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 A: methodology, study scenarios, hypotheses and data collection

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GLOSSARY

ATR:	Auto-transformer
AVR:	Automatic Voltage Regulator
AC:	Alternating current
DC:	Direct current
CCGT:	Combined Cycle Gas Turbines
CCT:	Critical Clearing Time
CSP:	Concentrating Solar Power
DFIG:	Double Fed Induction Generator
ENTSO-E/SCR:	European Network of Transmission System Operators of Electricity/Synchronous Continental Region
HV:	High Voltage
HVDC:	High Voltage Direct Current
MAI:	Morocco-Algeria interconnection
TAI:	Tunisia-Algeria interconnection
NTC:	Net Transfer Capacity (at the border)
PSS:	Power System Stabiliser
PV:	Photovoltaic
RES:	Renewable Energy Source

1 FOREWORD

The purpose of this report is to describe the methods (chapter 3) for attaining the targets stated in chapter 2, and to present hypotheses concerning the work involved (chapter 4). In Chapter 5 of this report, we shall then discuss the data used for the numerical simulations and the planned configuration of the production-transmission system in Tunisia connected to the network in Sicily via the new underwater High Voltage Direct Current (HVDC) transmission link. Lastly, we shall sum up the features of the HVDC transmission model and wind power units.

2 THE OBJECTIVES OF THE STUDY

The objectives of this study are:

a) To determine the network reinforcements required to guarantee static and dynamic security following the commissioning of the ELMED Production Units and the new 1000 MW Tunisia-Italy High Voltage Direct Current (HVDC) transmission link (Working Process 1, WP1);

b) To determine the maximum power produced by non-programmable renewable sources acceptable by the Tunisian production – transmission system in its configuration defined in objective a). The analysis shall take into account only the network reinforcements identified in the first working process (Working Process 2, WP2).

2.1 Tasks

To attain the above targets, we shall have to execute three main tasks:

- Task A: work out the study scenarios, agree on the hypotheses, describe the methods and collect the data
- Task B: static and dynamic analyses for objective a): network reinforcements required for the ELMED Production Units and the HVDC Tunisia-Italy transmission link
- Task C: static and dynamic analyses for objective b): maximum production capacity with unpredictable RES.

3 METHODOLOGY

3.1 Methodology for objective a): network reinforcements for setting up the ELMED station and Tunisia-Italy transmission link

In this case we assess the impact on the network of the new ELMED generators and, in particular, determine the reinforcements needed to operate the system in conformity with the security standards set down by the Network Operator, STEG (para. 4.1).

First of all, we need to determine where to install the new ELMED thermal power plant (Fig. 3-1). There are four alternatives, namely:

- ✓ El Hawaria with 3x400 MW CCGTs;
- ✓ Bizerte with 2x660 MW coal-fired power stations;
- ✓ Skhira with 2x660 MW coal-fired power stations;
- ✓ Enfidha with 2x660 MW coal-fired power stations.

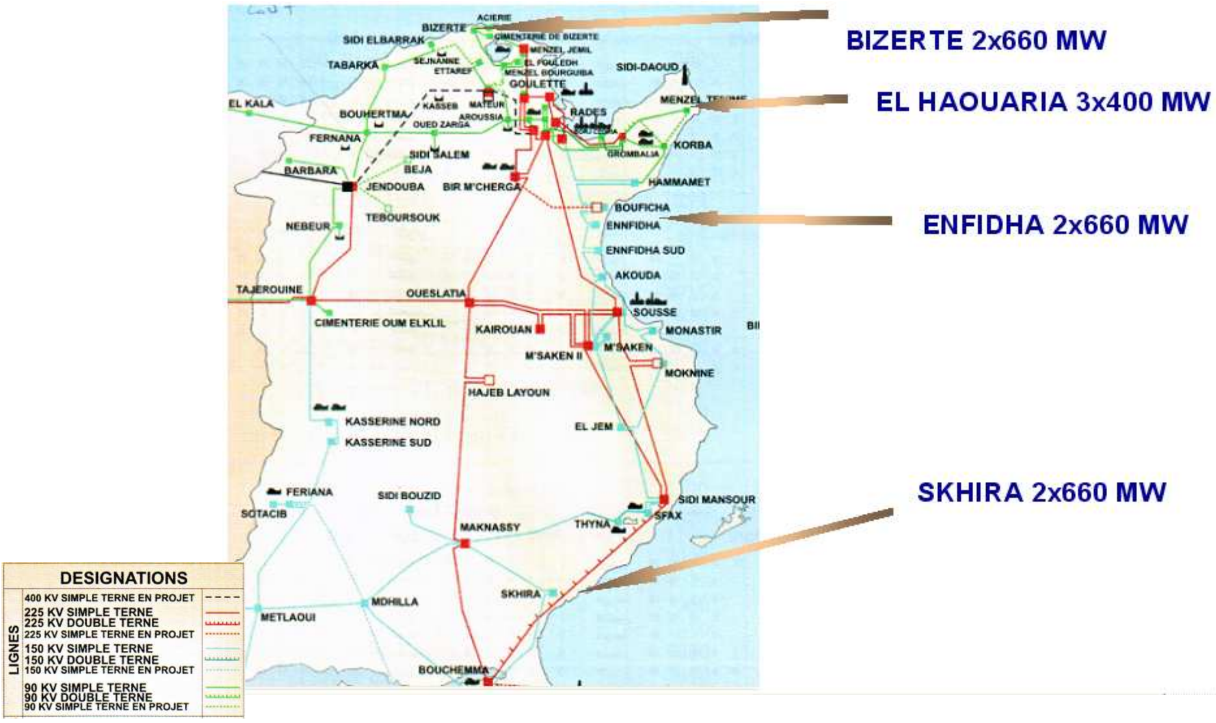


Fig. 3-1 – Possible alternatives for the installation of the new ELMED thermal power station

We shall execute static analysis to determine the network reinforcements (new lines, new transformers) required to guarantee sufficient power capacity, with the idea of exporting 800 MW to Europe over the new HVDC transmission link with Sicily (Fig. 3-2). The network reinforcements shall be chosen from among those proposed by the ELMED study, together with the network operator (para. 4.3). CESI may propose other possibilities for reinforcements based on its own experience. Once ELMED Etudes gives its approval, these additional possibilities shall be examined during the "screening" process.

Fig. 3-2 – Underwater HVDC link between Tunisia and Sicily, and anticipated power transmission

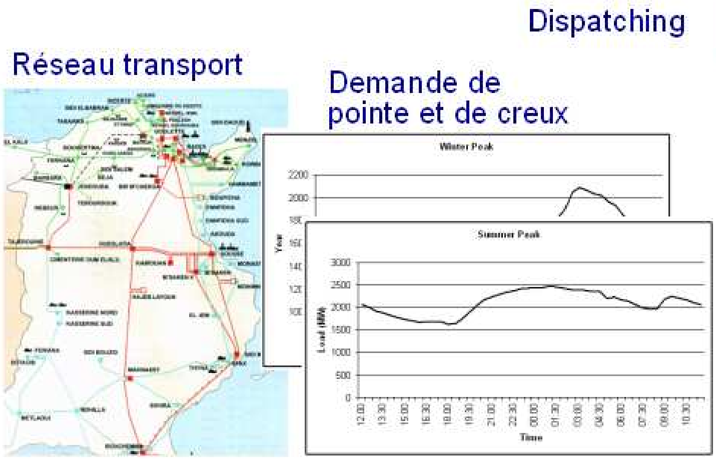
After this initial “screening” phase we shall choose the most restrictive location for the new ELMED power plant to be considered for dynamic analysis.

The criteria for this choice are based on minimisation of the distance, in km, of the new lines, in relation to the reinforcement options proposed by the network operator. In other words, the location of the new plant that requires the most onerous reinforcements (the Skhira site) shall be chosen for the dynamic simulations, to test the stability of the system in the event of disturbance. This network configuration shall also be the one of reference for subsequent analyses concerning unpredictable renewable energy production (RES production). Should we choose a site other than the one mentioned above we will of course have to examine its respective impact on the transmission network and determine which reinforcements shall be needed.

3.1.1 The stages of Task B

Stage 1

The first stage is to devise a model of the Tunisian production-transmission system for the year 2016 based on the data provided by the STEG (network operator) via ELMED Etudes (network configuration, power needs, generation dispatching) (Fig. 3-3).



GENERATION DISPATCH				
BUS				Pgen
#	NAME	BSKV	ID	MW
83001	BOUCHEMA	11	1	107.0
83008	RADES	15.5	1	155.0
83009	RADES	15.5	1	155.0
83010	RADES	15.5	1	160.0
83011	RADES	15.5	1	160.0
83013	SOUSSE	15.5	1	150.0
83014	SOUSSE	15.5	1	150.0
83015	SOUSSE	15.5	1	107.0
83016	SOUSSE	15.5	1	107.0
83017	SOUSSE	15.5	1	107.0
83022	B.M.CHERG	15.5	1	107.0
83023	B.M.CHERG	15.5	1	107.0
83027	FERIANA	14	1	97.0
83030	RADES2	15.5	1	108.0
83031	RADES2	15.5	1	108.0
83032	RADES2	15.5	1	224.0
83034	THYNA	14	1	105.0
83050	GHANOUCH	15.5	1	360.0
83053	HAWARIA1	15.5	1	360.0
83054	HAWARIA	15.5	1	360.0
83057	EL BIBAN	11	1	24.0
83072	THYNA	14	1	107.0
83074	SOUSSECC	15.5	1	333.0
83076	FERIANA1	14	1	97.0
83081	BIZRTCC1	5.5	1	580.0
83082	BIZRTCC2	5.5	1	580.0
TOTAL GENERATION				5015

Fig. 3-3 – Planning the model

Two load options shall be considered for the year concerned (2016):

- Annual peak load;
- Annual minimum load.

In each case we shall check conformity with the N and N-1 criteria for safe exploitation. The results obtained with the SPIRA package shall be compared to those provided by STEG via ELMED Etudes, in PSS/E vers. 29.

During this stage, we shall inform ELMED Etude if the data is insufficient or inconsistent.

In addition to the database there shall be an “equivalent” model for the rest of Maghreb sufficiently precise in terms of both static and dynamic analysis. CESI shall introduce this model if it is not provided by the STEG via ELMED Etudes. The model shall be the one CESI used for previous studies in 2009 ([4], [5], [6]).

Stage 2

We shall create the underwater HVDC line between the station at El Hawaria and Partanna, in Sicily, using the model agreed upon in Stage 1. The subject of analysis is the connected Tunisian system to Sicily shall have an equivalent model. The new 400 kV alternating current (AC) lines connecting the El Hawaria station to the rest of Tunisia's transmission system shall also be implemented. In principle, we anticipate the need for two 400 kV lines. The two ends of these lines shall depend on the location of the new ELMED power plant.

Furthermore, we shall install the new units for the ELMED power plant taking into account the four possible locations (El Hawaria, Bizerte, Enfidha and Skhira) and the redispatching of production, as follows:

- 800 MW for the link with Sicily;
- 400 MW for domestic demand. The redispatching of the other units shall be according to the "merit order" of the units used, in their two load conditions.

Stage 3

We shall execute static analysis (load sharing measurements) in conformity with the N and N-1 security criteria at each of the four possible locations of the ELMED plant and in the two load conditions, implementing the network reinforcements chosen from among those proposed by the STEG via ELMED Etudes (para. 4.3).

At the end of this stage we will have identified four preliminary sets of network reinforcements for:

- the connection of the new units, and
- the transmission of 800 MW to the AC/DC converter substation at El Hawaria.

The four sets of reinforcements shall be classified and the solution requiring the construction of the fewest new lines shall be chosen for subsequent analysis. The factor considered for classification is the length of new lines. We reckon it would be far more difficult to create new lines than to install new interconnecting transformers at the stations.

Stage 4

The purpose of dynamic analysis is to determine the conditions of the Tunisian electrical system that meet the constraints of dynamic security (see para. 4.2).

The dynamic model, like the static model, shall be based on data provided by STEG via ELMED Etudes. The dynamic models shall be introduced in the SICRE simulator developed by CESI for Terna. Any changes CESI makes to the dynamic models in the SICRE simulator, especially for the AVRs, PSSs and speed regulators, shall be based on its own experience and previous studies of the Tunisian and Maghreb network.

Dynamic analysis is executed to check the conformity of the Tunisian network with the minimum requirements for dynamic security and with the rules on exploitation, in relation to the intended HVDC Italy-Tunisia link and to the new ELMED Production Units. More specifically, the performance of the system shall be checked by simulating feasible disturbance such as three-phase short-circuits on a sample of the network and the sudden tripping of a large production unit. The following defects, in particular, shall be examined within the context of this study: tripping of one of the lines (or interconnecting transformer[1]) leading out of the new ELMED station, due to a three-phase short-circuit; tripping of the largest unit; loss of a pole at the AC/DC converter; lastly, and if necessary, a defect on a 400 kV line.

Specific inspections may be executed at the AC/DC transformer stations to resolve any limitation to the dispatching of production units due to dynamic constraints. E.g.: reduced transmission to Sicily due to tripping of a unit at the ELMED station. We would like to point out that the intended coal-fired units are larger (at 660 MW) than the existing units in Tunisia and the rest of the Maghreb (about 400 MW, in case all the Combined Cycle Gas units, 2 x TG and one TV, should trip). This would require a larger "tertiary" reserve and involve additional running costs which could however be reduced with an appropriate control system at the AC/DC converter substations.

A fault with the Tunisia-Sicily DC link would also have a considerable impact on the interconnected systems. However, as the link shall be bipolar (500 MW+500 MW), the N-1 security criteria requires us to make provisions for the potential loss of a single pole (500 MW). This disturbance is smaller in entity with regard to the coal units intended for the ELMED power plant, and represents the incident of reference for the system.

The factors below shall be valuated with simulations executed over time:

- The CCT (Critical Clearing Time) for the protection devices in the event of a short circuit (the protection devices will not be described in detail but their operation shall be simulated with equivalent ones). The CCT must be compatible with the tripping time of the protection devices (in the second "stage");
- The range and damping of oscillations after contingencies;
- Any instances of instability, such as unsynchronised operation of the generators, due to feasible defects.

