Journal of Energy

VOLUME 67 Number 2 | 2018 Special Issue

journal homepage: http://journalofenergy.com/

Power system static and dynamic security studies for the 1st phase of Crete Island Interconnection

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SUMMARY

The island of Crete is currently served by an autonomous electrical system being fed by oil-fired (Heavy fuel or light Diesel oil) thermal power plants and renewables (wind and PVs). The peak load and annual electric energy consumption are approximately 600 MW and 3 TWh respectively; wind and photovoltaic parks contribute approximately 20% of the electricity needs of the island. Due to the expensive fuel used, the Cretan power system has very high electric energy generation cost compared to the Greek mainland. On the other side the limited size of the system poses severe limitations to the penetration of renewable energy sources, not allowing to further exploit the high wind and solar potential of the island.

According to the Ten Year Network Development Plan (TYNDP) of the Greek TSO (Independent Power Transmission Operator S.A. IPTO S.A.), the interconnection of Crete to the mainland Transmission System of Greece will be realized through two links: A 150 kV HVAC link between the Peloponnese and the Crete (Phase I) and a HVDC link connecting the metropolitan area of Athens with Crete (Phase II). The total length of submarine and underground cable of the HVAC link will be approximately 174km; it is at the limits of the AC technology and the longest and deepest worldwide at 150 kV level.

A number of studies have been conducted by a joint group of IPTO and Hellenic Electricity Distribution Network Operator (HEDNO) for the design of this interconnection. This paper presents briefly the power system static and dynamic studies conducted for the design of the AC link and its operation. Firstly, the paper presents the main results of the static security study regarding the calculation of the maximum power transfer capability of the link and the selection of the reactive power compensation scheme of the cable. Results from dynamic security analysis studies are also presented. The small-signal stability analysis concludes that a new (intra-area) electromechanical oscillation is introduced to the National System after the interconnection. The damping of the electromechanical oscillations is sufficient; however the operation of power system stabilizers at power plants located both at the mainland and at Crete power system can increase significantly the damping of important oscillation modes. Finally with respect to the risk of loss of synchronism after a significant disturbance in the system of Crete, such as a three-phase fault ("transient stability")- enough safety margin is estimated by means of Critical Clearing Time calculations.

KEYWORDS

HVAC submarine cable, Interconnection, Crete, Static and Dynamic Security

1. INTRODUCTION

The island of Crete is currently served by an autonomous electrical system being fed by oil-fired (Heavy fuel or light Diesel oil) thermal power plants and variable RES installations (Renewable Energy Sources, mainly wind and PVs). Currently wind power plants and photovoltaic installations generate approximately 20% of electric energy. The peak load and annual electric energy consumption are approximately 600 MW and 3 TWh respectively. Due to the expensive fuel used, the Cretan power system has very high electric energy generation cost compared to the Greek mainland. On the other side the limited size of the system poses severe limitations to the penetration of renewable energy sources, not allowing to further exploit the high wind and solar potential of the island.

According to the Ten Year Network Development Plan (TYNDP) of the Independent Power Transmission Operator (IPTO) of Greece, the interconnection of Crete to the mainland Transmission System of Greece will be realized in two phases: A 150 kV HVAC link between the South East (SE) Peloponnese and the North West (NW) Crete (Phase I) and an HVDC link connecting the metropolitan area of Athens with Crete (Phase II). The double-circuit 2x200 MVA AC link will be an integral part of the 150 kV network of the Hellenic Transmission System connecting the existing substations of Molaoi (Peloponnese) and Chania (Crete).

The AC Interconnector of Crete is a project in the international forefront, due to the high length of the continuous cable part, which reaches approximately 174 km. In fact, during the last years, apart from the tendency towards HVDC interconnections, a trend for long HVAC cables can be also observed (e.g. the Mallorca-Ibiza interconnection of 126 km at 132 kV [1]). Beyond certain distance, the HVDC option is more cost-effective, however the exact distance is case dependent [2]. Besides, the experience from operational HVDC interconnections shows that in some cases costs had been underestimated [3]. Currently, the longest AC cable interconnection is the (single-circuit) 163 km 100 kV AC cable interconnection of the Martin Linge oil and gas platform with a design power of 55 MW [4].

A number of studies have been conducted by IPTO for the design of the interconnection. This paper presents briefly the power system security studies conducted for the design of main AC link parameters and its operation (i.e. before the realization of Phase II of the interconnection) by a working group of IPTO and HEDNO (Hellenic Electricity Distribution Network Operator, responsible also for the transmission systems of non-interconnected islands of Greece).

