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Operation of the Electrical System of Crete in Interconnection with the Mainland Grid: A Stability Study

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Abstract

Most of the autonomous island power systems suffer high electricity costs due to expensive fuels. Interconnection of such systems to large mainland systems is an option to reduce operational costs. Recent evolutions in both cable technology and AC/DC/AC conversion promise feasible solutions. Since interconnection projects are of high cost, their economic feasibility must be carefully investigated; static, transient and dynamic system performance is crucial to reliably assess the volume of exchanges between the island and the bulk system and consequently to estimate the economic feasibility of the interconnection. This paper presents such an investigation, focusing on the transient stability issues, for the planned interconnection of the island of Crete to the Greek mainland.

Introduction

Crete is the largest Greek island and by far the largest autonomous electrical system in the Aegean archipelago. Electricity needs of the island are served by an autonomous power system with a peak load of about 670 MW and total annual consumption of 3000 GWh (2012) corresponding to about 6% of the National load. The local production system is mostly served by thermal units burning diesel and heavy oil with a capacity of about 770 MW. There is also a substantial capacity of RES, mainly Wind and Photovoltaic totaling to about one third of the conventional generation capacity and contributing to about 20% of the annual consumption.

Due to the fuel used in conventional units and the low efficiency of several of those, the production cost in the island is much higher than that in the Greek mainland. The island has also vast RES potential (mainly wind and solar) which cannot be further exploited because of the electrical isolation of the area.

The electrical interconnection of Crete to the Greek mainland is in the agenda since the mid ‘80s. Technical and economic feasibility studies were carried out in that period assuming an interconnection by an HVDC link with a capacity of about 300 MW using line commutated technology and oil insulated cables. Because of the technical challenges associated with the technologies available at that period and the high relevant costs the project was stopped. Also, the consumption of the island in that period was low leading to marginal economic benefits.

Since the eighties the size of the electrical system of Crete, both in consumption and infrastructures, has been expanded dramatically. Fig. 1 shows the evolution of annual demand and peak load during last fifty years .

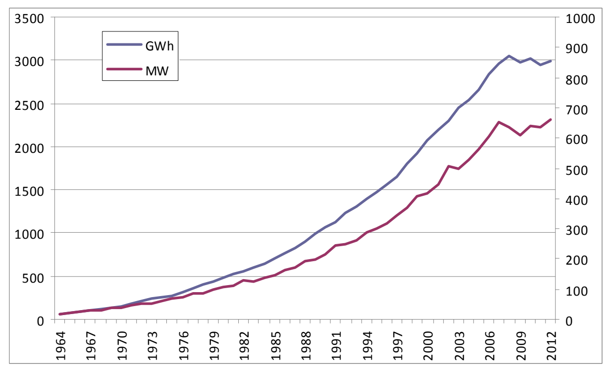

Fig 1: Evolution of Annual Demand and Peak Load in Crete

Under the current conditions, IPTO - the Independent Transmission System Operator in Greece- taking into account the current technological developments, increased fuel costs and RES potential is thoroughly considering the interconnection of the island to the mainland via submarine cables and HVDC links. A preliminary feasibility study has been carried out and recently updated in cooperation of IPTO, PPC S.A.[1] and RAE[2] [1]. Results from this study have been very promising: the interconnection can provide high fuel cost savings and will allow further RES development in Crete. The goal is

1 PPC S.A is the owner of the transmission and conventional generation facilities in Crete
2 RAE is the National Regulating Authority for Energy in Greece.

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to achieve this interconnection by the end of the current decade.

A critical technical issue affecting both the technical choices and the economics of the project is the static and dynamic behavior of the electrical system of Crete since it is crucial to reliably assess the volume of exchanges between the island and the bulk system and consequently to estimate the economic feasibility of the interconnection. More specifically, transient system stability under several conditions of power transfers (from/to Crete) and under various conditions of RES production and conventional generation in the island, is a very important issue. It is obvious that the quality of power supply in Crete after the interconnection shall stay at the current high standards, if not improved.