The analyses should also help us obtain information on the compatibility of large units with the performance of the interconnected Tunisian system. In particular, we shall test power oscillations at the Algerian border (Fig. 3-4) and the frequency values which should not fall below the set thresholds: specifically, in the case of the interconnected network, the minimum instantaneous frequency must be above 49.5 Hz (the dynamic change in frequency must not exceed the band of 500 MHz) (para. 4.1).

As regards the transient support of the systems connected to Tunisia, an equivalent model of the production-transmission systems for the neighbouring countries (Algeria, Morocco) and the ENTSO-E/SCR[2] systems could be considered taking into account the hypotheses and models adopted at the time of these studies (e.g. equivalent generator inertia and size) [4], [5], [6]. Such a model shall not be implemented at the eastern border where a more conservative approach is deemed appropriate as interconnection with Libya shall be considered out of service.

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[1] Refer to the case of 400/225 kV transformers in E/S on the 225 kV Sidi Mansour-Bouchemma double line for the Skhira option.

[2] ENTSO-E/SCR: European Network of Transmission System Operators of Electricity/Synchronous Continental Region

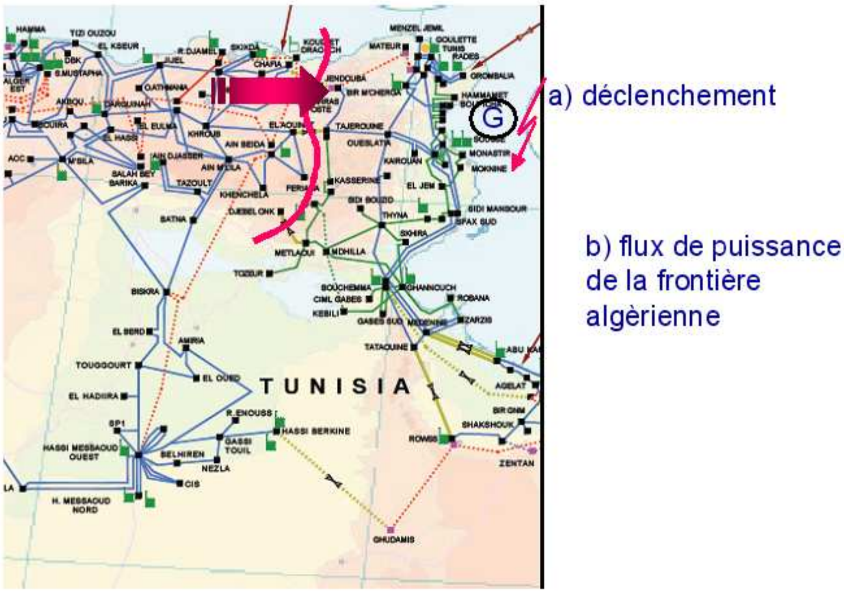

Fig. 3-4 – Example of a defect to be analysed

The purpose of the dynamic simulations shall be:

- To determine the maximum acceptable size of the system;

or

- To determine any limitations to production in certain load or exchange conditions at the border.

3.1.2 Expected results of task B

- Network reinforcements due to the “ELMED Production Cluster”. Maximum permitted size of the units for the system or restricted production in certain conditions.

3.2 Methodology for objective b): determining the maximum power produced using non programmable renewable sources

The analyses are executed with the transmission network in the same configuration as for the previous task, with reference to a chosen location of the ELMED power plant.

The purpose of this task is to valuate the maximum power produced with unpredictable renewable sources by the Tunisian system for the link with Sicily. One such unpredictable renewable source, to be discussed further on, is wind power, which can be extremely intermittent and therefore very difficult to predict. Moreover, the production of wind energy can tend to be during minimum load times, which makes it more difficult to exploit. In contrast, solutions already exist for mitigating the unpredictable nature of solar energy production (a source that could be developed in Tunisia) such as heat storage systems (e.g. CSP with heat storage[3]) or connection to batteries (e.g. PV and batteries). Moreover, solar energy production is strongly concentrated during the time of day when load is highest.

The analyses therefore consider the impact of wind energy farms on the Tunisian system. In any case the determined production limit applies in general to all unpredictable renewable energy sources, and production over the limit must be combined with use of energy storage devices for starting up and redispatching conventional units. Modifying the sites for the production of unpredictable renewable energy such as those examined in this study could present additional restrictions associated with the transit capacity of the lines and transformers.

[3] A form of heat storage for CSP plants is based on the use of “molten salts” at extreme heat (≈500 °C).

This task, like task B, shall be divided into stages as follows.

3.2.1 *Stages of Task C*

Stage 1

The purpose of this stage is to determine the maximum wind energy capacity in Tunisia regardless of the constraints of the transmission system, taking into account however the characteristics of the conventional generation park, the load and the interconnection link with Sicily.
Our approach with regard to interconnection with other Maghreb countries is as follows:

- The lines with Libya shall be put out of service;
- The lines with Algeria shall be in service but exploited only for temporary support. In other words, we shall respect the principle of autonomy for each country (no shared secondary and tertiary cross-border reserve).

It is a “single bus-bar” model with all the generation in service, the load and the HVDC interconnection link connected to the same intended hub.
Above all, the use of new wind energy should not affect the generation units in service, overall (“unit commitment”); all analyses shall therefore take into account the same “unit commitment” determined by the peak and minimum conditions for task B. This condition is justified by the fact that one has to guarantee sufficient levels of inertia, short circuit and reactive power margins to support the voltage.
The preliminary maximum limit (the “single bus-bar” model in Fig. 3-5) for wind energy penetration capacity is valuated during this stage as follows:

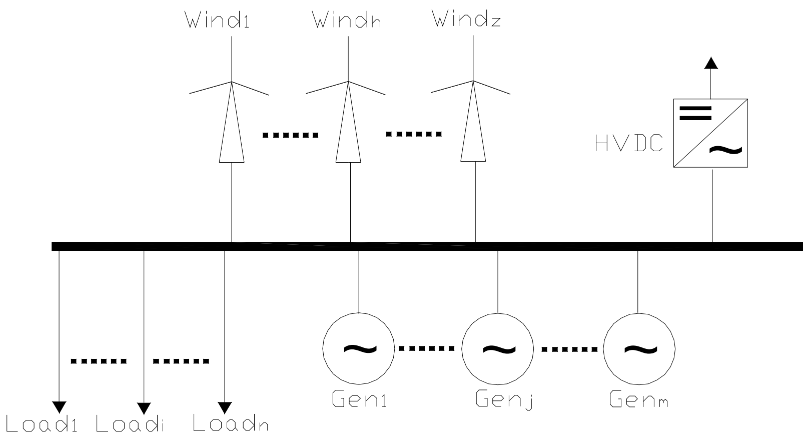

Fig. 3-5 – The “Single bus-bar” model of the system

- *calculating the secondary reserve:*

The secondary reserve must be sized to permit resetting of the frequency error and power exchange at the border (ACE: area control error). The secondary reserve is activated by the secondary control systems (see the definitions of the primary, secondary and tertiary control in Annex 1).
The secondary reserve, R_{sec}, is sized as follows:
a) Calculation of R_{sec-1} using the empirical formula adopted by ENTSO-E [1] and previously by UCTE:

$$R_{sec-1} = \sqrt{10 \cdot L_{max} + 150^2} - 150$$

Where:
$R_{sec\text{-}1}$: the recommended value for the secondary reserve in MW
L_{max}: the maximum load (in MW) according to area (e.g. Tunisia) and period of time (e.g.: day)

b) Comparison between the $R_{sec\text{-}1}$ and P_{max} for the largest generating unit in service:

$$R_{sec-2} = max\{R_{sec-1}; P_{max}\}$$

c) If necessary, multiplication of $R_{sec\text{-}2}$ by a coefficient (e.g. 1.05) to take into account any additional factors:

$$R_{sec} = R_{sec-2} * coeff$$

Point b) may be overlooked with regard to the largest unit in the system, so as not to overly increase the need for a secondary reserve.
In fact the system current reserve value (60 MW), in accordance with the Maghrebian agreement, is in the order of $R_{sec\text{-}1}$ obtained by applying the empirical formula stated in step a).

- *calculating the tertiary reserve:*
The tertiary reserve should be sufficient to make up for the largest foreseeable amount of power loss (incident of reference) in the control area under the responsibility of the system operator. There are at least two types of tertiary reserve:

- Tertiary increase reserve;
- Tertiary decrease reserve[4].

The need for a tertiary reserve R_{ter} also takes into account the secondary reserve R_{sec}, so: $R_{ter} \geq R_{sec}$. To determine the size of the tertiary reserve, it is possible to use either deterministic criteria (a list of events involving unavailability of the production units and/or load rejection) or probabilistic criteria (typically, the uncertainty of predicting demand or the probability of the production unit tripping). Moreover, the tertiary reserve should permit complete re-establishment of the secondary reserve and making up for delayed or anticipated increase/decrease in load.
In our experience, for the lower threshold of the tertiary reserve to ensure a greater than 99.7% chance of the load not tripping, the tertiary reserve should be about 7-8% the daily peak load [7].
In conclusion, the two values of the tertiary reserve are valuated as:

- "tertiary increase reserve":

a) $R_{ter-augm-1} = L_{\max} * 0.08$

b) Comparison between $R_{ter\text{-}augm\text{-}1}$ with R_{sec} and choice of the maximum value:

$$R_{tert-augm} = max\{R_{ter-augm-1}; R_{sec}\}$$

In particular, the value of $R_{ter\text{-}augm}$ should take into account the tripping of the largest unit.

- "tertiary decrease reserve":

a) $R_{ter-\dim-1} = L_{\min} * 0.08$; the units running in minimum conditions should have a decrease margin about 8% of the minimum load L_{min}.

[4] In the case of some systems, we also consider a replacement tertiary increase reserve

b) Comparison between $R_{ter\text{-}dim\text{-}1}$ and the largest pump unit. One has to choose between the two maximum values:

$R_{tert-dim-2} = max\{R_{ter-dim-1}; P_{pompage}\}$

c) Comparison between $R_{ter\text{-}dim\text{-}1}$ and the secondary reserve in minimum load conditions $R_{sec\text{-}min}$. One has to choose between the two maximum values:

$R_{tert-dim} = max\{R_{ter-dim-2}; R_{sec-min}\}$.

The two diagrams below illustrate the layout of the reserves in peak and minimum load conditions.

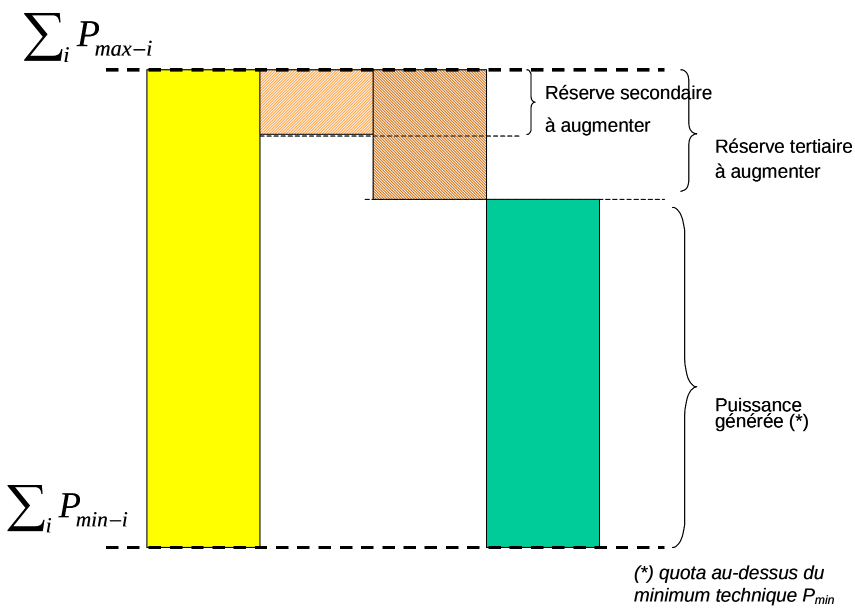

Fig. 3-6 – Layout of the "increase reserve" in peak condition

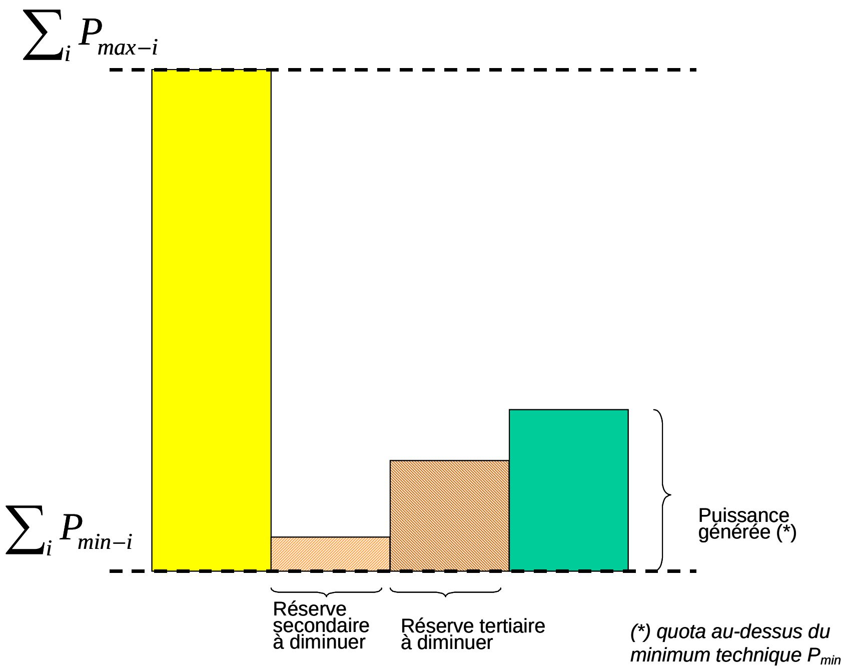

Fig. 3-7 – Layout of the "decrease reserve" in minimum condition

The use of wind energy could pose an additional constraint to the reserve due to the unpredictable nature of production. A preliminary level of the maximum wind energy capacity could however be envisaged for the additional maximum reserve, which could be made available after redispatching of the conventional units, but without changing the "unit commitment" (*Fig. 3-8*).