2. DESIGN CRITERIA

The most important aspects of the interconnection design can be summarized as follows:

- The power system of Crete is very small compared to the Hellenic Interconnected System, (which is part of the Continental Europe synchronous area).
- Environmental EU Directives impose important limitations on the operation of conventional power plants after 2020 and, thus, an imperative issue of security of supply emerges for the island of Crete.
- The interconnection is one of the most cost effective options for further exploitation of the important renewable energy potential of Crete. There is currently an important penetration of renewables in the power system of Crete (approx. 20% of annual electric energy supply).
- The high total length of the interconnection cable.

The main design criteria were:

- Economic optimization: The most cost-effective assurance of the security of supply of Crete was a main design objective.
- Power system reliability: Another important design objective was improving the reliability of the power system of Crete which is currently lower than the reliability of the Hellenic Interconnected System, due to its autonomous operation.
- Avoidance of complexity: Another objective of the project design was to avoid complex procedures real operation so that it will be fully exploited.
- Minimization of new transmission projects at Peloponnese and Crete.
- Operations automation and minimization of manual operations by the Control Center: It is foreseen to upgrade the Control Center of Crete in order to accommodate automated operations for the control of the interconnection. At the same time, the project was designed in a way to minimize the necessary manual operations for the interconnection control by the personnel of the Control Center of Crete.
- Equipment redundancy.

3. DESCRIPTION OF INTERCONNECTION SET-UP

The interconnection routing is depicted in Fig. 1. The interconnector between Crete and Peloponnese shall be implemented by using two 150 kV AC circuits; the thermal limit of each circuit is 200 MVA.

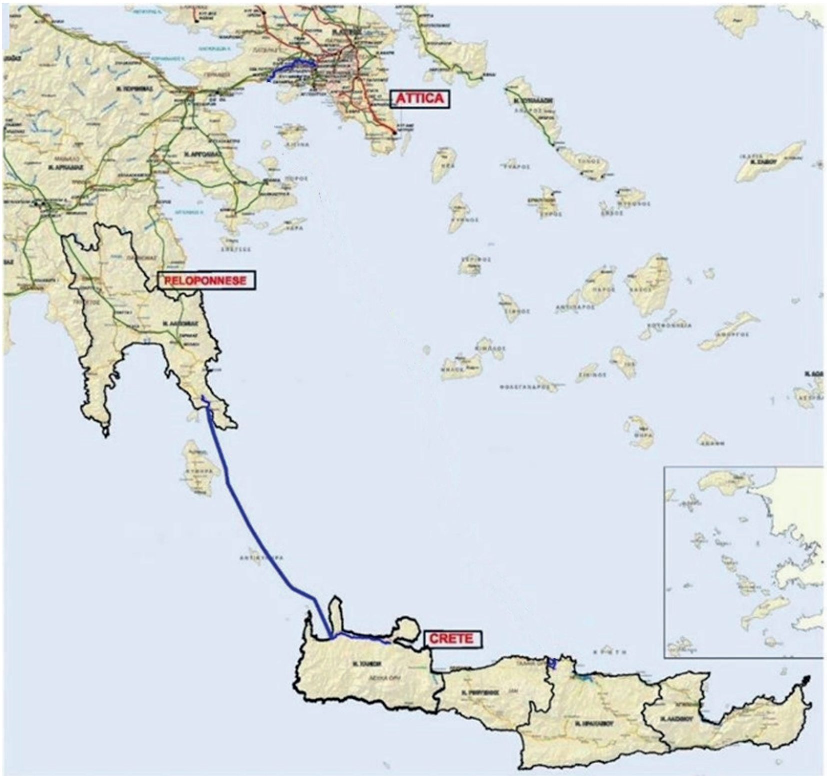


Figure 1. Interconnector routing

The lenth of each submarine cable is 132 kmconnecting the two landing points in SE Peloponnese and NW Crete. In addition, two underground double circuit cables connect:

- The new terminal station of SE Peloponnese to the sea shore (next to Neapoli) (10 km)
- The landing point in NW Crete (34 km) to the existing Chania I substation.

The total length of continuous underground and submarine cables will be thus 176 km, as the cable reactive power compensation will be installed at the Chania substation in Crete and at the terminal station in Peloponnese.

The new 150kV terminal station in SE Peloponnese will be constructed using GIS technology. It will be connected to the existing Molaoi 150kV substation at SE Peloponnese with an overhead double circuit line of 24 km (using ACSS conductors of the Grosbeak type with increased thermal rating) plus a 4 km double circuit cable part (at the Molaoi substation side).

4. STATIC SECURITY ANALYSIS

Static security analysis has been performed in order to investigate the following issues and relevant critical figures:

- Maximum power transfer capability of the cable interconnection and identification of the operational limitation of power transfer taking into account the cable loading limits under transient and steady-state conditions.
- Selection of appropriate compensation type and dimensioning.
- Investigation of necessity for installation of dynamic compensation (SVC/STATCOM), its dimensioning and placement.
- Identification of the must-run conventional units (if any) to operate in Crete independently of the load level for static security reasons.

