Deliverable 2.1.2

Mediterranean Master Plan of Interconnections

Network Analysis Guidelines

Network Analysis and Reinforcement Assessment

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“Mediterranean Project”

Task 2 “Planning and development of the Euro-Mediterranean Electricity Reference Grid ”

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1 Object and scope

This document describes the process followed by the Consortium (hereinafter CON) to run the power flow and contingency analysis over the different snapshots built in the context of the Mediterranean Master Plan of Interconnections, and the procedure to assess the identified reinforcements.

The document is structured as follows:

- Section 2 describes the Network Studies, namely, the data acquisition and the snapshots building processes;
- Section 3 presents the Security Analysis assumptions, namely, the criteria for contingency selection and the network model for carrying out the Network Studies;
- Section 4 describes the process for reinforcements' assessment;
- Section 5 highlights the most important results and draws conclusions for each project considered.

2 Network studies

The purpose of the Network Studies is to assess the adequacy of the interconnected Mediterranean network in terms of transmission capacity based on load flow calculations. More specifically, these studies aim at:

- determining the ability in terms of available transmission capacity of the interconnected Mediterranean network to transfer the power flows resulting from the energy scenarios considered in the context of the market studies taking into account security criteria, both in normal situations and in cases of disturbances
- identifying possible criticalities for the future development of interconnections, in terms of bottlenecks, on both interconnections and internal grids

The tasks consist in building the reference network model of the interconnected Mediterranean system on a regional basis, as an aggregate of national grid models, taking into account the planned reinforcements of internal grids and interconnections, which are included in the National Development Plans provided by the TSOs.

2.1 Data acquisition

The snapshots analyzed during this phase will be the result of the blend between the ones deriving from the "Market Studies" market studies and the networks of the involved interconnected power systems. Each considered interconnection project affects directly to a set of countries that need their network fully modeled to obtain valid reinforcement plans. The following paragraphs describe the data sources used during the snapshots building process.

PiT (Point in Time) files

A PiT contains, the demand, the generation and the energy interchanges as well as the dispatch of the snapshot for each country involved along with a breakdown of the used generation technologies. PiTs are balanced without considering losses, i.e. generation is equal to the demand plus the energy exported. Therefore, the active power losses estimated during the security analysis are subtracted from the demand.

Models for the different networks

Most of the network models have been provided by TSOs in PSS/E® format, while several are come in EXCEL files. Each file contains the basic information needed to build a power flow model. These information include buses (identification, type, nominal voltage...), generating units (location, technology, limits of operation...), branches (parameters, rates, status...), loads (location, status...) and areas.

Interconnections

The existing and the planned interconnections are described so as to incorporate them into the network model. This description includes the interconnected buses location, technology (HVAC or HVDC), length, parameters and rate.

Security criteria

To run the security analysis, several features of the security criteria are set The branches thermal rates are specified, as well as a compensation factor to consider the deviation from active power flow and the maximum apparent power, since the reactive power flows are not computed. Voltage ranges are defined in order to both identify those branches, which have to be watched out during the security analysis, and to establish the branches to be opened during the N-1 security analysis. Finally, some N-2 combinations are also considered.

2.2 Snapshots building process

The snapshot building process is the same for each project and starts by loading the networks of the involved systems. The corresponding network to be used will match the Scenario (S1, S2, S3 or S4) and seasonality (Winter or Summer). The uploaded network is checked in order to guarantee that it is fully operable, having verified the presence of electric islands or irregular parameters in lines, transformers or generating units.

The next step consists in merging them, this process involves both existing and planned interconnections. HVAC interconnections are added by defining corresponding interconnection buses in the boundary between systems at both sides and joining them using a low-impedance branch whenever there is no information regarding the actual impedance of the new link. HVDC interconnections are point-to-point links, thus, each is modeled as a pair of loads placed at corresponding substation and with positive or negative demand depending on whether the energy through the HVDC link is imported or exported.

Records on generation, demand and interchanges between systems as defined in the PiT are thus incorporated to the merged network model.. Generation dispatch comes with a breakdown of technologies (gas, nuclear, carbon, thermal solar, solar PV, wind, etc.). Since all generating units have their identified technology these are dispatched according to a defined merit order, and proportionally to their margin. If the connected units do not have enough margin to cover the energy to be dispatched, then the status of units will be also redefined. If the sum of maximum power limits of connected units is lower than the energy which needs to be dispatched, then switched off units are connected. On the contrary, if the sum of the minimum power limits of connected units is greater than the energy to be dispatched, some connected units will be turned off. Finally, the energy interchanges between networks are set up in the system. The next step is to test the snapshot (DC power flow, interchanges, initial overloads, losses estimation…) and save it in PSS/E v33 format.