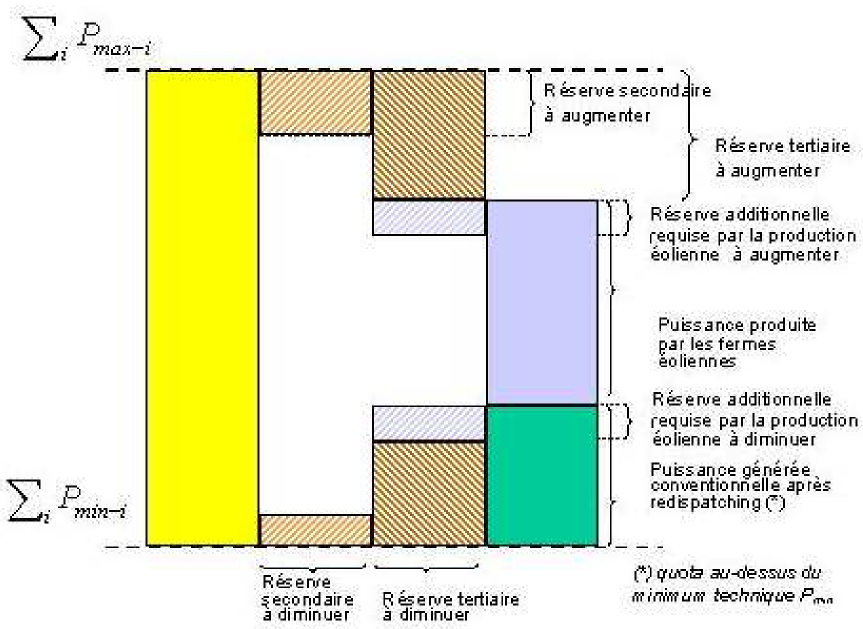

Fig. 3-8 – Wind energy production, the additional reserve and redispatching of the conventional units – peak load situation[5]

- Calculation of the additional reserve with wind energy production and estimated maximum wind energy production

To evaluate the maximum wind energy production we need to estimate the additional reserve to make up for the unpredictability of wind. This uncertainty depends on the wind forecasts: the more accurate the predictions, the less need we have for an additional reserve.

As wind energy production is only just being developed in Tunisia and we do not therefore have any historical data on errors forecasting strong winds, we have had to refer to international sources and, in particular, the studies of IEA-Wind [8]. The increased wind energy reserve in different countries is illustrated in Fig. 3-9. The additional reserve values were obtained with probabilistic analyses and/or simulations; each study involved different methods and acceptable statistical confidence levels. The one factor in common is the fact that the additional reserve increases in line with wind penetration.

[5] Diagram not to scale.

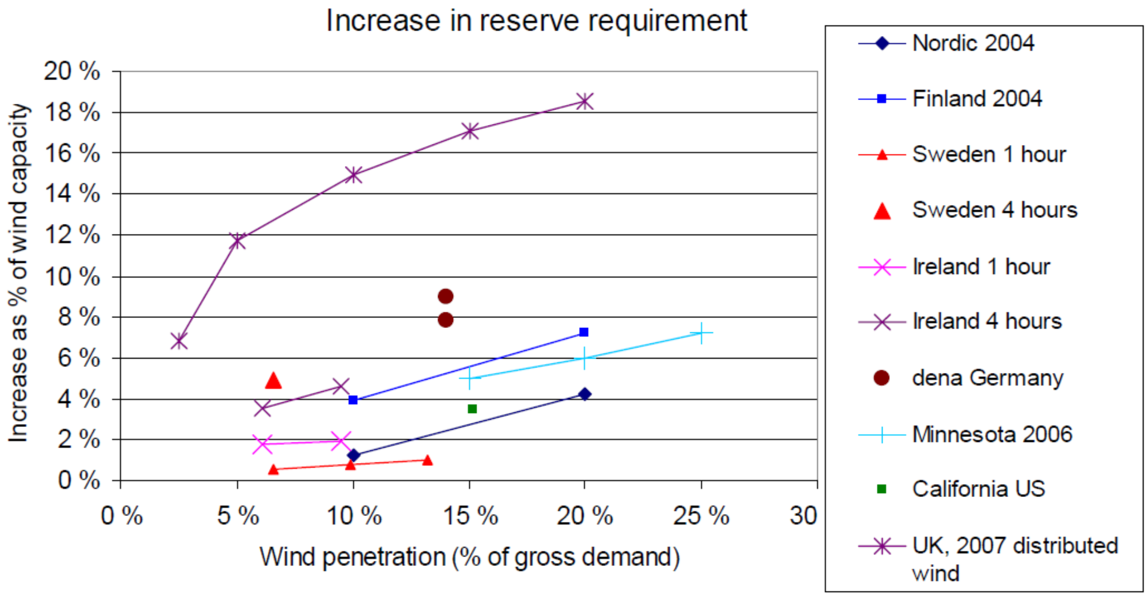

Fig. 3-9 – Increase in reserve in relation to the penetration of wind energy production

In this case the data has already been used in a CESI study of the Italian system based on a deterministic approach that considers the additional reserve in relation to the percentage of wind energy effectively available (average available power). The data is given in Table 3-1. The figures are slightly higher than the average ones in Fig. 3-9, as:

- They are based on a deterministic approach where it is best to use broader margins than for probabilistic approaches;
- In our valuation of the additional reserve, we have not considered other forms of production involving unpredictable RES (e.g. photovoltaic) which could however be available.

Linear interpolation is required to obtain penetration data similar to that in the table.

Tab. 3-1 – Additional reserve for wind energy penetration

Wind energy penetration %	**Additional reserve (% of wind energy capacity)**
5	6.5
10	9
15	11.5
20	14

Note:

- *Penetration: wind energy production in relation to load. It is clear that, for parity of wind energy production, penetration has to be higher in minimum load conditions;*

- *Additional reserve: expressed as a percentage of the installed wind energy capacity multiplied by a contemporaneous coefficient*[6].

The additional reserve and maximum acceptable wind energy capacity penetration is calculated in two different situations:

- without the DC cable link with Sicily;
- with the DC cable link with Sicily. In this case we presume the control systems of the converters can change the exchanged power automatically and contribute to the reserve.

The procedure for the initial determination of wind energy production compatible with the reserve of the conventional production system is shown in Fig. 3-10.

[6] The contemporaneous coefficient depends on the nature of the wind in the region where the wind farms are to be installed. The more uniform the level of wind (e.g. as in a flat country like Denmark), the higher the contemporaneous coefficient is. This coefficient is normally determined using wind-related data collected over a long period of time.

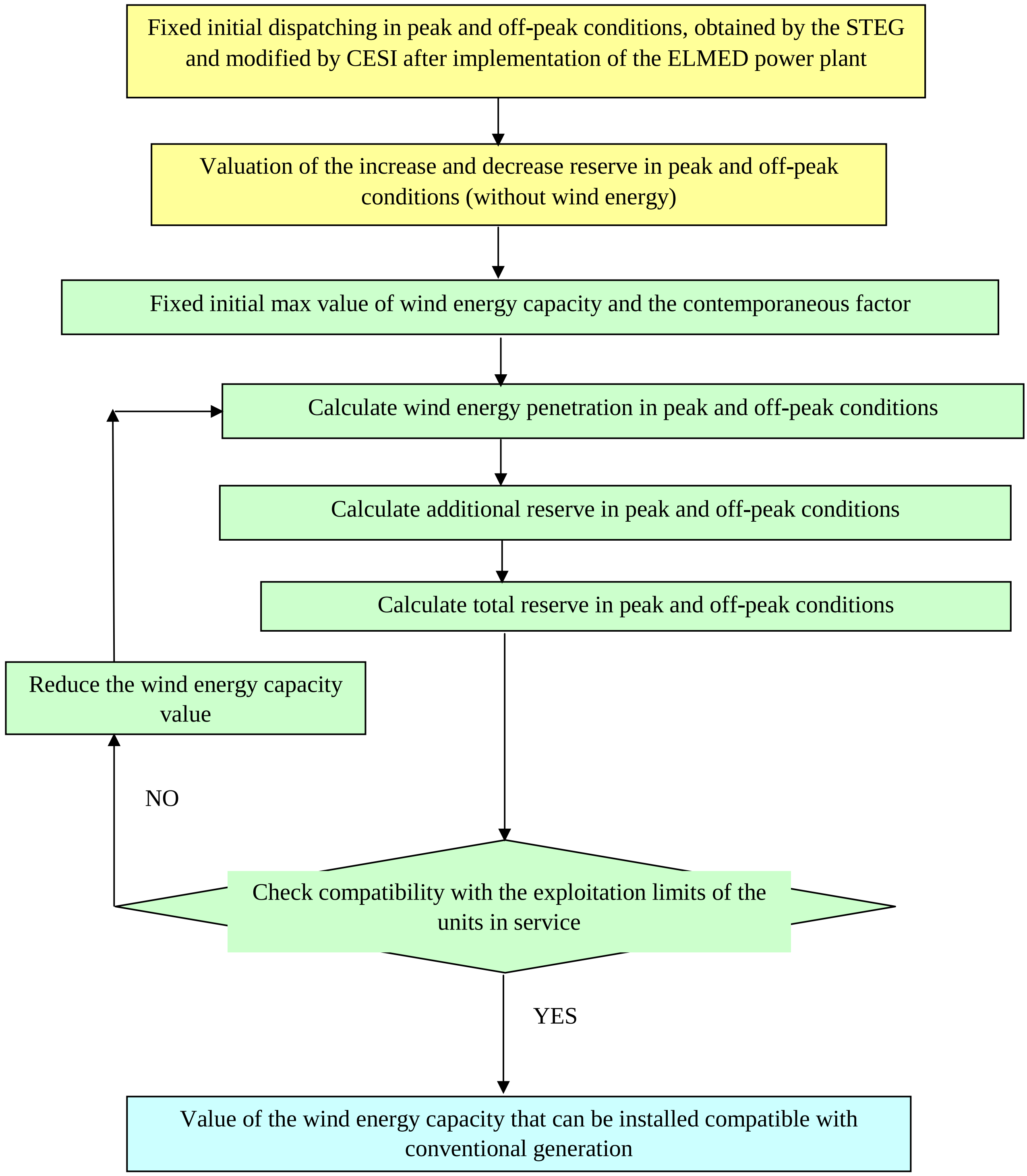

Fig. 3-10 –Procedure for valuating the max wind energy capacity compatible with the reserve of conventional units

- Acceptable gradients of max variation in increasing/decreasing wind energy power

Another constraint we have considered concerns the acceptable degree of variation (gradients or ramps) in wind energy production. In fact, even if the system has a sufficient tertiary reserve, the maximum power variations (MW/min) of conventional units can prove insufficient in transitional conditions, that is to say during variations in load and wind energy production. As the daily fluctuation in demand does not tally with wind energy production, transitions in times of increased or decreased demand can be restrictive, as shown in Fig. 3-11.

Fig. 3-11 – Example of variation in load and wind energy production in Spain (source: REE)

The future situation in Tunisia could be similar to the one in Fig. 3-12.

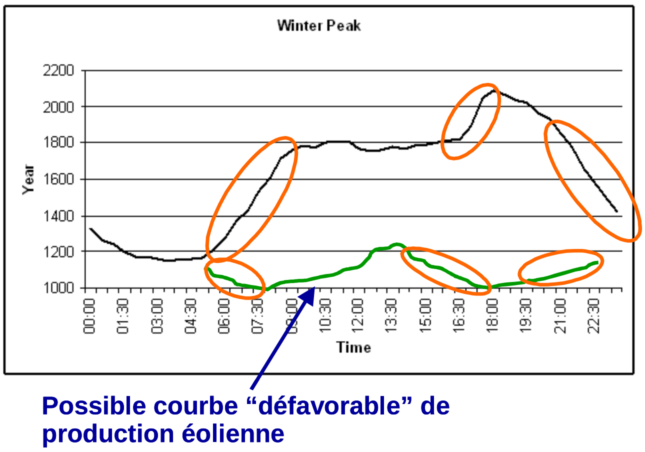

Fig. 3-12 – Possible "unfavourable" curve of wind energy production

We would need to execute simulations over a period of time for detailed analysis, though we can initially determine the compatibility of the power variation capacity of conventional generation during particularly restrictive transitional phases (Fig. 3-13). Support for the link with Sicily shall be discussed, without however forgetting that the response times of the converters' control systems are extremely fast.

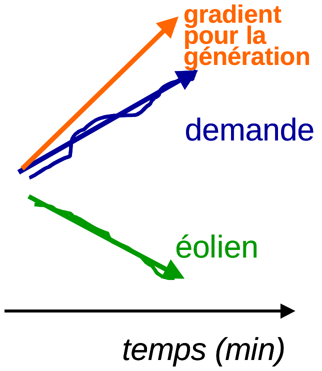

Fig. 3-13 – Gradient of conventional generation to cope with fluctuation in demand and wind energy production

By the end of this stage we will have a general idea of the maximum amount of wind energy capacity that can be accepted by the Tunisian system within the intended load conditions (with valuation of the peak and minimum load), with the conventional generating units and with the future link with Sicily.
We have not yet considered the wind energy feed points and the possible network constraints.

Stage 2

We will now assess the impact of wind energy production on the transmission network with static calculations (load flow) in conformity with the N and N-1 security criteria and the rules on exploitation set down by the network operator (STEG) (para. 4.1).
The analyses are based on the model of the production-transmission system devised during task B. Calculations shall again be made during peak and minimum load conditions.
For the choice of transformer stations we will refer to the wind sites proposed by the STEG (6.1). The priority for the transmission of wind energy capacity shall be as follows:

- existing power plants;
- power plants currently being installed;
- new power plants shall be set up starting with those at sites with the highest[7] estimated degree of capacity[8].

We shall choose the connection solutions that best meet the security criteria and involve the lowest connection costs (estimated in terms of the length of the lines for connection to the station).

The transmission of wind energy will require “redispatching” of the conventional units in service. “Redispatching” shall be executed according to the “merit order” of the units (para. 5.1).