Identification of these figures is a problem of high complexity. This is further aggravated due to the high level of variable RES installations, as it requires more detailed representation of the distributed generation (up to MV level) and multiple scenarios for various combinations of load and RES generation levels. For this reason, it was decided to separate the system into three sub-systems, which were initially examined separately: The Hellenic Interconnected

System, the links and the system of Crete. Possible limitations (e.g. operational constraints) and issues were identified for each subsystem and finally the proposed solutions were verified using an integrated complete model. More specifically the static security studies were conducted for the following subsystems:

- Hellenic interconnected system with interconnector
- Power system of Crete with interconnector
- Standalone interconnector to identify the permissible operation range.

The design of the interconnection is based on the typical power system security criteria, such as the N-1 criterion. In this respect, the complete loss of the interconnector (N-2 contingency) is considered only for the design and installation of a Special Protection Scheme, which will lead to partial load shedding to ensure normal operation of the power system. The examined contingencies are the following:

- Loss of a transmission element (N-1 in mainland, N-1 in Crete, loss of one cable system)
- Loss of a generator
- Loss of a compensation device (e.g. reactor)
- Open-end of the cable link due to the trip of circuit breaker either at the SE Peloponnese terminal substation or at the Chania substation (Crete).

Furthermore, prior to the static security analysis a preliminary analysis of the interconnected operation of the system was conducted. More specific a detailed day by day Unit Commitment and Economic Dispatch simulation for a period of one year and a time step of one hour was performed in order to investigate the impact of certain operational parameters to the variable cost of the power system. A number of cases was considered with regard to the operational parameters under study, as described below:

- Power Transfer Maximum Setpoint (4 cases):
    - 150 MW, 160 MW, 170 MW ,180 MW
- Local Units Spinning Reserve Required (3 cases):
    - 20 MW, 30 MW ,40 MW
- Must-Run Units (2 cases):
    - 2 Must-Run Units, 3 Must-Run Units

The combination of the above cases provides 24 scenarios each of which has been simulated in detail. The analysis of the simulation results indicates that there is no significant variation with regard to the annual operating cost among the scenarios. According to the simulation results in all cases-scenarios, spinning reserve provided by local units is maintained well above 40 MW and more than 3 generating units are in operation for the most part of the year, even if this is not required by the constraints.

The hourly results of the simulation of the system have been further processed in order to get a minute granularity, both under normal operation of the system and assuming the outage of the largest power unit. The residual load ramp and the generation trip disturbance is undertaken by the interconnection and local units according to their reserve levels and ramp –up and ramp-down technical limits. It will be required to minimize the number of minutes during which the interconnection exceeds its transfer capacity limit as it will be defined by the static analysis.

Taking the above considerations into account, it is recommended to operate the system under the following constraints:

- Power Transfer Maximum Setpoint ≤ 150 MW
- Spinning reserve by local units ≥ 30 MW
- Must-Run Units = 3

With regard to the must run units, it is recommended to use 2Atherinolakos power plant units due to their low cost and 1 unit at Linoperamata power plant.

4.1 Power System of Crete

The current transmission system of Crete is depicted in Fig. 2, together with some planned reinforcements. There are three thermal power plants at the west (Chania), center (Linoperamata) and east (Atherinolakkos) of the island.

