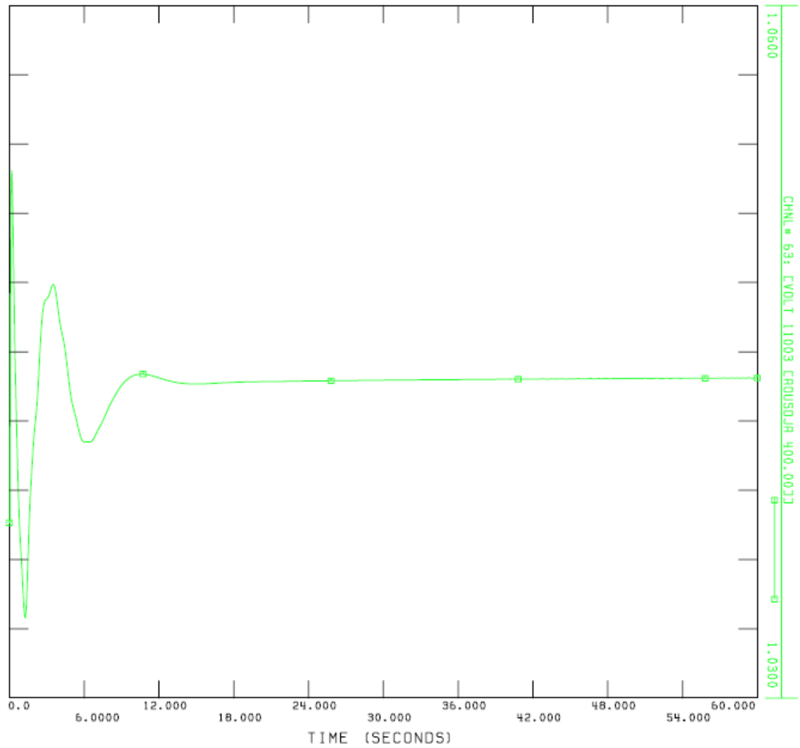

Fig.0.7 – Minimum load scenario – Tunisia isolated – PSS/E trace – Aousdja voltage after Aousdja 200 MW loss

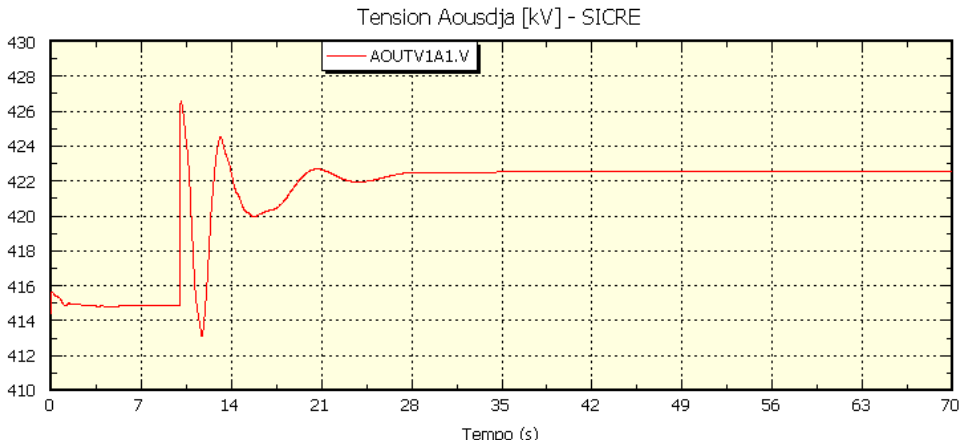

Fig.0.8 – Minimum load scenario – Tunisia isolated – SICRE trace – Aousdja voltage after Aousdja 200 MW loss