Note:

- *new wind energy production shall replace the production of the ELMED Production Cluster up to a level of 200MW;*
- *above this threshold, wind energy production shall replace the production of the other units in the Tunisian generation park according to the “merit order” arranged with the STEG.*

[7] This capacity factor is not known for some of the sites. We will estimate this capacity factor as best as possible (albeit in a very approximate manner) according to the proximity of these sites to those the capacity factor of which we already know.

[8] The capacity factor relates to the wind speed at the wind farm site and can be calculated as equivalent annual hours of the wind energy plant at full power, or as a percentage of the installed power.

The load sharing measurements will allow us to check the transmission network for bottlenecks (congestion). The results of the measurements will also allow us to assess the impact of wind energy production on the system's capacity to control the voltage profile. In fact, the effect on the voltage profile differs according to the type of wind energy unit (e.g. asynchronous generators, double fed asynchronous generators, synchronous generators connected via converters, etc.). Depending on the technology used, an appropriate degree of absorption/production V, Q shall be simulated to determine the need for means of reactive compensation and to test the conformity of the voltage profiles to the N and N-1 security criteria. Unless ELMED Etude provides more detailed information, we shall refer to the model described in para. 6.2.

By the end of this stage we will have determined the potential wind energy production capacity and possible solutions for connection to the network, all in conformity with the criteria on static security.

Stage 3

This stage of dynamic analysis involves several points. The most important point is to examine the fluctuations in power flux caused by intermittent production of wind energy. Simulations shall therefore be executed over a period of time to determine the various production curves at the wind farms. As the purpose of the analysis is to valuate the impact of the nature of wind production on the transmission and production system in Tunisia, the wind farms shall be represented in a simplified manner by an equivalent generator (power feed concentrated at the sites determined during the previous stage).

Moreover, it should not be forgotten that transitory phenomena caused by fluctuating wind energy production can last up to a minute, or several minutes in certain cases. As a result, we need to use dynamic models suited to simulations executed over a long period of time. It should also be noted that the control equipment of the wind energy units differ from those of traditional thermal power plants; this aspect affects the behaviour of the network in critical situations, for instance in the case of faults (short-circuiting and tripping of the production plant or transmission lines).

In conclusion, dynamic simulations shall be executed with all the components in working order and also in instances of a fault with one of the components of the production-transmission system, with the aim of examining:

- ✓ Frequency fluctuations due to increase or decrease in wind energy production, taking into account the most restricting conditions of fluctuating demand (the combined production of several wind farms could be considered);
- ✓ Frequency fluctuations due to major faults with the Tunisian system (tripping of the most loaded lines or largest generators). These frequency fluctuations can, in turn, cause tripping of the wind energy units with a possible "domino effect";
- ✓ Power fluctuations on the cross-border lines caused by intermittent production of the wind energy plants. Examination of these fluctuations can help determine the margins for the cross-border transmission of power (NTC[9] also taking into account the production of unpredictable renewable energy) or gain information on the need to limit the production of unpredictable renewable energy;

- ✓ The behaviour of the network in the event of faults: this type of analysis is essential to determine response of the network in terms of voltage and frequency, oscillation ranges, and stability margins in the event of major contingencies.

[9] NTC = Net Transfer Capacity

Dynamic analysis shall be executed in the same two conditions (peak and minimum load) as the previous stage. As well as the stability of the system, we shall check the dynamic responses are compatible with the "setting" of the protection devices and with the dynamic operating criteria (e.g. frequency variation range) (para. 4.1 and 4.2).

The point of the above analysis is to determine any restrictions to wind energy production due to dynamic constraints.

3.2.2 Expected results of task C

- Range of the maximum capacity of wind energy production (global values for the system)
- Information on maximum transmission at the connection stations and network components that are restrictive.

4 HYPOTHESES OF THE STUDY

The study is based on the following general hypotheses:

- *Intended year*: 2016, the year when the Tunisia-Sicily interconnection link shall be put into service;
- *Working conditions*: two conditions shall be examined:
    - Annual peak load,
    - Annual minimum load,

  These are the extreme conditions in which the system is used;
- *interconnections*:
    - five AC interconnection lines with Algeria:
        - Tajerouine-El Aouinet (225 kV)
        - Tajerouine-El Aouinet (90 kV)
        - Metlaoui-Djebel Onk (150 kV)
        - El Kala-Fernana (90 kV)
        - Jendouba-Chefia (400 kV)
    - The interconnection lines with Libya shall be put out of service
    - Underwater DC interconnection line with Sicily:
        - El Hadjar – Partanna: bipolar configuration, 500 MW + 500 MW, 400 kVcc. Characteristics illustrated in the feasibility study [2].

4.1 Rules for exploitation

The rules for exploiting the Tunisian system have been set down by the STEG and are as follows:

1-Static criteria for operation:

- **Normal situation (sound network):**

Voltage limits: the voltage of the hubs overall should be within an admissible range of **±7% of the nominal voltage.**
Transmission limits: during normal operation power flows should not exceed the nominal capacity of the various components (lines, ATRs and high voltage transformers).
Limits of active and reactive production: the active power produced by each unit should not be less than its technical minimum or exceed its nominal power. Similarly, the production units should not exceed the limits of reactive production (Qmin < Qg < Qmax).

- **Situation N-1 (with disturbance):**

When there is disturbance, a voltage limit **±10% of the nominal voltage** and an overload of **20% on the links (lines or cables) and at the transformers/auto-transformers** in relation to the nominal capacity of the structure is considered acceptable.

2-Dynamic criteria for operation (frequency range):

- **Normal Situation (interconnected network):**

The Tunisian network is connected to the European one via Algeria and Morocco. Normal exploitation of the network is based on the recommendations of the **UCTE**[10] concerning interconnected networks.

Rated frequency: this frequency is of **50Hz**

Frequency deviation:

- The primary control is set to react at a frequency deviation of **±20 MHz**
- In normal working conditions, frequency should not deviate by more than **±50 MHz**
- The quasi-stationary equilibrium frequency after disturbance should not deviate by more than **±180 MHz**
- The minimum instantaneous frequency must be more than **49.5Hz** (which corresponds to a dynamic frequency variation of **500 mHz**).

- **Situation with disturbance (isolated network):**

Safety measures should be implemented for the eventuality of disturbance, to control the frequency:

✓Important primary and secondary reserves need to be created, particularly for starting up additional units. Good partitioning between the generators is recommended, especially among the fast dynamic ones: hydraulic units, gas turbines and combined cycle gas turbines.

✓We will try, as best as possible, to choose a fuel that can ensure the best dynamics for the poly-fuel thermal units

✓The use of temperature limited gas turbines should be avoided (operation with limiter).

The equilibrium frequency should remain above **49.7Hz** to guarantee the flow of load. In the case of an N-1 unit (for average production), the minimum instantaneous frequency must be above **49.3Hz**. If two units, combined cycle or other is lost, load-shedding is inevitable and the frequency must not, in any case, fall below **48Hz**.

4.2 Protection system and load-shedding plan

The salient features of the protection system and load-shedding system were provided by the STEG on the request of CESI, via ELMED Etudes. The information is categorised as follows:

- Wattmeter relay system;
- Description of the HV protection system;
- Automatic load-shedding plan at lowest frequency.

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[10] Since 2009, ENTSO-E/SCR

4.2.1 *Wattmeter relay system*

All loss of production on the Tunisian network is almost completely made up for by the European network. The back-up offered by the European network is provided via the Morocco-Spain underwater cables, and is sent over the Maghrebian networks to the country concerned. The stress of the Maghrebian interconnections is as strong as the power lost is great.

The protection systems (with wattmeter protection and breaking step) are installed on the interconnection lines and act by opening the interconnection lines and limiting accidents and preventing these from crossing over to other networks.

The thresholds of the wattmeter protection systems on the TAI[11] (in the direction of Tunisia ⇒ Algeria) should not cause voltage constraints or overload on the Tunisian system.

The thresholds of the wattmeter protection systems on the TAI (in the direction of Algeria ⇒ Tunisia) should respect the coordination between the MAI[12] and TAI interconnections (in the event of considerable loss of production in Tunisia, the wattmeter protection system on the TAI should be activated rather than the one on the MAI). The thresholds of the wattmeter protection systems on the TAI are determined according to any voltage and overload constraints on the Algerian network.

After activation of the wattmeter relay system, the network on which the accident occurred is considered defective and the automatic load shedding system (at lowest frequency) is activated if the fixed thresholds are exceeded.

In addition to the wattmeter relay system is a remote load shedding system for active transmission on the interconnection lines, installed to minimise transmission over the interconnection lines below the thresholds of the wattmeter system and thereby ensure protection, to preserve the interconnection lines and connectivity of the networks. This remote load shedding system is determined according to the wattmeter thresholds of the interconnection and the size of the installed units (to ensure a N-1 level of security).

A relay based on wattmeter relay systems at the border and devised during the study Tunisia-Libya synchronisation is shown in Fig. 4-1.

[11] TAI : Tunisia-Algeria Interconnection
[12] MAI : Morocco-Algeria Interconnection

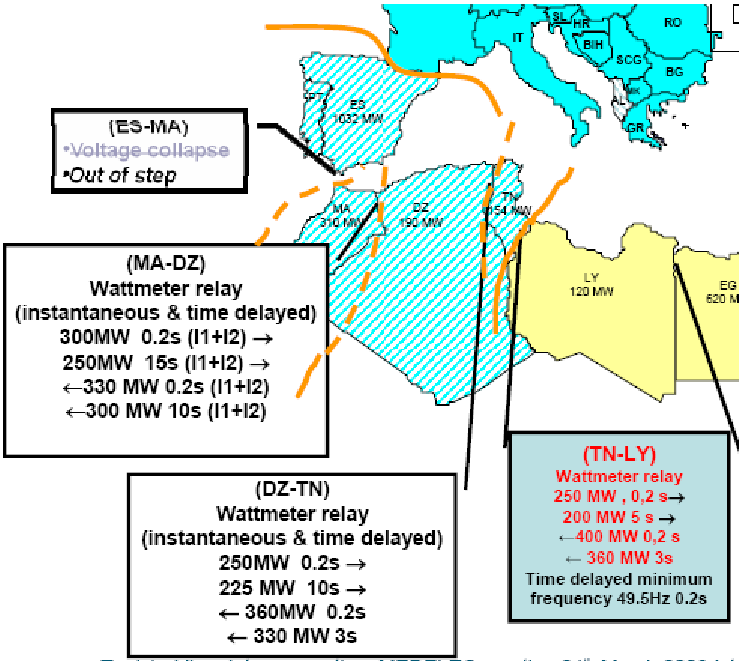


Fig. 4-1 – Protection system for Tunisia-Libya synchronisation (source: REE)

4.2.2 The HV protection system in brief

The STEG’s current protection system for the HV network consists mainly of the following:

- Remote protection systems (electromechanical, static and numerical) with the following thresholds:
  - 1st stage (forward): instantaneous.
  - 2nd stage (forward): 400 ms on the 225/150 kV network and 600 ms on the 90 kV network.
  - 3rd stage (forward): 1 second for the 225/150 kV network and 1.2 seconds for the 90 kV network.
  - 4th stage (non-directional): 2 seconds.
- Safety protection at maximum current for remote protection (1.6 In – 1.5 seconds). This protection on the 225 kV network is conditioned by burning of the fuse of the remote protection.
- Additional directional protection against extreme defects (following inverse time curves and a basic timing of 3 seconds).
- Minimum voltage protection (70% Vn – 3.2 seconds).
- Relay protection on certain lines connected to the Algerian network and several lines of the STEG network (see fig. 4-1).
- Minimum frequency protection on the lines connected to the Algerian network (see fig. 4-1).
- For single-phase faults there shall be a 1st single-phase load shedding-reset system with a dead-time of 1.5 seconds. Definitive load shedding occurs if the fault persists. Other types of faults cause definitive three-phase load shedding.

4.2.3 Plan for automatic load shedding at minimum frequency

Due to the connection of the Maghrebian network to the European one (ENTSO-E/SCR), load shedding with minimum frequency relays in the Maghrebian countries shall only be in the event of serious production downtime or separation of the network(s) of the European system.

To optimise operation of the Maghrebian interconnections and ensure mutual assistance between the Maghrebian countries, especially in the case of disturbance, interdependent metric frequency shedding thresholds shall be used to permit load shedding in all the interconnected Maghrebian countries; in this way, energy production and consumption can be stabilized and the Maghrebian interconnections and thresholds for each network can be maintained to protect the system in the event of production downtime after opening of these interconnections.

The interdependent shedding thresholds and their respective shedding power values are as follows:

Threshold 1 at F1 = 49.3 Hz: Shedding of 6% of total consumption.
Threshold 2 at F2 = 49 Hz: Shedding of 6% of total consumption.
Threshold 3 at F3 = 48.7 Hz: Opening of the interconnections.

Below the F3 network separation frequency, other thresholds are implemented to protect the defective network subject to disturbance. These thresholds are determined according to the size of the installed production equipment and the equivalent launch time for each network.

The table below details the plan for automatic shedding at minimum frequency of the Tunisian system:

Thresholds			Shedded load in %
N°	F(Hz)	T(sec)	
1	49.3	0.2	5.35
	49.25	0.2	0.73
Threshold total			6.08
2	49	0.2	5.92
Threshold total			5.92
3	48.7	0.2	-
	48.7	10	-
4	48.5	0.2	12.54
Threshold total			12.54
5	48.25	0.2	10.42
Threshold total			10.42
6	48	0.2	9.3
Threshold total			9.3
7	47.75	0.2	11.88
	47.7	0.2	-
Threshold total			11.88
Pmax to be shed (in %) in relation to total load			56.14%

4.3 Network reinforcements (task B)

The list of lines and transformers for the transmission of power at the ELMED power plant is given in Table 4-1. It should be noted that, due to the considerable size of the ELMED power plant, at least two corridors shall be required to transmit the power in accordance with N-1 security criteria[13].