Purpose of this paper is to present results of a stability analysis investigation of the interconnected operation under a selected set of representative scenarios. Selection of scenarios is based on typical future load conditions in Crete (high, medium and low load periods) in combination with expected future RES generation (wind and solar). For each scenario a set of contingencies is examined. The results of this analysis are presented and discussed, as of what are the possible power transfers in conjunction with the necessary amount of conventional units and reserves that shall be in operation at various load conditions and RES levels and as of what are the recommended actions so that system stability is maintained. The conclusions are very critical in order to determine the size of the interconnection and the viability of the project.

Main features of the Interconnection and Hypotheses

Two electrical systems of much different size are to be interconnected asynchronously. In one hand the electrical system of the Greek mainland being connected to the European system presents a huge inertia. On the other hand, the system of Crete, smaller in size by orders of magnitude, when interconnected shall operate with as little conventional generation as possible in order to maximize the utilization at the interconnection facilities and minimize operating costs. Therefore, it will present minimal inertia and short circuit levels. The volume of exchanges in both directions shall be as high as possible in order either to import less expensive electricity from the mainland or to export excess RES generation. The link should operate smoothly under varying exchange conditions and provide uninterruptible transition from export to import (and vice versa) regimes.

The distance between the island and the mainland involves long submarine cables at high sea depths. The choice of an HVDC interconnection is obvious. Nevertheless extended sea bed studies have to be realized in order to define a feasible cable route. On the other hand the operating conditions anticipated, lead to a solution utilizing Voltage Source Converter (VSC) technology [2,3].

Preliminary feasibility studies show that the optimal capacity of the link shall be in the range of 2x350MW to 2x500MW. Most appropriate location for the HVDC converter station in the island is a central point in the northern shore, in the center of gravity of the electrical load. The point of connection to the mainland shall be definitely done at a central 400kV substation strongly connected to the ultra high voltage backbone of the mainland transmission system.

A very significant issue is the security of the operation of the system in Crete in terms of transient stability upon transmission system and HVDC converter station contingencies. Obviously after the interconnection the normal operation shall not be hindered by often brownouts or blackouts. The operational security shall be improved or at least shall not deteriorate compared to the present conditions.

There is a high number of operating scenarios (snapshots) that can be devised for such an analysis. However the analytical effort has been limited so far to some indicative cases which include scenarios in high load, low load and high transfer conditions. More specifically, the following conditions have been examined for future operation: (a) high load with increased RES generation and therefore moderate imports, (b) high load with low RES generation leading to high imports and (c) low load with high RES generation leading to increased exports. In all examined scenarios as a starting point, limited local conventional production is assumed. This was intentionally chosen in order to test the stability of the system in stressed conditions i.e. with low local inertia. After all, the benefits of the interconnection shall come if the system (in Crete) can operate in a secure manner with small local generation in order to reduce fuel costs.

The analysis so far does not cover similar conditions at the other end of the interconnection, in the mainland. Any way the size of the power exchanges modeled are small compared with that of the interconnected system and in such conditions loss of the converter station is assumed harmless for the system in the mainland.

Modeling and Methodology

A. HVDC System Configuration

HVDC converters can be of various configurations such as symmetric monopole, asymmetric monopole with metallic or ground return, bipole with ground electrodes or metallic return. The need for a good compromise between redundancy and system total cost leads to adopt a "hybrid" configuration of the bipole arrangement with metallic return. This configuration, which is shown in Fig. 2, is characterized by higher availability because only 50 percent of the transmitted power is lost following a fault (N-1 criterion).

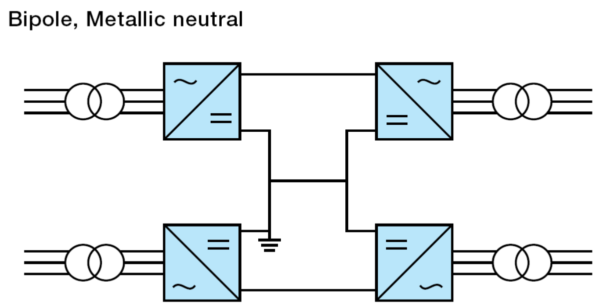

Fig 2: HVDC "hybrid" bipole configuration with metallic return

In HVDC links implemented with Voltage Source Converters (VSC) the current in the valves can be switched on and off at any time (self-commutated converter), so a weak or even a passive network can be fed. Using Pulse Width Modulation technology in high switching frequency components such as IGBTs, make possible to create any phase angle or amplitude (up to a certain limit) which can be done almost instantaneously [4,5]. So independent control of both active and reactive power is possible too and VSC can operate as rectifier or inverter at variable frequency and at the same time absorb or supply reactive power to the AC network.