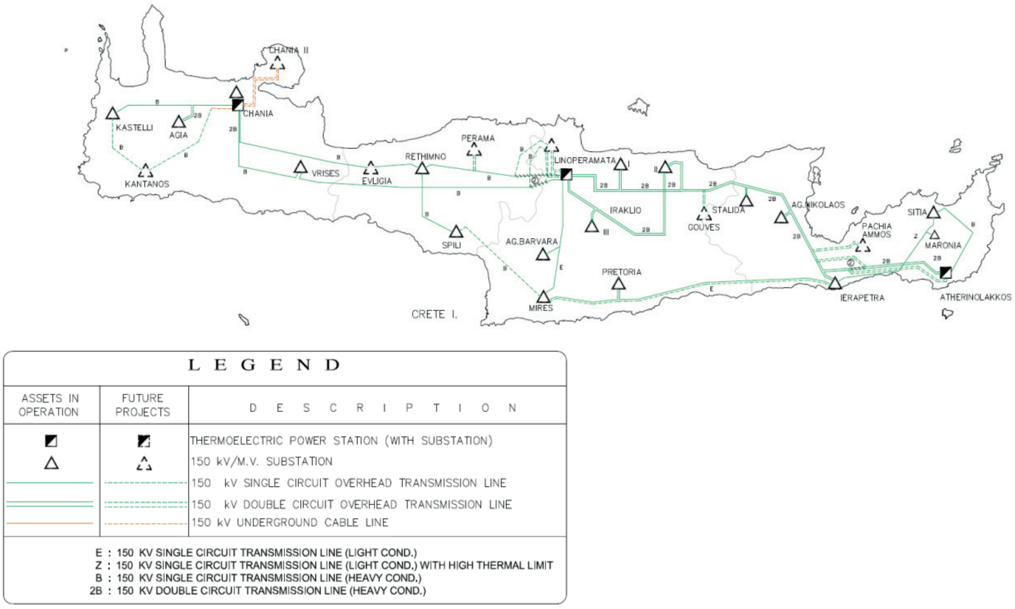


Figure 2. Transmission system of Crete

The main scenarios examined referred to year 2020, taking into account the planned evolutions in both the transmission and the generation system of Crete. The examined system model under investigation includes the power system of Crete (Fig. 3) together with the interconnection SE Peloponnese - Chania (Fig. 2). The Hellenic Interconnected System is modelled as a Thevenin equivalent at SE Peloponnese.

The snapshots analyzed correspond to 4 load levels (including minimum and maximum), 5 RES generation levels and 2 voltage levels at SE Peloponnese. Ten scenarios were finally selected to be analyzed in details representing extreme and intermediate operational conditions of the power system of Crete after the AC interconnection with Peloponnese. The main result of the analysis is that a serious lack of voltage control can emerge as the power import through the interconnector displaces local conventional generation with voltage control capabilities. Therefore, dynamic reactive compensation (SVC or STATCOM) needs to be installed.

4.2 Interconnector range of operation

In order to calculate the maximum power transfer through the AC interconnector, a model of its cable systems based on two-port networks has been used to identify the interconnector permissible range of operation. The analysis is based also on studies for similar interconnections [5-8], as well as the methodology proposed in [9] by the CIGRE Working Group on technical performance issues related to the application of long HVAC cables.

In specific, the interconnector was modeled by a series of two-port networks according to Fig. 3.

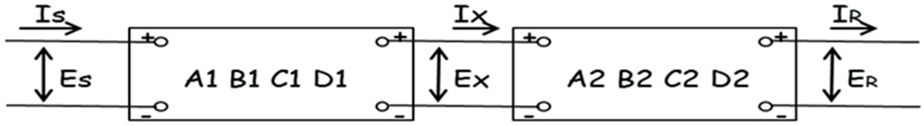


Figure 3. Series connection of two two-port generic networks

Each two-port network represents an equipment element of the interconnector, i.e. the overhead line, the compensation reactors at each side of the cable part, the underground and submarine cables modeled in multiple parts. For the modeling of the lines and cables, the distributed parameters model was used. Therefore, the following holds for each two-port network representing a line or cable part:

$$\begin{bmatrix} \tilde{E}_s \\ \tilde{I}_s \end{bmatrix} = \begin{bmatrix} \cosh \gamma l & Z_C \sinh \gamma l \\ \dfrac{\sinh \gamma l}{Z_C} & \cosh \gamma l \end{bmatrix} \cdot \begin{bmatrix} \tilde{E}_R \\ \tilde{I}_R \end{bmatrix}$$

where

$$\gamma = \sqrt{zy} = \sqrt{(R + j\omega L) \cdot (G + j\omega C)}$$

A simplified one-line diagram of the interconnector model developed is shown in Fig. 4.