Tab. 4-1 – List of lines and transformers for the transmission of power at the ELMED power plant

ELMED site	Lines	Transformer stations
Hawaria	- Hawaria – Mornaguia 400 kV - 150 km line - Hawaria – Oueslatia 400 kV - 280 km line	- 3rd ATR 400/225 kV – 400 MVA at Mornaguia - 2nd and 3rd ATR 400/225 kV - 400 MVA at Oueslatia
Bizerte	- Bizerte – Mornaguia 400 kV – 110 km line - Bizerte –Mateur 400 kV - 60 km line - Bizerte –Jendouba 400 kV - 120 km line - Bizerte – Mnihla 400 kV – 110 km line - Bizerte – Hawaria 400 kV – 250 km line	- 3rd ATR 400/225 kV – 400 MVA at Mornaguia - 2nd and 3rd ATR 400/225 kV - 400 MVA at Jendouba - 2nd and 3rd ATR 400/225 kV - 400 MVA at Mateur - 3rd ATR 400/225 kV – 400 MVA at Mnihla
Skhira	- Skhira – Oueslatia 400 kV – 230 km line - Skhira – Bouchemma 400 kV - 70 km line - Skhira – Mornaguia 400 kV - 350 km line - Oueslatia – Bouchemma 400 kV - 280 km line - Skhira – Hawaria 400 kV - 410 km line - E/S ligne Bouchemma – Sidi Mansour 225 kV – 20 km line - E/S ligne Bouchemma – Oueslatia 400 kV at the Skhira station – 25 km and line from this station to the power plant at Skhira: Oueslatia-Shkira 245 km and Bouchemma-Skhira 85 km - Skhira – Maknassy 400 kV - 70 km line - Oueslatia – Maknassy 400 kV - 180 km line - Maknassy – Bouchemma 400 kV - 120 km line	- 2nd and 3rd ATR 400/225 kV - 400 MVA at Bouchemma - 2nd and 3rd ATR 400/225 kV - 400 MVA at Oueslatia - 3rd ATR 400/225 kV – 400 MVA at Mornaguia - 3rd ATR 225/150 kV – 100 MVA at Sidi Mansour - 400/225 kV station at Oueslatia (a priori, no bay or ATR constraints)
Enfidha	- Enfidha – Mornaguia 400 kV – 100 km line - Enfidha – Oueslatia 400 kV - 110 km line - Mornaguia –Oueslatia 400 kV - 130 km line - Enfidha – Hawaria 400 kV - 150 km line	- 3rd ATR 400/225 kV – 400 MVA at Mornaguia - 2nd and 3rd ATR 400/225 kV – 400 MVA at Oueslatia

[13] In other words, we would avoid any solution involving two circuits on the same line

4.4 Rules on the exploitation and connection of the wind energy units (task C)

The rules on exploitation and connection of the wind energy units are given in the report *"Study of the integration of Wind Energy Plants in the Tunisian Electrical System"* [3], in particular chapter 6 *"Technical conditions for the connection of wind farms to the HV transmission network"*. These technical conditions consist of, among other things, all the rules on operational control (registered capacity, putting into service, shutdown, maximum power ramp), as well the quality aspects of supply, the needs for compensation of reactive power and the conditions for the protection relays.

5 MODEL OF THE PRODUCTION-TRANSMISSION SYSTEM

5.1 The production system in Tunisia

As regards the production system in Tunisia, we refer to the list of power plants provided by the STEG via ELMED Etude in the PSS/E files for the year 2016. This list includes existing units and new ones to be set up as from now up to 2016 as per the STEG's development plans.

As regards the units currently in service, their technical characteristics are described in Table 5-1 where the units are listed according to a « merit order » based on the specific energy consumption (Tep) per unit of electricity produced (GWh). We estimate the specific consumption of the new power plants on the basis of anticipated yield, evaluated with reference to the most advanced technologies for combined cycle gas turbines (CCGTs) and coal-fired units. The « merit order » of the units shall determine the redispatching of production after implementation of the new ELMED power plant and renewable production as explained in chapter 3.
The key data of the new power plants planned by the STEG for 2016 is given in Table 5-2.

Other data on the exploitation of the power plants:

<u>Power developed by the production units</u>

The maximum power that could be developed by the production park takes the following points into account:

- Temperature factors (seasons: summer and winter);
- Permanent and temporary decline in performance.

NB: The power that can be developed by the combustion turbines is 15% less than the net nominal power that can be developed during the summer season (between June 15th and September 15th).

1) ***<u>Classification of existing units according to merit order:</u>***

The active power of the production devices is best classified according to the criteria of minimisation of specific consumption. This optimisation of active power influences all the network parameters, guaranteeing the balancing of offer and demand for electricity on the network, at minimal cost and at optimal conditions in terms of the quality of service, security and continuity.
As a result, **the location of the production facilities is essentially based on the criteria of specific consumption in ascending order.**

2) ***<u>Production units used</u>***

<u>The STEG owns two types of production unit which are:</u>

- <u>Basic production units</u>: (combined cycle, thermal units) that run 24/24 hours.
- <u>Semi-basic production units</u>: (large-scale combustion turbines) that run, on average, 10 to 16 hours at a time according to the utilities of the electrical system.

3) ***<u>Exploitation reserve</u>***

The hot reserve is of 60 MW, as per the Maghrebian agreement.

4) Gradients

Radès power plant:	the thermal units	**TV1-2**: 1.5 MW / min
	the thermal units	**TV3-4**: 2 MW / min
Sousse power plant:	the thermal units	**TV1-2**: 3 MW / min
	Combined cycle	**TVcc**: 1.5 MW / min
		TG 1-2: 10 MW / min

Table 5-1 – Technical specifications of the existing power plants: the situation in 2009

Type	Power plants	Manufacturer	Unit	Fuel	Gross installed capacity (MW)	Power (MW)		C S M Tep/GWh
						Max	Min	
THERMAL	RADES	MITSUBISHI	TV1	FUEL - GAS	170	150	65	260
			TV2		170	150	65	
		ANSALDO	TV3	FUEL - GAS	185	160	65	255
			TV4		185	160	65	
	SOUSSE	SIEMENS	TV1	FUEL - GAS	160	135	60	265
			TV2		160	135	60	
		ALSTOM	TG1	GAS - GAS OIL	118	118	220	195
			TG2		118	118		
			TV cc	-	128	128		
	GHANNOUCH	ALSTOM	TV1	FUEL - GAS	30	28	12	340
			TV2		30	28	12	
	TOTAL				1454	1310		
GAS TURBINES	BIR MCHERGUA	GE	TG1	GAS - GAS OIL	118	118	40	300
			TG2		118	118	40	
	TUNIS SUD	ALSTOM	TG1	GAS	22	20	10	400
			TG2		22	20	10	
			TG3		22	20	10	
	MENZEL BOURGUIBA	ALSTOM	TG1	GAS OIL	22	20	10	400
			TG2		22	20	10	
	KORBA	ALSTOM	TG1	GAS	22	20	10	
		FIAT	TG2	GAS - GAS OIL	34	30	15	
	SFAX	ALSTOM	TG1	GAS	22	20	10	
			TG2		22	20	10	
	KASSERINE NORD	FIAT	TG1	GAS - GAS OIL	34	30	15	
			TG2		34	30	15	
	GHANNOUCH	ALSTOM	TG2	GAS	22	20	10	
			TG3		22	20	10	
	BOUCHEMMA	FIAT	TG1	GAS	30	28	15	
			TG2		30	28	15	
		GE	TG3	GAS - GAS OIL	118	118	40	300
	THYNA	GE	TG1		118	118	40	
			TG2		122	122	40	
			TG3		126	126	40	
	FERIANA	GE	TG1		118	118	40	
		GE	TG2		126	126	40	
	GOULETTE	GE	TG		118	118	40	
	ROBBANA	FIAT	TG	GAS OIL	34	30	15	400
	ZARZIS	FIAT	TG	GAS OIL	34	30	15	
	TOTAL				1532	1488		
HYDRAULIC	SIDI SALEM	CHARMILLE	GH		33	33		
	FERNANA	NEYRPIC	GH1(amont)		8.2	8.2		
	FERNANA	NEYRPIC	GH2(aval)		1.3	1.3		
	NEBER	NEYRPIC	GH1		6.6	6.6		
		ALSTOM	GH2		6.6	6.6		

	AROUSSIA (MT)	FRANCO TOSI	*GH*		4.8	4.8	
	KASSEB (MT)	RUSSE	*GH*		0.66	0.66	
	BOUHERTMA(MT)		*GH*		1.6	1.6	
WIND	TOTAL				*62.76*	62.76	
IPP	**HAOUARIA (SIDI DAOUD)**				**53**	53	
	RADES II (CPC)	ALSTOM	*TG1A*	GAS - GAS OIL	115.5	105	
			TG1B		115.5	105	
			TVcc	-	240	230	
	TOTAL				***471***	**440**	
	ZARZIS (ELBIBENE) -SEEB	CATERPIL-LAR	*TG1**	GAS	13.5	12	
			*TG2**		13.5	12	
	TOTAL IPPs				*498*	*460*	*220*
T O T A L					*3600*	3378	

Table 5-2 – New power plants planned by the STEG for 2016

Power plant	Type**	Rated voltage (kV)	Apparent power (MVA)	Active power*		Reactive power	
				max	min	max	min
Aousdja G1	CC	15.5	500	400	0	300	-150
Aousdja G2	CC	15.5	500	400	0	300	-150
Ghannouch	CC	15.5	500	400	240	300	-150
Sousse	CC	15.5	500	400	0	300	-150

** Net active power put into the network*

** Legend:

- CC: Combined Cycle

5.2 Peak and minimum load conditions

STEG provided to CESI through ELMED Etudes two PSS/E files concerning the two loading conditions for the year 2016:

- peak load conditions (RT16-Pointe.sav)
- minimum load conditions (RT16-Creux.sav)

The amount of generation, load and losses are reported in the following tables. Moreover, the list of all Tunisian generators present in the network, the unit commitment and the power dispatch is also depicted for the two loading conditions. For each of them are indicated:

- the active and reactive production;
- the operational status (if they are in or out of service)
- the active power limits: in particular, for the peak load condition the upper limits and for minimum load condition the lower ones are considered. These values are used to calculate the reserve available in the two scenarios.

5.2.1 Peak load

The following tables sum up the main characteristics of the system in peak loading conditions.

Tab. 5-3 – Generation and load in peak load conditions

	Actual		**Nominal**	
	[MW]	**[Mvar]**	**[MW]**	**[Mvar]**
From generation	4005.8	830.1	4005.8	830.1
To constant power load	3961.5	1981.0	3961.5	1981.0
To constant current	0	0	0	0
To constant admittance	0	0	0	0
To bus shunt	0	-304.5	0	-281.8
To facts device shunt	0	0	0	0
To line shunt	0	0	0	0
From line charging	0	1597.5	0	1477.4

Tab. 5-4 – Active and reactive losses in peak load conditions

LOSSES						
Voltage		**Losses**		**Line shunts**		**charging**
Level [kV]	**Branches**	**[MW]**	**[Mvar]**	**[MW]**	**[Mvar]**	**[Mvar]**
400	9	3.26	36.90	0	0	485.30
220	113	19.28	226.79	0	0	695.80
150	55	15.97	63.24	0	0	168.70
90	63	5.80	22.13	0	0	143.80
15.5	18	0	355.63	0	0	0
14	5	0	38.89	0	0	0
11	2	0	7.38	0	0	0
0	1	0	0	0	0	3.90
TOTAL	**266**	**44.32**	**750.96**	**0**	**0**	**1597.50**

Tab. 5-5 – Generation dispatching in peak load conditions

Bus Number	Bus Name	Group	Note	Code*	V Sched [pu]	Pgen [MW]	P min [MW]	P max [MW]	Increase reserve [MW]	Qgen [Mvar]
83081	AOUSDJA	CC		2	1.03	380	240	400	20	130.59
83082	AOUSDJA	CC		2	1.03	380	240	400	20	130.59
83022	B.MCHERG	TG		2	1.05	107	40	120	13	25.20
83023	B.MCHERG	TG		2	1.05	107	40	120	13	25.20
83001	BOUCHEMA	TG		2	1.06	107	40	120	13	3.27
83057	EL BIBAN	TG		2	1.02	24	12	27.5	3.5	1.62
83027	FERIANA	TG		2	1.04	97	40	110	13	19.62
83076	FERIANA1	TG		2	1.04	97	40	110	13	19.62
83050	GHANOUCH	CC		2	1.06	380	240	400	20	11.59
83008	RADES	TV		2	1.04	150	65	160	10	24.99
83009	RADES	TV		2	1.04	150	65	160	10	24.99
83010	RADES	TV		2	1.04	160	65	170	10	26.78
83011	RADES	TV		2	1.04	160	65	170	10	26.78
83030	RADES2	TG		2	1.04	108	50	115.5	7.5	17.85
83031	RADES2	TG		2	1.04	108	50	115.5	7.5	17.85
83032	RADES2	TV		2	1.04	224	120	240	16	37.49
83013	SOUSSE	TV		2	1.05	140	60	150	10	32.96
83014	SOUSSE	TV		2	1.05	140	60	150	10	32.96
83015	SOUSSE	TG		2	1.05	107	70	118.5	11.5	25.20
83016	SOUSSE	TG		2	1.05	107	70	118.5	11.5	25.20
83017	SOUSSE	TV		2	1.05	107	60	128	21	25.20
83074	SOUSSECC	CC	*slack*	3	1.01	346.8	240	400	53.2	90.65
83034	THYNA	TG		2	1.04	105	40	119.4	14.4	17.94
83072	THYNA	TG		2	1.04	107	40	119.4	12.4	17.94
83073	THYNA	TG		2	1.04	107	40	119.4	12.4	17.99
83002	BOUCHEMA	TG	*out of service*	4	1.06	---	15	27.5	---	---
83025	GOULETTE	TG	*out of service*	4	1.04	---	40	120	---	---
83003	KAS.NORD	TG	*out of service*	4	1.06	---	15	32	---	---
83004	KAS.NORD	TG	*out of service*	4	1.06	---	15	32	---	---
83005	KORBA	TG	*out of service*	4	1.06	---	10	20	---	---
83006	KORBA	TG	*out of service*	4	1.06	---	15	32	---	---
83042	M BOURGU	TG	*out of service*	4	1.025	---	10	20	---	---
83043	M BOURGU	TG	*out of service*	4	1.025	---	10	20	---	---
83007	O.ZERGA	*n.d.*	*out of service*	4	1.00	---	0	28	---	---
83019	ROBBANA	TG	*out of service*	4	1.02	---	15	32	---	---
83040	SFAX	TG	*out of service*	4	1.04	---	10	20	---	---
83041	SFAX	TG	*out of service*	4	1.04	---	10	20	---	---
83018	ZARZIS	TG	*out of service*	4	1.03	---	15	32	---	---
	TOTAL					**4005.8**		**4361.7**	**355.9**	**830.06**

** Legend:*

- *code 2: PV node*
- *code 3: slack node*
- *code 4: disconnected node*

The following table reports a different dispatching for the generators in service (unit commitment) where the total reserve is equal only to 60 MW according to the actual Maghrebian convention.