3 Security analysis

The internal transmission network adequacy is assessed by running a security analysis over the different snapshots built in the previous step. The security analysis focuses on potential overloads on the transmission network, not only in the base case situation, but also in N-1 and N-2 situations. The energy lost for outage of generating units is compensated using different criteria, namely, generating unit redispatch, and/or by using the existing interconnections with other countries. . Security criteria considered have been agreed with corresponding TSOs in order to take into account the peculiarities of each network.

3.1 Contingency selection

The selection of contingencies to be run is a key issue in the security analysis. The vast majority of outages considered correspond to N-1 criteria, i.e., to switch off only one element of the network.

3.1.1 N-1 for branches

First set of contingencies considered corresponds to the outage in the network of one branch at a time , i.e. a line or a transformer. The criterion to select the branches for contingency analysis is the nominal voltage.

The table below contains the voltages levels, minimum and maximum, of lines and transformers to be considered in the outages set.

		Voltage levels [kV]	
	System	**min**	**max**
2	Algeria DZ	220	400
3	Cyprus CY	132	132
4	Egypt EY	220	500
6	Greece GR	400	400
8	Italy IT	150	500
9	Jordan JO	400	400
11	Libya LY	220	400
13	Morocco MA	150	400
15	Portugal PT	150	400
17	Spain ES	220	400
18	Syria SY	230	400
19	Tunisia TN	150	400
20	Turkey TR	400	400
22	Bulgaria BG	220	400

Table 1 – Nominal voltage levels for lines and transformers outage selection

It is important to highlight that the interconnection lines (existing or planned) are not included in this set. Contingency of interconnections are defined at a later stage.

3.1.2 N-1 for generating units

The N-1 outage of generating units implies the removal of one unit at a time. This process was based on indications by the TSOs. Hence, in some projects, the units selected to be tripped are those with the largest active power maximum capacity from each bus with generation resources. Outage of the slack bus is not considered. In other projects, the N-1 contingency of all was also considered.

This set of contingencies implies energy unbalance in the system, thus an active power redispatch is required after an outage has been applied. The main criterion selected for energy compensation is internal compensation. Thus, the lack (or surplus) of energy due to the loss of a generating unit or of an interconnection is balanced by the generating units of the full systems involved. Other criterion can be defined, namely to strategically place the reference bus to simulate the increase/decrease of import/export power from external interconnected systems.

3.1.3 Interconnections

Outage of an interconnection implies energy unbalance in the interconnected systems and modifications on the planned exchanges. As well as in the N-1 of generating units, the contingency of an interconnection implies energy unbalance in the system, thus an active power redispatch is required after the outage occurs . The compensation criteria applied depends on the sign of the unbalance (i.e. if the interconnection is exporting or importing energy).

3.1.4 N-2 outages

For each project, a set of critical N-2 outages was specified. These multiple outages include the network elements close to the planned interconnections, double-circuit failure, multiple end circuits, combination of interconnection and other circuits, or combination of circuits placed at some level of proximity to the interconnections.

3.2 DC power flow (DCPF) as tool for the security analysis

Power flow is the basic tool for solving AC power circuits. State equations of AC power circuits are non-linear, thus power flow must be designed as an iterative process. Due to the subsequent computational effort, in case of many solutions should be computed in a short time, then linearization techniques become very useful. Among all the linearization techniques in the literature applied to power flow equations, the most widely linearized model of an AC power circuits is the classic DC power flow (DCPF).

DCPF consists of the linearization of the active power state-equations in the AC power circuit with respect to only bus voltages angles, plus some other simplifications. One of the most special features of DCPF is that the resulting model consists of an analogous DC circuit, where voltages represent angle of bus voltages, and currents represent active power flows.

Main features that make DCPF a very useful tool are [1] linearity, uniqueness of solution, simplicity of methods and software, minimization of required input data and great accuracy, among others. All those features are the reason why DCPF has been incorporated to many tools and applications for energy systems assessment. In addition, the alternative of using full AC power flow implies more computing time, more data to be collected (shunts, setting of generating voltage, etc.), plus the risk of having convergence issues. Thus DCPF allows evaluating larger set of network situations quicker, despite the simplifications.

First simplification to formulate the DCPF is to consider that all branches are modelled using only their series reactance, i.e. neglecting series resistance and shunt susceptance. Considering this simplification, active power flow through reactance is simplified as follows.

$$P_{i>j} = \frac{|V_i|\cdot|V_j|}{xs_{ij}} \sin\left(\theta_i - \theta_j\right) \sim \frac{\theta_i - \theta_j}{xs_{ij}} \qquad (0)$$

Approximation (0) has been formulated assuming that bus voltages magnitude are equal to 1.0 pu, and using first-order Taylor series about the point $\theta_i - \theta_j = 0$. The result is a linear approximation of the active power flow that reminds the Ohm's law in DC circuits.