B. System modeling

The power system of Crete is supplied by three conventional power plants consisting of 27 thermal units of total capacity 770 MW. There are also several wind and photovoltaic parks in operation distributed all over the island with a total capacity of about 180 MW and 80 MW respectively. Furthermore, there are a high number of authorized new RES plants (mostly wind farms) which are stacked due to the limited size of the system. In this study a subset of said plants has been considered with a total installed capacity of 900 MW. Transmission needs are served by a 150 kV transmission system as shown in Fig. 3. (~600 km of OHL and 21 substations).

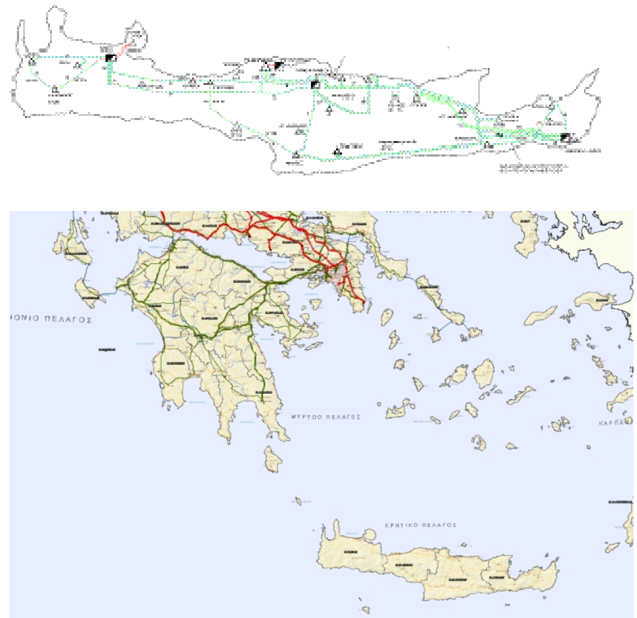

Fig 3: The Power System of Crete and the map of the island over the map of the country

In order to evaluate the performance of the interconnected power system of Crete, first a load flow model is set up and studied. For this purpose an increased forecasted future load is assumed.

Next, an analytical dynamic model of Cretan power system was developed using the PSS/E simulator [6]. This model was enhanced by a model which was provided by ABB [7] for representing the HVDC converter station with voltage source converters.

Specifically synchronous generators of thermal power plants were modeled using the "classical" models GENROU and GENSAL from PSS/E library for round – rotor and salient pole machines respectively. A far as speed governors four models were used, namely GAST2A for gas turbines, GGOV1 for combined cycle plants, DEGOV1 for Diesel Generators and the general model IEEEG1 for Steam turbines. For exciter and Automatic Voltage Regulator modeling, EXST1, IEEET2, ESST4B models and the simplified model SEXS (in cases with unavailable data), from PSS/E library were used. System on mainland was represented by a slack generator (GENCLS model) with parameters based on Thevenin equivalent calculations.

Dynamic behavior of the DC transmission is modeled by the user model CABBO2 from ABB. The appropriate settings have been chosen to represent a bipolar converter of 2x400 MW and the cable parameters were properly adjusted for an interconnection length of 380 km [8]. DC converters in mainland were set up to be in dc voltage control and the others in Crete in frequency control mode, while both converters were also set to perform ac voltage control. Each DC converter station in Crete functions as a swing bus and delivers as much power, up to its limits, from/to the DC side in order to balance the current load demand with conventional/renewable generation.