Tab. 5-6 – Generation dispatching in peak load conditions

Bus Number	Bus Name	Group	Note	Code*	V Sched [pu]	Pgen [MW]	P min [MW]	P max [MW]	Increase reserve [MW]	Qgen [Mvar]
83081	AOUSDJA	CC		2	1.03	380	240	380	0	129.51
83082	AOUSDJA	CC		2	1.03	380	240	380	0	129.51
83022	B.MCHERG	TG		2	1.05	90	40	100	10	25.42
83023	B.MCHERG	TG		2	1.05	90	40	100	10	25.42
83001	BOUCHEMA	TG		2	1.06	90	40	100	10	3.44
83057	EL BIBAN	TG		2	1.02	20	12	20	0	1.41
83027	FERIANA	TG		2	1.04	90	40	100	10	19.24
83076	FERIANA1	TG		2	1.04	107	40	107	0	19.24
83050	GHANOUCH	CC		2	1.06	380	240	380	0	12.21
83025	GOULETTE	TG		2	1.04	90	40	100	10	13.25
83008	RADES	TV		2	1.04	143	65	143	0	20.61
83009	RADES	TV		2	1.04	143	65	143	0	20.61
83010	RADES	TV		2	1.04	152	65	152	0	22.08
83011	RADES	TV		2	1.04	152	65	152	0	22.08
83030	RADES2	TG		2	1.04	100	50	100	0	14.72
83031	RADES2	TG		2	1.04	100	50	100	0	14.72
83032	RADES2	TV		2	1.04	228	120	228	0	30.92
83013	SOUSSE	TV		2	1.05	130	60	130	0	33.25
83014	SOUSSE	TV		2	1.05	130	60	130	0	33.25
83015	SOUSSE	TG		2	1.05	100	70	100	0	25.42
83016	SOUSSE	TG		2	1.05	100	70	100	0	25.42
83017	SOUSSE	TV		2	1.05	122	60	122	0	25.42
83074	SOUSSECC	CC	*slack*	3	1.01	380	240	380	0	95.45
83034	THYNA	TG		2	1.04	90	40	100	10	17.57
83072	THYNA	TG		2	1.04	104	40	104	0	17.57
83073	THYNA	TG		2	1.04	107	40	107	0	17.62
83002	BOUCHEMA	TG	*out of service*	4	1.06	---	15	24	---	---
83003	KAS.NORD	TG	*out of service*	4	1.06	---	15	26	---	---
83004	KAS.NORD	TG	*out of service*	4	1.06	---	15	26	---	---
83005	KORBA	TG	*out of service*	4	1.06	---	10	17	---	---
83006	KORBA	TG	*out of service*	4	1.06	---	15	26	---	---
83042	M BOURGU	TG	*out of service*	4	1.025	---	10	17	---	---
83043	M BOURGU	TG	*out of service*	4	1.025	---	10	17	---	---
83007	O.ZERGA	*n.d.*	*out of service*	4	1.00	---	0	0	---	---
83019	ROBBANA	TG	*out of service*	4	1.02	---	15	26	---	---
83040	SFAX	TG	*out of service*	4	1.04	---	10	17	---	---
83041	SFAX	TG	*out of service*	4	1.04	---	10	17	---	---
83018	ZARZIS	TG	*out of service*	4	1.03	---	15	26	---	---
	TOTAL					**3998.0**		**4297.0**	**60.0**	**815.36**

5.2.2 Minimum load

The following tables sum up the main characteristics of the system in minimum loading conditions.

Tab. 5-7 – Generation and load in minimum load conditions

	Actual		Nominal	
	[MW]	**[Mvar]**	**[MW]**	**[Mvar]**
From generation	1412.0	-421.6	1412.0	-421.6
To constant power load	1402.4	701.3	1402.4	701.3
To constant current	0	0	0	0
To constant admittance	0	0	0	0
To bus shunt	0	324.9	0	298.0
To facts device shunt	0	0	0	0
To line shunt	0	0	0	0
From line charging	0	1627.6	0	1476.6

Tab. 5-8 – Active and reactive losses in minimum load conditions

LOSSES						
Voltage		**Losses**		**Line shunts**		**charging**
Level [kV]	**Branches**	**[MW]**	**[Mvar]**	**[MW]**	**[Mvar]**	**[Mvar]**
400	9	0.49	5.60	0	0	493.20
220	113	5.25	55.70	0	0	713.80
150	55	3.10	11.66	0	0	173.40
90	62	0.75	2.86	0	0	243.10
15.5	13	0	103.50	0	0	0
11	1	0	0.44	0	0	0
0	1	0	0	0	0	4.10
TOTAL	**254**	**9.59**	**179.77**	**0**	**0**	**1627.60**

Tab. 5-9 – Generation dispatching in minimum load conditions

Bus Number	Bus Name	Group	Note	Code	V Sched [pu]	Pgen [MW]	P min [MW]	P max [MW]	Decrease reserve [MW]	Qgen [Mvar]
83081	AOUSDJA	CC		2	1.045	240	240	400	0.00	-104.87
83057	EL BIBAN	TG		2	1.00	12	12	27.5	0.00	-2.05
83050	GHANOUCH	CC	*slack*	3	1.00	240	240	400	0.00	-87.06
83008	RADES	TV		4	1.065	65	65	160	0.00	-13.99
83009	RADES	TV		2	1.065	65	65	160	0.00	-13.99
83010	RADES	TV		2	1.065	65	65	170	0.00	-13.99
83011	RADES	TV		2	1.065	65	65	170	0.00	-13.99
83030	RADES2	TG		2	1.065	50	50	115.5	0.00	-9.99
83031	RADES2	TG		2	1.065	50	50	115.5	0.00	-9.99
83032	RADES2	TV		2	1.065	120	120	240	0.00	-24.98
83015	SOUSSE	TG		2	1.03	70	70	118.5	0.00	-20.27
83016	SOUSSE	TG		2	1.03	70	70	118.5	0.00	-20.27
83017	SOUSSE	TV		2	1.03	60	60	128	0.00	-20.27
83074	SOUSSECC	CC		2	1.03	240	240	400	0.00	-65.87
83082	AOUSDJA	CC	*out of service*	2	1.045	---	240	400	---	---
83022	B.MCHERG	TG	*out of service*	4	1.03	---	40	120	---	---
83023	B.MCHERG	TG	*out of service*	4	1.03	---	40	120	---	---
83001	BOUCHEMA	TG	*out of service*	4	1.07	---	40	120	---	---
83002	BOUCHEMA	TG	*out of service*	4	1.07	---	15	27.5	---	---
83027	FERIANA	TG	*out of service*	4	1.03	---	40	110	---	---
83076	FERIANA1	TG	*out of service*	4	1.03	---	40	110	---	---
83025	GOULETTE	TG	*out of service*	4	1.065	---	40	120	---	---
83003	KAS.NORD	TG	*out of service*	4	1.06	---	15	32	---	---
83004	KAS.NORD	TG	*out of service*	4	1.06	---	15	32	---	---
83005	KORBA	TG	*out of service*	4	1.06	---	10	20	---	---
83006	KORBA	TG	*out of service*	4	1.06	---	15	32	---	---
83042	M BOURGU	TG	*out of service*	4	1.025	---	10	20	---	---
83043	M BOURGU	TG	*out of service*	4	1.025	---	10	20	---	---
83007	O.ZERGA	*n.d.*	*out of service*	4	1.00	---	0	28	---	---
83019	ROBBANA	TG	*out of service*	4	1.02	---	15	32	---	---
83040	SFAX	TG	*out of service*	4	1.02	---	10	20	---	---
83041	SFAX	TG	*out of service*	4	1.02	---	10	20	---	---
83013	SOUSSE	TV	*out of service*	4	1.03	---	60	150	---	---
83014	SOUSSE	TV	*out of service*	4	1.03	---	60	150	---	---
83034	THYNA	TG	*out of service*	4	1.02	---	40	119.4	---	---
83072	THYNA	TG	*out of service*	4	1.02	---	40	119.4	---	---
83073	THYNA	TG	*out of service*	4	1.02	---	40	119.4	---	---
83018	ZARZIS	TG	*out of service*	4	1.03	---	15	32	---	---
	TOTAL					**1412**			**0.00**	**-421.58**

It is worth noting that in the minimum loading condition the units is service are at their technical minimum; hence, we have a very constrained situation where the system hasn't any margin to cope with unforeseen decrease of the load with respect to the estimated pattern or sudden increase in wind generation in case of presence of wind farms. As a consequence, to cope with these events, which can normally occur, one shall rely on the interconnection capability with Algeria or, in the future, on the HVDC link with Sicily. Alternatively, a less constrained unit dispatching shall be decided where the overall generation set has a downward reserve margin (see Fig. 3-7).

5.3 Dynamic data of generating units

STEG provided CESI through ELMED Etudes a PSS/E file concerning dynamic data of generating units. It includes:

- Generator parameters (time constants, reactances, etc.);
- Type and data of AVR;
- Type and data of GOVERNOR;
- Type and data of PSS.

The types of generators are:

- GENROU: Round Rotor Generator Model (Quadratic Saturations)
- GENSAL: Salient Pole Generator Model (Quadratic Saturation on d-Axis)

The types of Automatic Voltage Regulators are:

- SEXS: Simplified Excitation System Model
- EXAC1: 1981 IEEE type AC1 Excitation System Model
- EXAC2: 1981 IEEE type AC2 Excitation System Model
- IEEEX1: 1979 IEEE type 1 Excitation System Model and 1981 IEEE type DC1 Model
- IEEET1: 1968 IEEE type 1 Excitation System Model
- IEEX2A: 1979 IEEE type 2A Excitation System Model
- EXBAS: Basler Static Voltage Regulator feeding DC or AC Rotating Exciter Model.

The types of Governors are:

- IEEEG1: 1981 IEEE type 1 Turbine-Governor Model
- GAST2A: Gas-Turbine Governor Model
- GAST: Gas-Turbine Governor Model
- GASTWD: Gas-Turbine Governor Model
- IEESGO: 1973 IEEE Standard Turbine Governor Model

The type of Power System Stabilizer is:

- IEEEST: IEEE Stabilizing Model

Tab. 5-10 summarises the situation of dynamic elements presents in the Tunisian network: the types of AVR, Governor and PSS are reported with the information if they are in service or not.

Tab. 5-10 – Map of dynamic components associated to the generating units.

Bus Number	Bus Name	Generator	Exciter	In Service	Governor	In Service	Stabilizer	In Service
83081	AOUSDJA	GENROU	SEXS	1	IEEEG1	1	None	0
83082	AOUSDJA	GENROU	SEXS	1	IEEEG1	1	None	0
83022	B.MCHERG	GENROU	EXAC2	1	GAST2A	1	None	0

Bus Number	Bus Name	Generator	Exciter	In Service	Governor	In Service	Stabilizer	In Service
83023	B.MCHERG	GENROU	EXAC2	1	GAST2A	1	None	0
83001	BOUCHEMA	GENROU	EXAC2	1	GAST2A	1	None	0
83002	BOUCHEMA	GENROU	IEEEX1	1	GAST	1	None	0
83057	EL BIBAN	GENSAL	EXAC1	1	GASTWD	1	None	0
83027	FERIANA	GENROU	IEEEX1	1	GAST2A	1	None	0
83076	FERIANA1	GENROU	IEEEX1	1	GAST2A	1	None	0
83050	GHANOUCH	GENROU	SEXS	1	IEEEG1	1	None	0
83025	GOULETTE	GENROU	IEEEX1	1	GAST2A	1	None	0
83003	KAS.NORD	GENROU	IEEEX1	1	GAST	1	None	0
83004	KAS.NORD	GENROU	IEEEX1	1	GAST	1	None	0
83005	KORBA	GENROU	SEXS	1	GAST	1	None	0
83006	KORBA	GENROU	IEEEX1	1	GAST	1	None	0
83042	M BOURGU	None	None	0	None	0	None	0
83043	M BOURGU	None	None	0	None	0	None	0
83007	O.ZERGA	None	None	0	None	0	None	0
83008	RADES	GENROU	IEEEX1	1	IEEEG1	1	None	0
83009	RADES	GENROU	IEEEX1	1	IEEEG1	1	None	0
83010	RADES	GENROU	IEEET1	1	IEEEG1	1	None	0
83011	RADES	GENROU	IEEET1	1	IEEEG1	1	None	0
83030	RADES2	GENROU	IEEX2A	1	GAST2A	1	IEEEST	1
83031	RADES2	GENROU	IEEX2A	1	GAST2A	1	IEEEST	1
83032	RADES2	GENROU	IEEX2A	1	IEEEG1	1	IEEEST	1
83019	ROBBANA	None	None	0	None	0	None	0
83040	SFAX	GENROU	SEXS	1	GAST	1	None	0
83041	SFAX	GENROU	SEXS	1	GAST	1	None	0
83013	SOUSSE	GENROU	IEEEX1	1	IEEEG1	1	None	0
83014	SOUSSE	GENROU	IEEEX1	1	IEEEG1	1	None	0
83015	SOUSSE	GENROU	EXBAS	1	GAST2A	1	None	0
83016	SOUSSE	GENROU	EXBAS	1	GAST2A	1	None	0
83017	SOUSSE	GENROU	EXBAS	1	IEESGO	1	None	0
83074	SOUSSECC	GENROU	SEXS	1	IEEEG1	1	None	0
83034	THYNA	GENROU	IEEEX1	1	GAST2A	1	None	0
83072	THYNA	GENROU	IEEEX1	1	GAST2A	1	None	0
83073	THYNA	GENROU	IEEEX1	1	GAST2A	1	None	0
83018	ZARZIS	GENROU	IEEEX1	1	GAST	1	None	0

Legend:

- In service: 1 yes; 0: no.