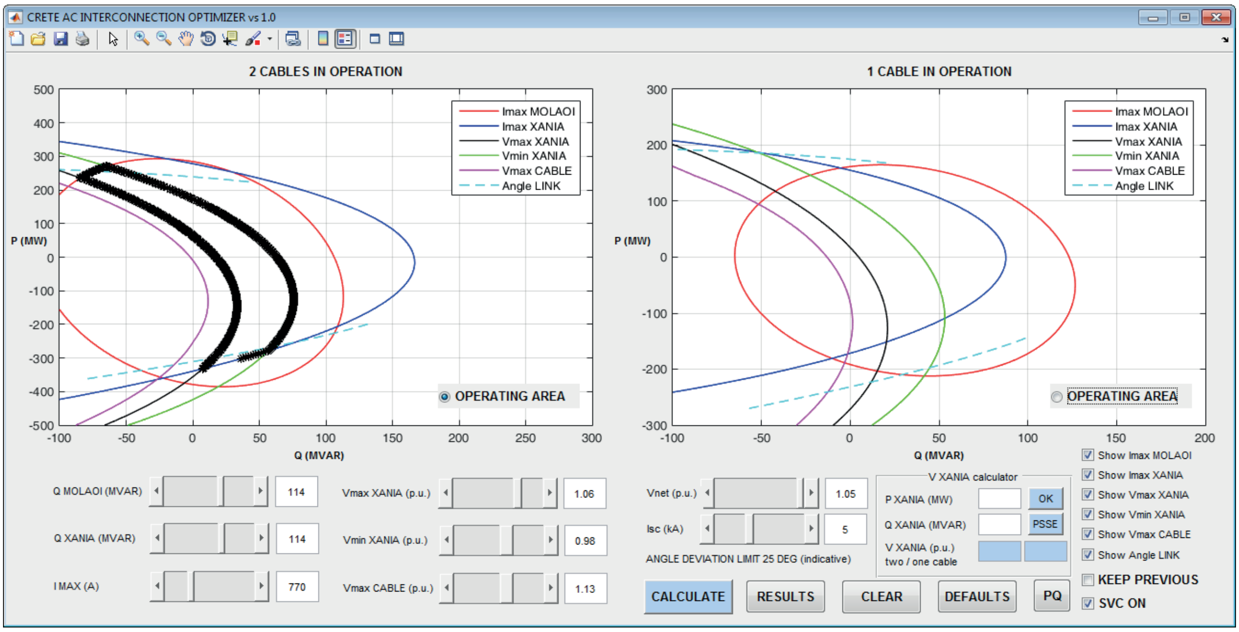
Figure 4. Interconnector model

This is a multi-parameter model depending on the following:

- Reactive power compensation at each side (QS, QR)
- Cable ampacity (Imax)
- Voltage operation range at Chania substation (Vmax, Vmin)
- Maximum voltage along the Interconnector (Vmax)
- Short-circuit level at Molaoi substation at SE Peloponnese
- Thevenin equivalent voltage (Es)
- Angle difference

Introducing the necessary parameters, the calculation of the operational ranges can be demonstrated in P-Q diagrams as shown in Fig. 5, where P and Q are the active and reactive power received at Crete (Chania substation). In Fig. 6 the following limits are depicted:

- Maximum current at sending point ("Imax MOLAOI")
- Maximum current at receiving end ("Imax XANIA")
- Maximum voltage at 150kV bus of Chania substation ("Vmax XANIA")
- Minimum voltage at 150kV bus of Chania substation ("Vmin XANIA ")
- Maximum voltage along the Interconnector ("Vmax CABLE")
- Maximum angle difference ("Angle LINK"). An indicative limit of 25 degrees is assumed whilerotor angle stability was examined by means of a dynamic security study.



Q MOLAOI (MVAR) 114

Q XANIA (MVAR) 114

I MAX (A) 770

Vmax XANIA (p.u.) 1.06

Vmin XANIA (p.u.) 0.98

Vmax CABLE (p.u.) 1.13

Vnet (p.u.) 1.05

Isc (kA) 5

ANGLE DEVIATION LIMIT 25 DEG (indicative)

P XANIA (MW)

Q XANIA (MVAR)

V XANIA (p.u.) two / one cable

☑ Show Imax MOLAOI
☑ Show Imax XANIA
☑ Show Vmax XANIA
☑ Show Vmin XANIA
☑ Show Vmax CABLE
☑ Show Angle LINK
☐ KEEP PREVIOUS
☑ SVC ON

Figure 5. Calculation of AC Interconnector operational range

The area defined by all the above mentioned limits is the root locus of the permissible operational range. Next, the P-Q pairs that correspond to the power flows of the examined operation points of the power system of Crete were drawn on the P-Q plane. The capability of the static and dynamic reactive compensation is selected so that the points fall into the permissible root locus as shown in Fig. 6.