As of the wind farms three different types of wind turbine technologies were considered:

- Fixed speed wind turbines equipped with induction generators. These are mainly located in “old” wind parks in the eastern area of the island.
- Variable speed wind turbines with double fed induction generator (DFIG, referred also as type 3)
- Variable speed wind turbines with synchronous generator and full converter unit (type 4)

The majority of the future wind farms were assumed to be of type 3 or 4. Model CIMTR1 from PSS/E library was used to implement the constant speed wind turbines. Accordingly several PSS/E models dedicated to represent wind turbine technologies were used for modeling type 3 and 4 wind turbines. These are WT3G1 for double-fed induction generator, WT3E1 and WT3T1 for the electrical control and the mechanical system respectively and WT3P1 for the pitch control model for type 3 wind generator. Finally WT3G2 and WT3E1were adjusted as required in order to represent adequately operation of type 4 wind turbines. All the above models were parameterized appropriately using typical settings from existing wind turbines. Note also that each wind park operating in Cretan Power System was represented based on the aggregated turbine approach.

Current voltage and frequency protections of the existing wind parks were also modeled while for the new wind parks fault ride-through capabilities (FRT) were assumed and frequency protection cut off settings of 47 and 51 Hz with a time delay of 100msec were assumed.

The existing under frequency load shedding scheme acting to several distribution lines connected to HV substations, was implemented by the models from PSS/E library for standard (based on frequency level) and rate of change of frequency (ROCOF) relays. This system operates in various stages and can lead to a maximum load shedding of 35 percent of system total load.

Finally the loads were considered to be of mixed type consisting of 60% constant admittance and 40% constant power load components.

The response of the power system under the defined scenarios and critical disturbances is analyzed in the simulation platform. Critical variables of the system such as transient variations of system frequency, loads being shed due to under frequency relays, wind farms being set out of operation due to voltage/frequency protection relays, oscillations of local machines etc. are reported and analyzed.

Study Cases and Results

The analysis was carried out for three indicative scenarios considered to characterize adequately the future operation of the system. Said scenarios (basic cases) are summarized below:

- **Case A:** Typical daily peak load scenario with high wind power production, leading to a medium volume of power transfer from the mainland to Crete.
- **Case B:** Typical daily peak load scenario with low wind power production, leading to a maximum power import from the mainland to Crete.
- **Case C:** Typical daily low load scenario with high wind power production, maximizing the power export from Crete to the mainland.

The first scenario can be considered as the basic scenario used to evaluate the operational performance of the future interconnected system under common conditions. The second and third scenarios are used to investigate system security under more stressed conditions of the dc link under importing and exporting regimes respectively. Table 1 below provides more details for the operating conditions assumed at the three main scenarios.

Table 1: Basic characteristics of three scenarios

Case	**A**	**B**	**C**
Load Demand (MW)	825	825	250
Wind Power Generation (MW)	500	120	500
PV Power Generation (MW)	0	0	100
Thermal Units in operation	3	5	0
Thermal Power (MW)	70	115	0
Spinning Reserve (MW)	31.5	83	0
HVDC Power (MW)	285	640	340
DC losses (MW %)	17 (5.9%)	36 (5.6%)	19 (5.6%)
Total losses (MW)	30	50	29

For each of the above scenarios simulation of the transient system behavior is performed for a set of critical disturbances. These disturbances, that include severe but rather likely to happen fault conditions, are:

- **D1:** Loss of local power production and specifically loss of the larger unit in operation; that is a combined cycle plant.
- **D2:** Partial loss of dc interconnection leading to monopole operation of the dc link.
- **D3:** 3-phase short – circuit (S.C.) fault in a critical line of the system under the assumptions of either a fast clearing time of 100 msec (Zone I distance protection)

or a slow clearing time of 500 msec (Zone II distance protection).

- **D4:** 3-phase fault in a transformer connecting one pole dc converter to the AC system in Crete under the assumptions of either a fast clearing time of 100 msec (differential protection) or a delayed clearing time of 250 msec (backup protection) leading again to the operation of dc link in monopole configuration.

For all the cases exhaustive N-1 static security assessment was performed. This static assessment indicates the need for additional shunt capacitor compensation in the order of 100 MVAR in HV level. However the emphasis is here given to the transient analysis results since it is anyway reasonable to assume that in the years to come and also in view of the interconnection, the transmission system in Crete will be enhanced.