5.4 Transmission network

In the PSS/E files provided to CESI, a detailed representation of the Tunisian transmission network is present. In particular, the following voltage levels are detailed:

- 400 kV
- 220 kV
- 150 kV
- 90 kV.

Moreover, for all transmission lines the (thermal) limits of the current are available: this is key information particularly for task B where the network reinforcements will be identified, depending on the location of the new ELMED power plant, to comply with the security criteria.
In addition to the generating units already mentioned above, the following networks elements are present in the model:

- busses
- power withdraw points (loads)
- shunt Var compensation devices
- branches (lines or cables)
- 2-winding transformers.

Focusing on 400 kV transmission components, the following lines are present in the basic configuration:

- Mornaguia – Mateur;
- Mornaguia – Aousdja;
- Mornaguia – Oueslatia;
- Mornaguia – Mnihla;
- Jendouba – Mateur;
- Aousdja – T. Telecom City;
- Oueslatia – Bouchemma;
- P. Financier – T. Telecom City;
- P. Financier – Mnihla.

A preliminary representation of 400kV Tunisian transmission lines is reported in Fig. 5-1.

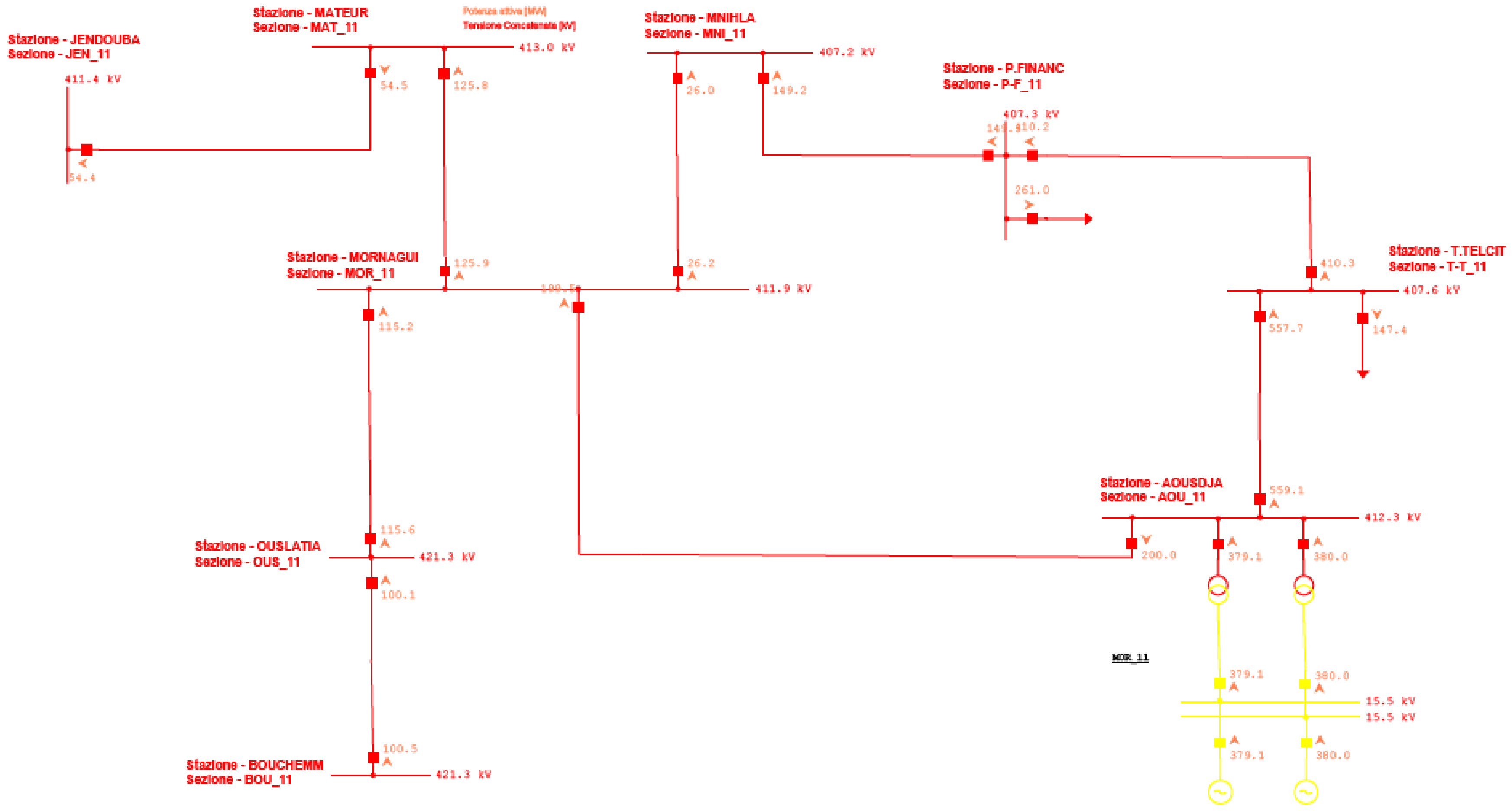


Fig. 5-1 – 400kV Tunisian transmission lines

5.5 Equivalent model for the rest of the Maghreb

Fig. 5-2 shows the interconnections between Tunisia and the neighbouring countries. The map shows that Tunisia, Algeria and Morocco are connected in AC with Spain and are part of the ENTSO-E/SCR area; instead, the lines between Tunisia and Libya are considered always opened in our analysis.

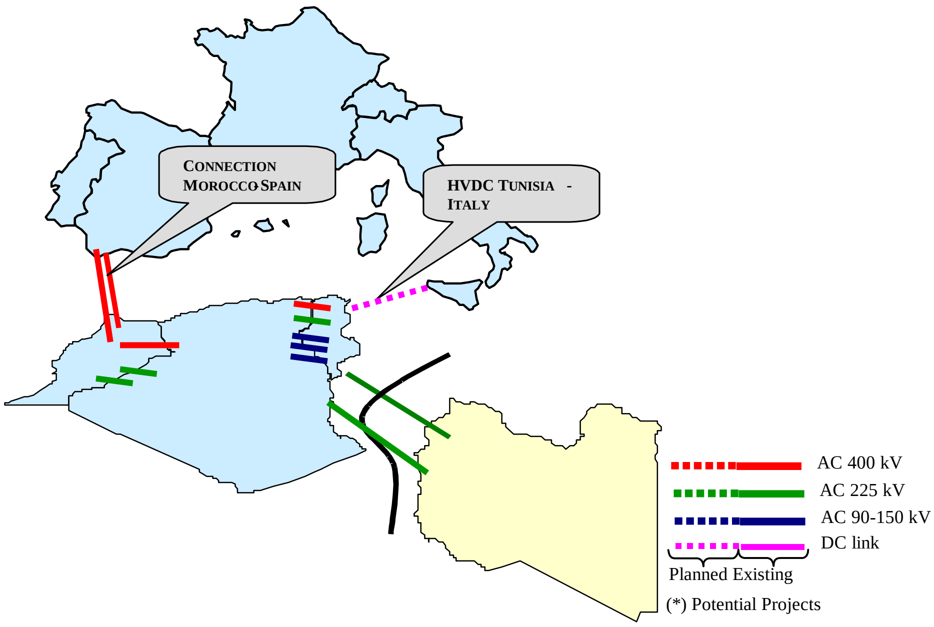


Fig. 5-2 – Interconnections among Tunisia and other countries

Hence, an equivalent dynamic model of Algeria, Morocco and ENTSO-E/SCR is necessary for the execution of the dynamic analyses.
Upon agreement with ELMED Etudes, STEG and Terna[14], the equivalent models of the other Maghreb countries and ENTSO-E/SCR are provided by CESI. These equivalent models have already been used by CESI and validated in the framework of the studies [4], [5], [6] carried out in the year 2009. Two models are provided: the first one for the peak load conditions and the other one for the low load conditions. The equivalent models include the dynamic characteristics of the systems external to Tunisia with an appropriate representation of Algeria and Morocco including the dynamic contribution of ENTSO-E/SCR (inertia and short circuit power).
After having joined the equivalent model with the Tunisian system in both loading conditions, we verified the coherency of the overall interconnected system model with the results obtained when running load flows considering the Tunisian system alone. Specifically, we checked, among others:

- the net power flow at the border Tunisia-Algeria which shall be negligible[15];
- the voltage profile inside Tunisia;
- the power flows and losses inside Tunisia.

[14] See the “conference call” on 8th June 2010 and related Minutes of Conference
[15] The net flow turned out to be less than 4 MW, due to some loop flows across the border.

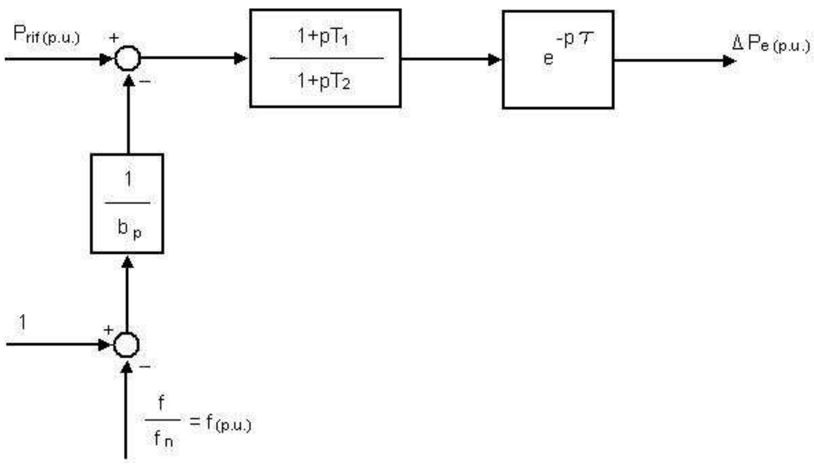
5.6 Tunisia-Sicily interconnection model

The HVDC link from El Hawaria 400 kV to Partanna 380/220 kV will have a size of 1000 MW. This connection will be modelled as a “special load” in SICRE with the active and reactive power exchanges managed by adequate control systems, representing the behaviour of the control systems in the converter stations. This model allows us to simulate the dynamic effects on the Tunisian network due to the HVDC link, without a complete representation of converters and DC transmission line parameters.

The converters are modelled as time-variable active and reactive injections with associated the controls and regulations in order to simulate the electromechanical behaviour in the usual operating conditions of the DC link.

The most important control associated to this model is the Primary Frequency Regulation, whose block diagram is represented below. The symbols have the following meaning:

- $P_{rif(p.u.)}$ active power reference (in per unit)
- f real frequency at HVDC station
- f_n nominal frequency (equal to 50Hz)
- b_p HVDC droop for frequency regulation
- T_1, T_2 zero and pole time constants
- τ delay in dynamic response
- ΔPe change in the set point of active power



The associated transfer function is the following:

$$\boxed{\Delta P_{e(p.u.)} = \frac{1}{b_p}\cdot\frac{1+sT_1}{1+sT_2}\cdot e^{-s\tau}\cdot\Delta f_{(p.u.)} = F(s)\cdot e^{-s\tau}\cdot\Delta f_{(p.u.)}}$$

This relation shows that the HVDC control system modifies the active power reference according to its regulating energy and according to frequency deviation: if frequency increases, the active power reference will be decreased and vice-versa.

This type of regulation takes into account also the following limits:

- minimum value of active power in export;
- minimum value of active power in import;
- maximum value of active power in export;

- maximum value of active power in import;
- maximum active power gradient during the transitory.

Moreover, the model owns the following functions:

- at the occurrence of external faults, if the voltage to HVDC station becomes too low, the system is switched off until the voltage comes back to a correct level: in this way a temporary interruption of DC link is considered;
- the losses can be modelled as a percentage of nominal power;
- the power flow can be inverted, if necessary, to import in Tunisia;
- the reactive power absorbed by the converters can be modelled according to the active power flow and to the controls adopted;
- the effects of reactive power compensation (typically associated to filters) can be considered.

The accuracy of this HVDC model has been tested by comparing its dynamic response with that obtained from a detailed modelling of all the main components of the link. Tests have been applied to the SACOI and SAPEI HVDC links.

6 WIND ENERGY PRODUCTION

6.1 Wind farm sites proposed by the STEG

The impact of wind energy production on the network is valuated starting with the sites proposed by the STEG and the maximum wind energy power that can be generated at each site. CESI shall execute static and dynamic simulations to determine the most suitable connection substations as well as the maximum acceptable capacity, taking into account the possibility of exporting power to Sicily, and the regulation characteristics of the AC/DC converters.

The table below presents the data of the wind farms to be analysed. The priority for introducing wind energy production is described in stage 2 of Task C.

Table 6-1 – Wind farm sites proposed by the STEG

Name of the site	Region	Coordinates of the measuring equipment	Proposed converter station	Wind speed at 30 m (m/s)		Estimated capacity factor for a 1500 kW turbine (%)	Potential wind power (MW)
				Annual average	Maximum annual average		
Sidi Daoued (1)	Cap Bon	N 37°01' 48.5'' E 10°55' 43.1''		8	13	30	54
Metline (2)	Bizerte	N 37°14' 33.9'' E 10°02' 10.8''		9.5	15	38	97
Kechabta (2)	Bizerte	N 37°06' 27.0'' E 09°56' 35.5''		8.8	15	35	93
Ben Aouf	Bizerte	N 37°18' 51.9'' E 09°46' 36.4''		9.2	15	37	25
Jebel Abderrahmen	Cap Bon	N 36°50' 29.7'' E 10°46' 34.4'		9.8	13	39	200
Ferkik	Kerkennah	N 34°48' 22.5'' E 11°15' 45.2''		6.5	8	-	40
Akarit	Gabés	N 34°08' 14.9'' E 09°55' 38.3''		6.8	-	-	50
Sidi Mechreg	Bizerte	N 37°10' 02.7'' E 09°08' 04.6''		6.5	-	-	40
Jbel Tbaga	Kébili	N 33°44' 49.0'' E 09°09' 07.0''		6.8	7.8	-	150
Thala (3)	Kasserine	N 35°33' 20.1'' E 08°39' 46.1''		7	-	22	60
Zonkar (4)	Bizerte	-		8	-	32	200

(1): Existing power plant
(2): Power plant currently being installed (to be put in service by the end of 2012).
(3): Data collected by ANME.
(4): Incomplete data.