Although this approximation usually performs well, it can be improved by incorporating an estimation of the active power losses . To do that, the resulting system of linear equations must be solved twice. First solution is run without considering active power losses. Once this first solution has been computed, is used to estimate the active power losses at each of the branches with the Joule's law, i.e $rs_{ij}\left|I_{i>j}\right|^2$. If the magnitude of bus voltages is equal to 1.0, then the magnitude of the series current is approximated by the magnitude of the apparent power flow.

$$\left|I_{i>j}\right|^2 \sim \left|P_{i>j}\right|^2 = \left(\frac{\theta_i - \theta_j}{xs_{ij}}\right)^2 \qquad (0)$$

Once the active power losses have been estimated they are incorporated to the model as extra loads. For each of the branches, its losses are split into two halves and placed as extra loads at corresponding buses. This second solution with active power losses incorporated provides much better results than the original formulation of the DCPF.

In addition to the aforementioned advantages, the DCPF results to be very useful to run N-x security analysis. AC power flow could need many iterations to converge under contingency, even it may diverge. On the contrary, DCPF is linear and behaves as a linear circuit, thus recomputation of the solution is much faster.

For several specific snapshots, where voltage might be critical for the security of the system, TSOs required to run the contingency analysis using full AC.

4 Assessment of reinforcements

The assessment of reinforcements was carried out based on the maximum overload of each of the circuits after the security analysis. Firstly, the overloads were ranked according to their value and location in the network. Secondly, proposals for reinforcements were discussed with the TSOs to select the most effective to solve the overloads. Thirdly, the ability of the reinforcements selected to solve the overloads was determined by running the security analysis once again. This process was followed until the critical overloads have been tackled.

The process for the assessment of reinforcements in the projects with significant overloads in the base case were determined based on a differential analysis approach. In basic terms, the differential analysis consists on running the security analysis with and without project to determine the increase in the circuits' maximum overload. Redispatch of generating units for the same PiTs was carried out in the security analysis without the project to remove the cross border interchanges in the new project. The circuits with significant increase in the maximum overload were selected for reinforcement. A threshold for the difference of the maximum overload in percentage of the circuits' thermal rate was used for the selection process. Hence, if the maximum overload in a given circuit increased more than 15% of its base rate, then the circuit was reinforced.

The assessed reinforcements included reconductoring interventions/duplication of existing transmission lines and the installation of new transmission lines, new transformers and new substations.

5 Power losses calculation

The variation of active power losses with and without project was also determined for all PiTs. The losses in each system were determined with the new interconnection projects and without the new interconnection projects. The set of reinforcements determined were considered to determine the losses with project. Generation redispatch was used in the case without project.

The annual losses in the new interconnection projects were determined following the expected hourly MW flows.

- In the case of HVDC, the losses include the converter station losses as well as the cable losses;
- In the case of HVAC, the losses include only the cable losses.

The following equations were used to estimate the losses in each hour h for the new HVDC interconnection projects:

$$p_{cable}(h) = r_l d \left(\frac{P(h)}{V}\right)^2 \tag{3}$$

$$p_{converter}(h) = A\frac{P(h)}{V} + B \tag{4}$$

where r_l corresponds to the per-unit-length linear resistance of the cables/OHL that constitutes the new interconnection, d to the length of the cables, V the nominal voltage, $P(h)$ the active power exchanged, and A and B loss coeficients of the converters.

Finally, costs considered for CBA are presented in the table below.

Technology	Type	OHL (M€/km)	Underground Cable (M€/km)	Submarine Cable (M€/km)	1 Converter (M€)
DC	LCC Bipolar 2 x 500 MW (Type1)	0.25	0.8	1.24	104
	LCC Bipolar 2 x 500 MW (Type2)	0.2	0.6	0.98	104
	LCC Bipolar 2 x 1000 MW (Type1)	0.25	1.6	2.48	217
	LCC Bipolar 2 x 1000 MW (Type2)	0.2	1.2	1.96	217
	VSC Bipolar 2 x 500 MW (Type1)	0.25	0.8	1.24	135
	VSC Bipolar 2 x 500 MW (Type2)	0.2	0.6	0.98	135
	VSC Bipolar 2 x 1000 MW (Type1)	0.25	1.6	2.48	281
	VSC Bipolar 2 x 1000 MW (Type2)	0.2	1.20	1.96	281
Technology	**Type**	**OHL (M€/km)**	**Underground Cable (M€/km)**	**Submarine Cable (M€/km)**	**1 Circuit Breaker (M€)**
AC	AC OHL 400kV single	0.5	1.3	3.8	1.5
	AC OHL 400kV double (on common carrier)	0.6	-	-	-

Table 2 –Standardized costs for cost benefit analysis

6 Results

Next subsections summarize the results obtained on the security analysis and reinforcements assessment for each of the projects considered in the context of the Mediterranean Master Plan, compiled in the next table.