Table 2 bellow summarizes the main results running contingencies over scenario A

Table 2: Scenario A comparative results

Disturbance	D1	D2	D3		D4	
			Clearing time		Clearing time	
			100 msec	500 msec	100 msec	250 msec
Frequency Variation (Hz)	<0.1	<0.1	49.3÷51	49÷51	49.8÷50.8	Collapse
Oscillations of local units	No	Stable	Stable	Unstable	Stable	Unstable
Load Shedding (MW)	No	No	145	155	60	Yes
Wind Power Outages (MW)	No	No	50	500	20	Yes

Scenario A refers to conditions with high consumption in the island, rather high wind, small conventional generation and a moderate loading of the interconnection towards Crete, at 35% of its capacity.

In case of loss of the biggest unit in Crete (D1) the quick response of HVDC link ensures the uninterrupted supply of the load. In Figs 4 and 5 basic responses of Cretan system are presented in case of loss of one of the HVDC poles (D2). Specifically in Fig. 3 system frequency and voltages at three critical buses located at the east, central and west area of Crete are shown. In Fig. 4 active power through HVDC positive and negative poles and total thermal generation in Crete are shown. These figures reveal the smooth reaction of the HVDC converters remaining in operation after the disturbance in case of a moderate power transfer through HVDC link. On the other hand local machines oscillate but these oscillations are stable and are damped within less than 3 seconds. Variations in frequency and voltages appear to be inappreciable.

Most critical contingency is the loss of one of the HVDC poles following a S.C. cleared after 250 msec. This leads to system collapse. Loss of one pole following a fault duration of up to 100 msec leads to load shedding because of under frequency and small wind generation outages, but the system does not collapse. Other contingencies related to loss of a critical internal line following a S.C cleared within 100 msec maintain the supply of the local load but again with under frequency load shedding and also loss of a small amount of wind production. Delayed (after 500 msec) clearing of a fault at a critical line maintains the load supply but at the sacrifice of local units (that oscillate unstably and are finally desynchronized) and the total loss of wind generation.