6.2 Model of wind energy production

There are two main ways of connecting the wind energy generators to the network:

- Synchronous connection;
- Asynchronous connection.

As the type of generator shall be chosen by the investor, our best approach at this stage of the study is to consider a Double Fed Induction Generator (DFIG). There are two reasons for this:

- This is the most commonly used type of generator. It accounts for more than 70% of all generators in Italy and the same applies in Spain;
- It is “hybrid” in nature, in that it is an asynchronous alternator with excitation. Consequently, the unit can control reactive power in a manner similar to that of synchronous units.

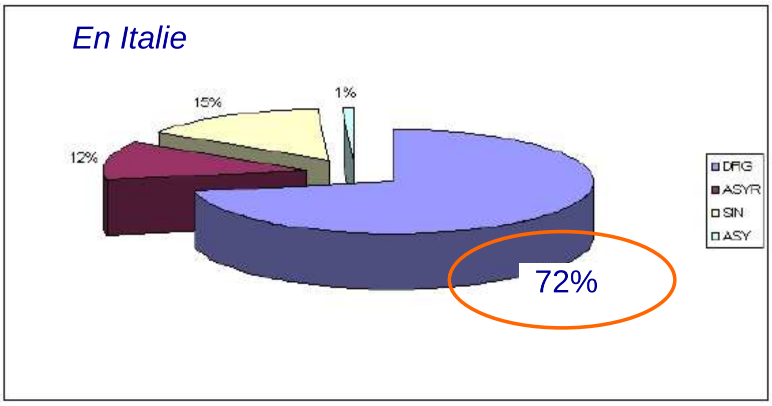


Fig. 6-1 – The type of wind energy units used in Italy

Legend: DFIG: Double Fed Induction Generator;
ASYR: asynchronous unit with variable resistance of the rotor;
SIN: synchronous unit (connected to the network via a converter)
Asy: asynchronous unit

The DFIG units consist of an asynchronous generator with a stator connected directly to the network and a rotor powered by an AC/AC converter.

The configuration of the DFIG is shown in the figure below (Fig. 6-2).

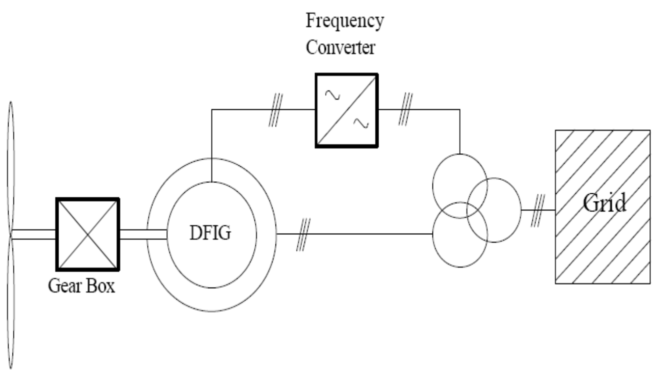


Fig. 6-2 – Model of a DFIG unit

The benefits of this generator are:

- The capacity to work at different wind speeds, as the (AC/AC) converter is able to change the current frequency of the rotor, so the frequency of the stator variables is always equal to its nominal value (50 Hz);
- Lower costs (compared to configuration with a synchronous generator connected, via a stator, to the AC/AC frequency converter), as the converter, generally the most expensive component, is sized for only 30% of the nominal power.

This model clearly produces active power which depends on wind speed at all times, as shown in the graph in Fig. 6-3. In the example, the nominal speed is 12 m/s.

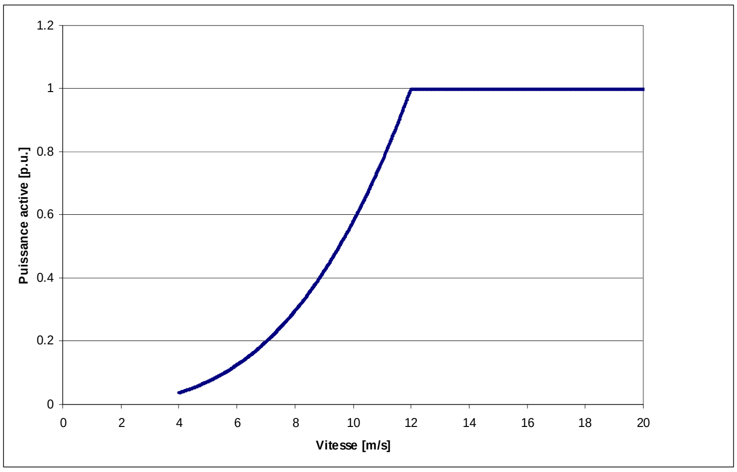


Fig. 6-3 – Active power produced according to wind speed

In the simulator, the model is divided into four sub-models (Wind Model, Aerodynamic Model, Mechanical Model, Electrical Model[16]) as shown in the diagram below (Fig. 6-4). A control system controls and regulates all the units.

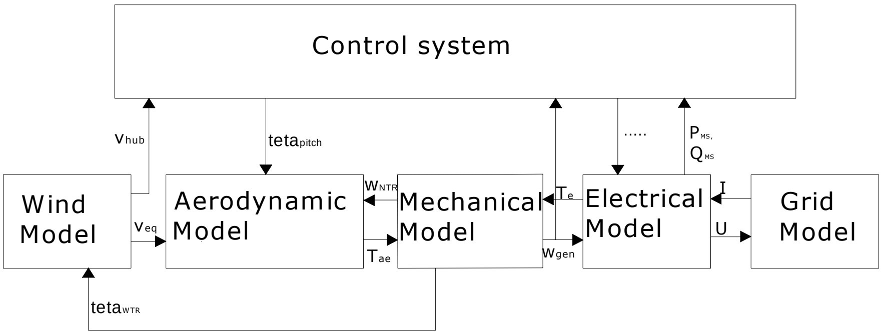


Fig. 6-4 – Model of the wind energy unit

The models have the following functions:

- "Wind Model": simulates wind fluctuations; its output is instantaneous wind speed;
- "Aerodynamic Model": calculates the wind power with the classic formula:

$$P_w = \frac{1}{2} \cdot C_p \cdot \rho \cdot \pi \cdot R^2 \cdot v^3$$

[16] Wind model, aerodynamic model, mechanical model, electrical model

where:
v: *wind speed;*
Cp: *aerodynamic efficiency;*
ρ: *air density;*
R: *radius of the propeller blades.*

- "Mechanical Model": simulates operation of the gearbox, but is not generally used and the aerodynamic power and mechanical power are effectively the same at all times;
- "Electrical Model": the only model connected to the network; it represents the action of the asynchronous generator and calculates the active and reactive power produced by the wind energy unit.

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ANNEX 1. PRIMARY, SECONDARY AND TERTIARY RÉGULATION

A1.1 Primary regulation

It is well known that the sudden loss of a generating unit (or tripping) causes a drop (or increase) in network frequency. Frequency deviation is dynamic in nature and associated with the regulation loops. Fig. A-0-1 shows the typical curve of frequency in the case of primary regulation; the deviation is caused by unbalancing of power in the system (tripping of a unit).

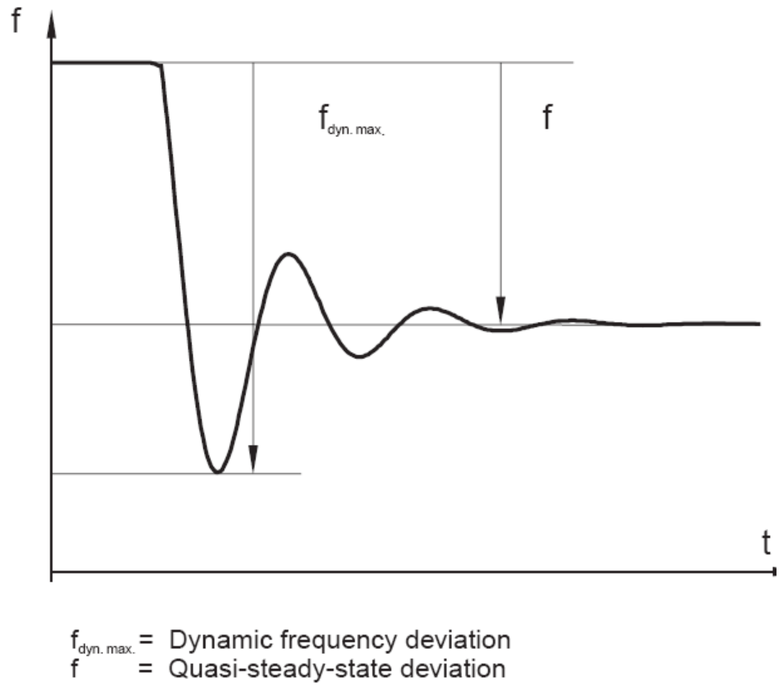

Fig. A-0-1 – Typical course of frequency after intervention of primary regulation (source [1])

The network operators (ENTSO-E in Europe [1]) set the rules for the maximum decrease (increase) in frequency during deviation and idle time after disturbance. ENTSO-E/SCR refers to the tripping of the largest units (loads).
The maximum dynamic variation in frequency is essentially due to:

- The value and dynamics of the disturbance that caused unbalanced between production and demand;
- The kinetic energy of the rotating units (or, in other words, their inertia)
- The number of generators subject to primary regulation, the primary regulation band and location among the regulation units;
- The dynamic properties of the production units;
- The dynamic properties of the loads (in particular, their reactions to frequency errors).

The maximum static variation in frequency is essentially due to:

- The droop values of the generators during primary regulation;
- The sensitivity of the power absorbed by the loads upon variations in frequency.

In Europe, the ENTSO-E rules [1] state that the interconnected system must always be exploited to make up for a sudden loss in production of 3000 MW using only primary regulation with the constraint that the frequency should not fall below 49.2 Hz. On the other hand, a sudden loss in load of 3000 MW should be managed with primary regulation in such a way as not to increase frequency to above 50.8 Hz. Moreover, the corresponding static error during operation should not exceed ±180 MHz, with a load auto-regulation effect of 1%/Hz.
The regulating energy of a control area (e.g. Tunisia or Italy) is calculated using this formula:

$$\lambda_i = -\frac{\Delta P_i}{\Delta f} \qquad (1)$$

where:
λ_i : the regulating energy of the control area (in MW/Hz);
Δf : frequency variation during operation (in Hz) due to disturbance that causes unbalance ΔP;
ΔP_i : power variation in a control area (in MW) due to disturbance ΔP, measured at the border of the area concerned.

To respect the limits of primary regulation, it has been established that in Europe the regulating energy of the interconnected system should remain under the threshold of 15000 MW/Hz at an average value of 19500 MW/Hz. Each area of the interconnected system has to agree upon a minimum contribution coefficient (e.g. in 2006, this coefficient stood at 0.1106 for Italy).

A1.2 Secondary regulation

Primary frequency regulation restores the balance between production and demand at a frequency value other than the nominal value. As all the control areas involved in an interconnected system contribute to primary regulation with consequent variation in production and demand in each area, unbalancing in a single area eventually affects the exchange of power in relation to the set value. The purpose of secondary regulation is therefore to reset the frequency error and restore the exchanges of power in the control areas to the set values.
The secondary regulator in each area has to reset the exchange frequency-power error (ACE: Area control error) G_i as follows:

$$G_i = \Delta P_i + K_{ri}\Delta f \qquad (2)$$

where:
G_i : frequency-power error (in MW) of the *i* area (ACE = Area Control Error);
ΔP_i : power exchange error (in MW) of the *i* area in relation to the set value;
Δf : frequency error calculated as the difference between the instantaneous value and the nominal frequency value (in Hz);
K_{ri} : parameter of participation (in MW/Hz) of the secondary regulator.

The secondary regulator has to have a proportional-integral transfer function to ensure an adequate degree of static and dynamic precision:

$$\Delta P_{di} = -\beta_i G_i - \frac{1}{T_{ri}} \int G_i dt \qquad (3)$$

where:

ΔP_{di} : level signal of the secondary regulator (in MW);
β_i : proportional gain of the secondary regulator (in MW/MW);
T_{ri} : time constraint of the secondary regulator (in s).

To ensure secondary regulation is executed only in the area that caused the disturbance (criteria of non-interaction between the areas, on both a static and dynamic level), the value K_{ri} has to be the same in each area as the « regulating energy » value λ_i in the same area. This constraint theoretically involves constant variation of the K_{ri} parameter to take into account the generators in service at the time. Moreover, independent correction of the K_{ri} values could cause difficulties due to lack of coordination among the secondary regulators of the various areas. To avoid this problem in the case of the interconnected systems, the K_{ri} values are set the centralised level to guarantee good coordination among all the areas of the system. ENTSO-E sets these coefficients in Europe.

A1.3 Tertiary regulation

Tertiary regulation consists of automatic or manual actions that cause a variation in the production of the units, in order to:

- Guarantee an adequate secondary reserve at all times,
- Distribute the power of secondary regulation as best as possible among the generators (to minimise costs).

Changes to the units' production profile due to tertiary regulation can be made by doing the following:

- Starting or stopping the generators (gas turbines, pump stations), or increasing or decreasing the power produced by the generators already in service;
- Redistribution of the power of the generators involved in secondary regulation;
- Changes to the plans for exchanging power with neighbouring areas;
- Load shedding.

In general, tertiary regulation can have the same impact on the electrical system as secondary regulation, even if the operations involved in tertiary regulation are temporally associated with the actions of programming the exploitation.