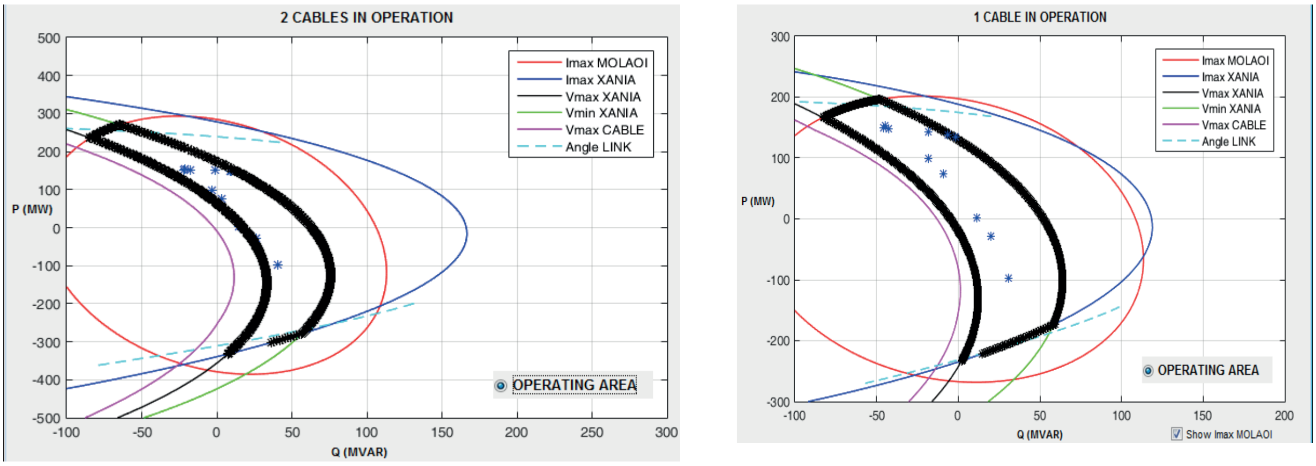


Figure 6. Operating loci of AC link with P,Q points representing Crete system load conditions

4.3 Static security analysis conclusions

According to the analysis the main limiting factors regarding maximum transfer capacity comes from:

- Thermal limits of underground and submarine cables.
- Voltage operational limits in High Voltage level (150 kV) in Crete power system
- Angular differences between the conventional generating units in mainland and Crete power system, which operate under synchronizing conditions.

Based on the above the main conclusions from the static security analysis of the Interconnector are the following:

- Each circuit of the cable interconnection will be compensated by 96% with installation of 6 independent reactor units (non-variable), 38 MVAr each, per circuit, equally distributed at the two Interconnector ends.
- The necessary capability of the dynamic reactive compensation (SVC or STATCOM) is ±60 MVAr with optimal placement at Linoperamata substation or closeby.
- The maximum power transfer due to static security limitations is 180 MW (after the Interconnector losses) with main limitation factor the voltage levels at the power system of Crete and the angle difference.
- It is possible to transfer at least 100 MW from Crete to the Hellenic Interconnected System.

5. DYNAMIC SECURITY ANALYSIS

Based on the results of the static security analysis, a dynamic security analysis was performed focusing on maximum load conditions with and without high RES generation. In both cases, high import of power from the Interconnector to Crete (150 or 180 MW) is assumed. A complete dynamic model of the Hellenic Interconnected System and Crete is used, including the EHV systems of SE Europe (Balkan Peninsula). The rest of the Continental Europe synchronous zone is represented with a Thevenin equivalent. In both scenarios high power import to the Hellenic System is assumed as shown in Fig. 7.

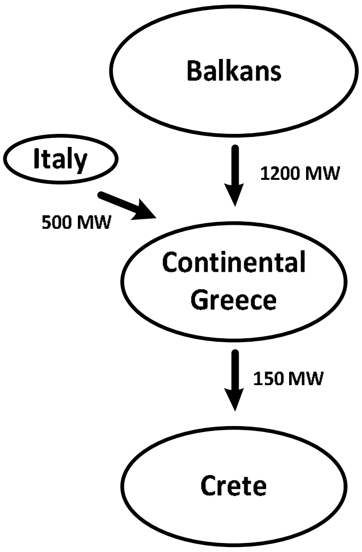


Figure 7. Power imports to Greece and transfer to Crete

5.1 Small-signal stability

The small-signal stability study (modal analysis) identified the emergence of a new intra-area electromechanical oscillation mode of relatively low frequency and damping between the synchronous generators of Crete and the Hellenic Interconnected System (Peloponnese mainly). The frequency of the new mode was calculated 0.8 Hz approximately under maximum load conditions and its damping at least 5%, which can be considered satisfactory. The synchronous generators of Crete also participate in two already existing intra-area modes (with frequency of 0.7 - 0.8 Hz), which results to a very small reduction of their frequency and damping. Their participation to the inter-area oscillation modes of the Hellenic System is negligible. Results of the modal analysis are summarized in Table I for the case without RES contribution, with and without the interconnection of Crete.

Table I. Main electromechanical oscillation modes under maximum load conditions (no RES) with and without AC interconnection of Crete

	With Interconnection				Without Interconnection			
Mode	**Real**	**Imag.**	**Damping (%)**	**Freq. (Hz)**	**Real**	**Imag.**	**Damping (%)**	**Freq. (Hz)**
Intra-area “Crete”	-0.263	5.020	5.2	0.799				
Intra-area “Central GR”	-0.251	4.874	5.2	0.776	-0.286	4.931	5.8	0.785
Intra-area “South GR”	-0.137	4.501	3.1	0.716	-0.168	4.559	3.7	0.725
Interarea “GR”	-0.106	3.508	3.0	0.558	-0.092	3.650	2.5	0.581
Interarea “SE Europe”	-0.260	1.706	15.1	0.272	-0.249	1.741	14.2	0.277

It is also concluded that:

- After the AC interconnection of Crete, the operation of the power system stabilizers installed at large synchronous generators becomes even more important, in particular at the Megalopoli power plant in Peloponnese. It is noteworthy that increasing the oscillations damping reduces the possibility of resonance, taking into account that the frequency of the new intra-area oscillation mode is at the same frequency range (0.7 - 0.8 Hz) with already existing intra-area modes, which involve some generators in common.