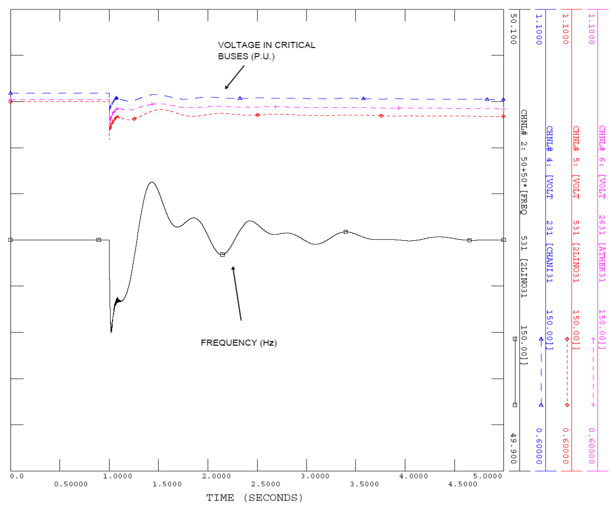

Figure 4: Frequency & voltage variation / Case A-D2

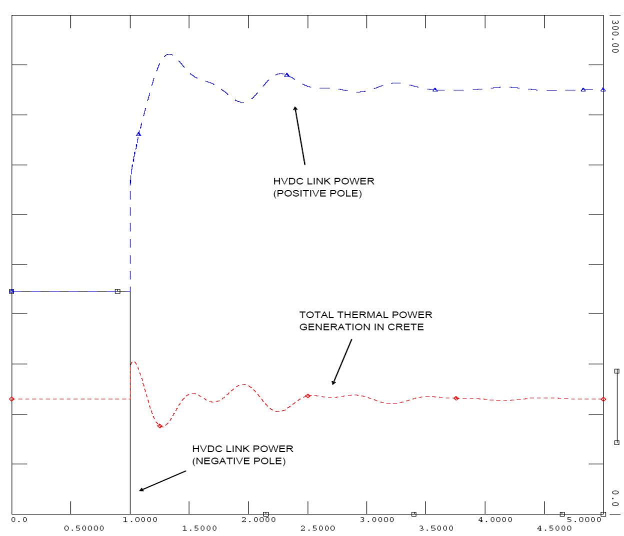

Figure 5: Active Power for DC link and thermal units / Case A-D2

Tables 3a & b summarize the main results running contingencies over scenario B. This scenario (B) refers also to high load consumption in the island and low conventional generation, but with small wind generation. This leads to high imports via the HVDC converter station, being loaded to about 80% of its capacity. Under said conditions loss of one of the HVDC poles (immediate or following a S.C.) leads to total system collapse. The loss of one internal critical line, after fast or slow fault clearing, leads to moderate load shedding (due to under frequency) and minimal or moderate wind generation outages respectively. This scenario is definitely very critical. It was further analyzed assuming action of a special protection system (SPS). The idea is to detect fault at the converter station and automatically shed a significant amount of load. This scheme is proved useful, preventing collapse in most examined cases but at the sacrifice of a significant amount of local load lost (30% of total load).

Table 3a: Scenario B comparative results

Disturbance	D1	D2	D2 (with Special Protection System)	D3 Clearing time 100 msec	D3 Clearing time 500 msec
Frequency Variation (Hz)	<0.1	Collapse	<0.2	49.7÷50.4	49.3÷50.4
Oscillations of local units	No	Unstable	Stable	Stable	Marginal Stable
Load Shedding (MW)	No	Yes	240 (auto load shedding)	90	110
Wind Power Outages (MW)	No	Yes	No	10	100

Table 3b: Scenario B comparative results

Disturbance	D4 (with Special Protection System) Clearing time 100 msec	D4 (with Special Protection System) Clearing time 250 msec
Frequency Variation (Hz)	49.8÷50.1	49.7÷50.1
Oscillations of local units	Stable	Stable
Load Shedding (MW)	250 (auto load shedding)	260 (auto load shedding)
Wind Power Outages (MW)	6	10

In Fig. 6 evolution of machine electrical angles in case of loss of one HVDC poles after a fault is shown. In case where no special measures are taken, angles rapidly deviate and within 3 seconds lead to operation of pole-slip or out-of step protection function of the machines. The tripping of all local machines in operation while HVDC link also operates in monopole configuration under stressed conditions, inevitable leads to total system collapse.

A further research made for this scenario was a step-by-step decrease of HVDC link loading with the power shortages being replaced by addition of thermal units in Crete. Based on the results of this analysis, instead of implementing a special protection system as the one proposed above, the maximum loading of HVDC link should be limited to 450 MW approximately (55% of its capacity) so as the system can withstand critical disturbances.

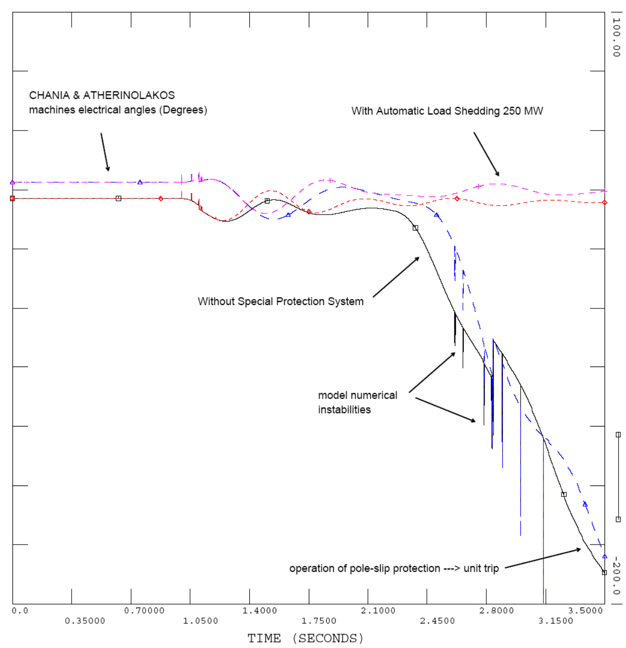

Figure 6: Machine electrical angles with & without auto load shedding - Case B-D4

Table 4 summarizes the main results running contingencies over scenario C. Scenario C refers to low consumption in Crete combined with rather high RES generation and zero conventional production. The converter station is exporting to the mainland at 45% of its capacity. In all contingencies examined the load supply in the island is maintained with small load shedding. However line faults with fast or slow clearing as well as HVDC transformer fault with slow clearing can lead to total loss of the wind production. Furthermore line faults have a severe impact on the system frequency since high amplitude oscillations appear and also the frequency is transiently decreasing down to very low levels of 44.5 Hz.