Code	Cluster (Project)	Corridor	Code	Cluster (Project)	Corridor
MAPT	Morocco - Portugal (+1000 MW)	WEST	**TNLYEY**	Tunisia - Libya (+1000 MW) + Libya - Egypt (+1000 MW)	CENTRAL
MAES	Morocco - Spain (+1000 MW)	WEST	**TREY**	Turkey - Egypt (+3000 MW)	EAST
DZES	Algeria - Spain (+1000 MW)	WEST	**TRIS**	Turkey - Israel (+2000 MW)	EAST
DZIT	Algeria - Italy (+1000 MW)	CENTRAL	**EYJO**	Egypt - Jordan (+550 MW)	EAST
TNIT	Tunisia - Italy (-600 MW)	CENTRAL	**JOSYTR**	Jordan - Syria (+800 MW) + Syria - Turkey (+600 MW)	EAST
TNIT2	Tunisia - Italy (+600 MW)	CENTRAL	**GRBGTR**	Greece - Turkey (+500 MW) + Bulgaria - Turkey (+500 MW)	EAST
DZTN	Algeria - Tunisia (+700 MW)	CENTRAL	**GRCYIS**	Greece - Cyprus (+2000 MW) + Cyprus - Israel (+2000 MW)	EAST

Table 3 – Projects and Corridors for the Mediterranean Master Plan

Concerning the different snapshots built, next table comprises the size of each of them.

Project	Buses	Lines	Transformers	Generators	Loads
MAPT	3308	3308	1788	3935	3114
MAES	3272	3272	1776	3906	3114
DZES	3310	3310	1788	3935	3065
DZIT	5131	5131	2330	4553	2633
TNIT	5131	5131	2330	4550	2632
TNIT2	5131	5131	2330	4550	2632
DZTN	897	897	509	319	290
TNLYEY	715	715	403	154	484
TREY	284	284	0	518	160
TRIS	284	284	0	518	160
EYJO	462	462	456	144	187
JOSYTR	1130	1130	843	748	452
GRBGTR	2150	2150	460	917	1094

GRCYIS	4752	4752	406	229	2339

Table 4 – Size of the snapshots built for each project

For the security analysis, a set of contingencies has been defined for each of the projects, including lines, transformers, generators and some critical N-2 outages. Next table summarizes the number of contingencies considered for each of the projects. Note that these contingencies have been applied to all snapshots of each project.

Project	**Lines**	**Transformers**	**Generators**	**N-2**	**TOTAL**
MAPT	3308	1788	3935	250	9281
MAES	3308	1788	3935	250	9281
DZES	3308	1788	3935	250	9281
DZIT	1721	390	1899	8	4018
TNIT	1721	390	1874	3	3988
TNIT2	1722	390	1867	4	3983
TNLYEY	761	5	122	0	888
DZTN	842	124	144	0	1110
TREY	432	0	140	36	608
TRIS	431	0	139	36	606
EYJO	67	28	59	1	155
JOSYTR	648	28	299	38	1013
GRBGTR	663	6	370	129	1168
GRCYIS	1307	0	156	45	1508

Table 5 – Number of contingencies analyzed for each project

Finally, next table summarizes the numbers on new and upgraded circuits, bays transformers, etc. involved in the new interconnections projects and reinforcements considered.

		New interconnection					**Reinforcements**		
project		**OHL [km]**	**Cable [km]**	**HVDC station**	**Bays**		**OHL [km]**	**Bays**	**Transf.**
MAPT		45	220	2			277	2	3
MAES		10	60		2		259		3
DZES		110	240	2			240	2	
DZIT		100	350	2	2		60	2	
TNIT			200	2			300	4	
TNIT2			200	2			440	8	1
DZTN		82		2			290	6	1
TNLYEY		650		4			158	8	2
TREY			700		2		149		
TRIS			600		2		4		
EYJO		27	12	2			400	4	1
JOSYTR		163		1	4		121		
GRBGTR		270			4		190	8	
GRCYIS			3240						

Table 6 – Number of new and upgraded circuits and devices involved in the new interconnections projects and reinforcements

7 REFERENCES

1	B. Stott, J. Jardim and O. Alsac, "DC Power Flow Revisited," IEEE Transactions on Power Systems, vol. 24, (3), pp. 1290-1300, 2009		

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