- Activation of the power system stabilizers of the synchronous generators at Atherinolakkos power plant of Crete is expected to provide important damping to the new intra-area oscillation mode, as well as to the other two intra-area models.

The case with the lowest damping was without RES generation and assuming no stabilizers are active, remaining however above the 5% limit. Just the activation of the stabilizers of the largest generator in Megalopoli power plant increases the damping significantly. In the case with RES contribution, the frequency of the Crete intra-area mode is increased as fewer synchronous generators are in operation in Crete. The damping is also increased.

5.2 Dynamic security assessment

The dynamic security assessment consists of time-domain simulations of critical disturbances for the two examined scenarios assuming initial import of 180 MW to Crete from the Interconnector. Solid three-phase faults are simulated regarding clearing after 100 ms. The main conclusions of this study can be summarized as follows:

- In case of a three-phase fault at one Interconnector circuit, close to Chania substation, which is cleared by opening the circuit with a time delay of the order of 100 ms, it is possible that an important part of wind power is lost, because some old wind power plants in Crete are not equipped with Low Voltage Ride-Through (LVRT) capability. This would result to an import of possibly more than 220 MW via the remaining Interconnector circuit, and, thus, unacceptably low voltages in Crete.
- Similarly, in case of loss of a large conventional generator (e.g. at Atherinolakkos station) after a severe fault, it is possible that an additional loss of important amounts of wind power generation also occurs. This could result to a very high import of power from the Interconnector (e.g. 300 MW) and, thus, to marginally secure or even insecure voltage levels.

As a conclusion, a Special Protection Scheme should be adequately designed in order to operate in case events such as the above mentioned actually emerge, e.g. by monitoring voltage at Chania, current and power through the Interconnector, etc. In addition, the load shedding should (be able to) take place in various substations (e.g. Chania, Iraklio). As a proof-of-concept example, Fig. 8 shows the voltage at Chania HV bus in case after a solid three-phase fault which is cleared by opening of one Interconnector circuit in two cases:

- Without SPS: The active power transfer through the remaining circuit is close to 250 MW. The voltage at Chania does not recover above 90% which is the emergency low voltage limit.
- With SPS: It is assumed that load shedding takes place at Chania. The active power transfer through the remaining Interconnector circuit is limited to approximately 225 MW and the voltage recovers above 90%. In order to limit the power transfer to 180 MW, loads from other substations need to be shed as well.

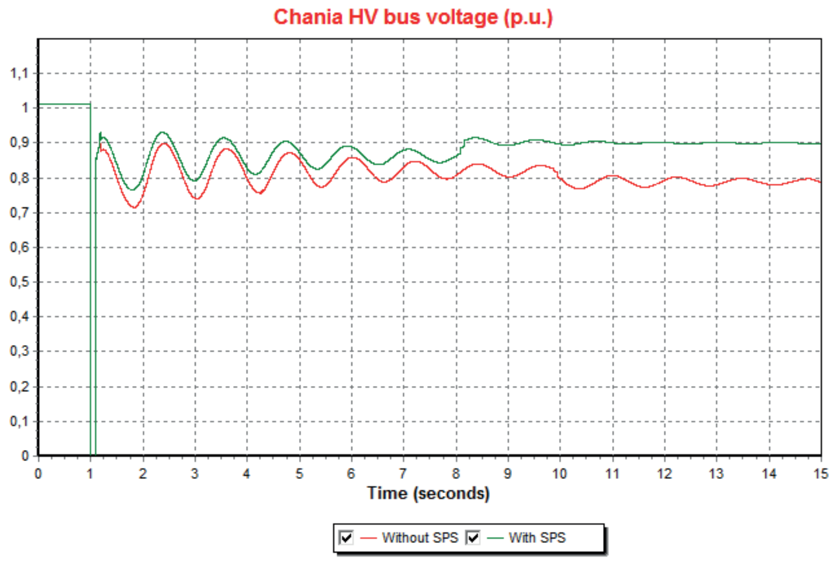


Figure 8. Voltage at Chania HV bus and active power to Chania with and without Special Protection Scheme

5.3 Transient stability

The dynamic security analysis did not detect any loss of synchronism issues. In order to assess a security margin with respect to transient stability (large-disturbance rotor-angle stability), the critical clearing time of solid three-phase fault at the transmission system of Crete was calculated for a worst-case scenario with high load conditions, all synchronous generators of Crete in operation at maximum output and an export of approximately 150 MW from Crete through the Interconnector. As the lowest critical clearing time found was 200 ms, it can be concluded that there is an adequate margin with respect to transient stability, taking into account that adverse assumptions were used (e.g. solid three-phase fault) and typical fault clearing times are close to 100 ms. An example of a fault at Chania, cleared with opening of one Interconnector circuit, is shown in Fig. 9 for the marginally stable and marginally unstable cases. It can be seen that in the unstable case all generators of Crete lose synchronism with respect to the generator in Megalopoli (Peloponnese).