Table 4: Scenario C comparative results

Disturbance	D1	D2	D3		D4	
			Clearing time		Clearing time	
			100 msec	500 msec	100 msec	250 msec
Frequency Variation (Hz)	<0.1	<0.1	44.5÷51	46.0÷51	49.5÷51.7	49.8÷52.2
Load Shedding (MW)	No	No	16	11	23	23
Wind Power Outages (MW)	No	No	500	500	30	500

Based on the above remarks scenario C was further examined. Firstly the effect of relaxation of Wind Park overfrequency protection from 51 Hz with time delay of 100 msec to 52 Hz with time delay of 300 msec was examined. The result is illustrated in Fig. 7 where active power through HVDC link is plotted. There are less Wind Park outages of about 315 MW in case of more insensitive overfrequency protection.

Then the effect of operation of three thermal units in Crete (instead of none) on frequency transient variation in case of line fault was examined. The important impact of the operation of local units on the dynamic security of the system is illustrated in Fig. 8. The frequency response is shown for both cases, with and without machines in operation in Crete. Note that in the presence of a minimum inertia in Crete, frequency dips only down to 49 Hz and so the number and the total capacity of wind farms which are cut off due to underfrequency are significantly reduced.

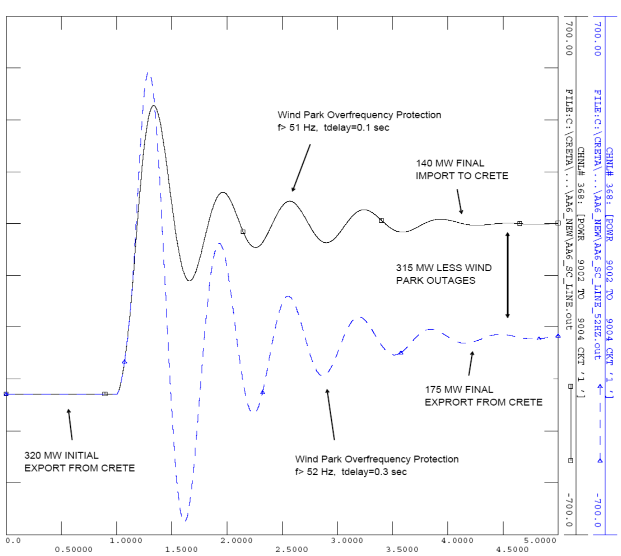

Figure 7: Effect of Wind Park Overfrequency Protection / Case C-D3

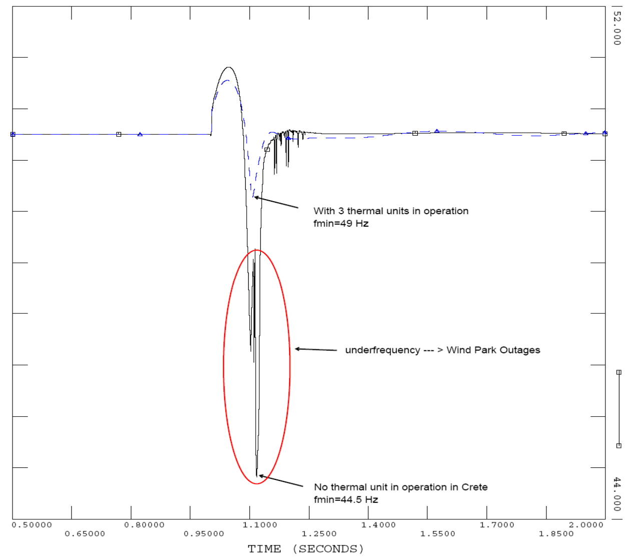

Figure 8: Effect of operation of thermal units in frequency transient variation / Case C-D3