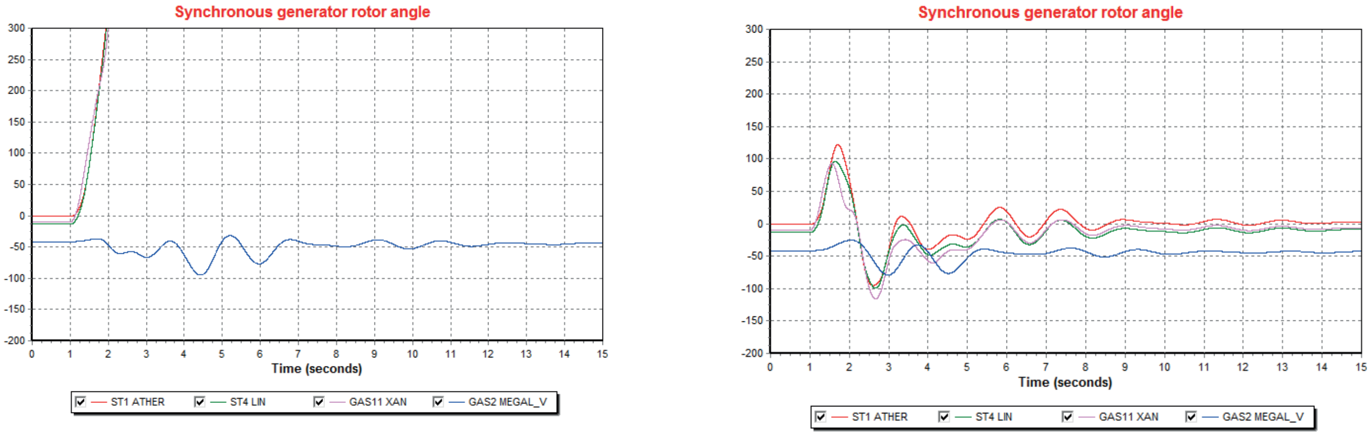


Figure 9. Synchronous generator rotor angles in marginally unstable and stable cases

6. CONCLUSIONS

According to the Ten Year Network Development Plan (TYNDP) of the Independent Power Transmission Operator (IPTO) of Greece, the interconnection of Crete to the mainland Transmission System of Greece will be realized in two phases: A 150 kV HVAC link between the SE Peloponnese and the NW Crete (Phase I) and a HVDC link connecting the metropolitan area of Athens with Crete (Phase II).

The AC Interconnector of Crete is a project with certain characteristics that place it in the international forefront of cable interconnections, such as the high length of the continuous cable part which reaches approximately 174 km. In this paper power system security studies conducted for the design of AC link parameters and its operation (i.e. before the realization of Phase II of the interconnection) were presented.

The main conclusions of the static security analysis can be summarized as follows:

- In order to achieve adequate voltage control at the power system of Crete after the AC interconnection, it is necessary to install a dynamic reactive compensation device such as an SVC or STATCOM close to the electrical center of Crete.
- Each Interconnector cable circuit will be compensated at approximately 96% by installation of 6 independent reactors (non-controllable), equally distributed at both ends of the Interconnector.
- The maximum power transfer through the Interconnector, as defined by static security limitations is 180 MW. Main limiting factors are the voltages of Crete power system and the angle difference. Possible transient overloading of the cables does not constitute a limiting factor for static security.

From the dynamic security analysis, the following conclusions were drawn:

- The AC interconnection of Crete practically eliminates the frequency stability issues currently faced due to its autonomous operation.
- The 180 MW maximum power transfer limit is not decreased due to dynamic security constraints. However, the installation of a Special Protection Scheme is deemed necessary, not only for the extreme case of total loss of the Interconnector (N-2 contingency), but also for ensuring that the power transfer through the Interconnector is not excessively increased in case of critical disturbances so that the system security is not jeopardised
- The small-signal stability analysis identified changes in the inter-area and intra-area electromechanical oscillation modes in the mainland system after the interconnection of Crete with the AC link.
- With respect to the risk of loss of synchronism right after a significant disturbance in the system of Crete, such as a three-phase fault (“transient stability”), an adequate safety margin is estimated by means of Critical Clearing Time calculations.

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