Conclusions

The interconnection of the island of Crete to the mainland requires a heavy capital investment. It is obvious that in order to take full advantage of the benefits of this investment, the utilization of the transfer capacity offered by the HVDC converter station shall be maximized in most operating conditions. Under normal operating conditions and at several contingencies the operation is safe. Nevertheless, severe faults especially those involving the converter station or critical transmission lines near the converter substation, lead to moderate or significant loss of load and/or loss of wind generation. In some cases at high power transfer, severe faults at the converter station can lead to total collapse. A special protection system, that automatically sheds load, provides a solution but with an impact on loss of load to prevent collapse. On the other hand a moderate use of DC link up to 55% of its capacity seems to provide a solution not affecting system reliability but with possible impact in economic feasibility of the project. It is obvious that a revised feasibility analysis is needed taking into account these results.

Total loss of the converter station (both poles) for any reason, under moderate or high loading conditions, leads inevitably to system collapse. Nevertheless due to the inherent component redundancy of the modern HVDC converters and the N-1 redundancy offered by a bipolar design with return cable, the occurrence of such event seems extremely rare.

In any case the operating conditions and practices of the power system in Crete after the interconnection, will be much different than today. The system will operate with much less rotating inertia making the frequency gradient upon events much steeper. Also in several conditions the amount of imported or exported power will be much higher than that of the capacity of a single generating unit used in a power system of the size of the one in Crete.

Simulation provides also the following conclusions:

- In the presence of HVDC link the necessary reserve to serve continuous load changes or loss of generating power is provided almost exclusively by the link, due to the relatively slower response of governors driving local thermal machines.
- A minimum set of units operating in Cretan power system should be in operation, independently of load and wind condition, due to their high impact to static and dynamic security.
- Duration of fault clearing time is critical in system evolution following severe faults. In this aspect as of the protection system of HVDC converter station, the practice of installing double protection devices for any selected protection function applied (as is implemented in 400 kV system) should be adopted.
- Overfrequency protection settings applied to Wind-turbine generators should be reconsidered to become more insensitive to frequency transients that do not introduce risk for wind machines.
- Special Protection System is found also to be necessary in case of very high imports or exports via the HVDC link from the Cretan power system to the mainland. In this case SPS should be activated under severe faults involving HVDC converter stations and automatically command load shedding or wind park cut offs in order to maintain stability of the system.

In this framework it is clear that the protection scheme in the island, in view of the interconnection, has to be thoroughly reexamined and enhanced as well as the under frequency load shedding scheme. The use of an intelligent special protection system, offering quick load shedding and wind park cut offs upon converter station faults, seems also mandatory to reduce the risk of a total collapse. Under said conditions it is estimated that an adequately safe operation can be achieved. Finally upper limits in loading of HVDC link should be one of the main concerns to be clarified in view of system reliability and economic feasibility of the interconnection.

References

[1] Working Group HTSO-PPC S.A. –RAE "Development of the Electric Power System of Crete- Interconnection to the System of the Mainland", Athens Greece March 2011 http://www.desmie.gr/fileadmin/user_upload/Files/study/MELETI_DIASYNDESIS_TIS_KRITIS_EKTENIS_PERILIPSI.pdf

[2] Horle, Eriksson, Maeland, Nestli, "Electrical Supply for Offshore Installations made possible by use of VSC Technology", Presented at Cigre 2002, August 2002.

[3] Axelsson & Holm, Liljegren, Aberg & Eriksson, Tollerz, "The Gotland HVDC light project – Experiences from trial and commercial operation, CIRED 2001, 18-21 June, Conference Publication No.482, IEE 2001.

[4] L. Ronström, M. L. Hoffstein, R. Paho, M. Lahtinen, "The Estlink HVDC Light Transmission System", CIGRE Regional meeting, Tallinn, Estonia, June 18-20, 2007.

[5] Asplund G. "Application of HVDC light to Power System Enhancement, IEEE, 2000.

[6] PSS/E-32.0.5, Power System Simulator, Program Operation Manual.

[7] User guide PSS/E HVDC Light Open model Version 1.1.11, ABB Power Technologies AB.

[8] "HVDC Light - It's time to connect", ABB 2013.

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