2013 IREP Symposium-Bulk Power System Dynamics and Control –IX (IREP), August 25-30, 2013, Rethymnon, Greece

Operation and Security Assessment of the Power System of Crete with Integration of Pumped Storage and Concentrated Solar Thermal Plants

N. Sakellaridis, J. Mantzaris — Center for Renewable Energy Sources and Saving (CRES)

G. Tsourakis, C. Vournas — National Technical University of Athens (NTUA)

I. Vitellas — Hellenic Electricity Distribution Network Operator (HEDNO S.A.)

Greece

Abstract

This paper deals with operation and security assessment of the autonomous power system of the island of Crete, which has reached high levels of RES penetration. In particular the paper investigates the effect of including in the system a number of concentrated solar plants, as well as hybrid power plants consisting of wind farms and hydro generators with pumped storage. Results indicate that integration of the proposed new resources will require minor system upgrades and/or modifications of operating practice to assure static and dynamic security.

Introduction

The value of storage typically increases along with the increase of Renewable Energy Sources (RES) penetration in a power system, because of their variable production. Historically, all other variation in power systems (e.g. due to system loads or generation commitment and dispatch changes) has been handled at the system level, because overall costs are generally lower when variability is aggregated before being balanced. However, today there is also a trend towards Hybrid Power Plants (HPPs) which exploit the characteristics of different power sources while they integrate storage capability. In Crete there is an increased interest for HPPs, mostly for wind farms combined with hydro generation and pumped storage, while there are also plans for Concentrated Solar Thermal Power (CSP) plants.

The wind potential of Crete is rich and can cover a large percentage of the island load especially since there are usually high winds during summer, which is the peak load period for the system. However, several technical considerations (unit commitment limitations, static and dynamic security constraints) impose limits on the acceptable level of wind penetration in the autonomous system.

The pumped storage capability of HPPs can help towards increasing the percentage of wind share in electricity generation. Their operation should follow a specific policy framework as described in [1], but a generic rule is that pumping operation is scheduled during light load hours and the recovery of the energy stored is performed through hydro turbine generators during peak load hours to substitute the most expensive thermal generation.

The operating principle of a CSP is the concentration of sunlight onto a small area and the use of the concentrated energy as a heat source to drive a steam turbine generator. Even though CPS production depends on sunlight and is therefore statistical, it can be partially controlled within a day through heat storage, unlike grid-connected photovoltaics (PVs), which typically have no storage and are therefore intermittent energy sources.

Integrated operation of RES plants raises the issues of static and dynamic security, as well as re-scheduling of conventional power plants dispatch. In this paper static and dynamic security of the Autonomous System of Crete is investigated, in order to determine possible problems arising from the increased RES penetration, and propose solutions. The study presented was performed by the research team of NTUA for the Hellenic Electricity Distribution Network Operator (HEDNO S.A.), as a follow-up of previous studies presented in [2-4].

Description of the power system of Crete

Conventional Thermal Power Plants

The power system of Crete is the largest autonomous system in Greece with high wind and solar potential. The transmission system operates at 150 kV and incorporates three Power Stations (PS) of 851 MW total installed capacity (724 MW net), in the West, Central, and East part of the island: Chania PS, Linoperamata PS, and Atherinolakkos PS respectively, as seen in Fig. 1.

978-1-4799-0199-9/13/$31.00 ©2013 IEEE

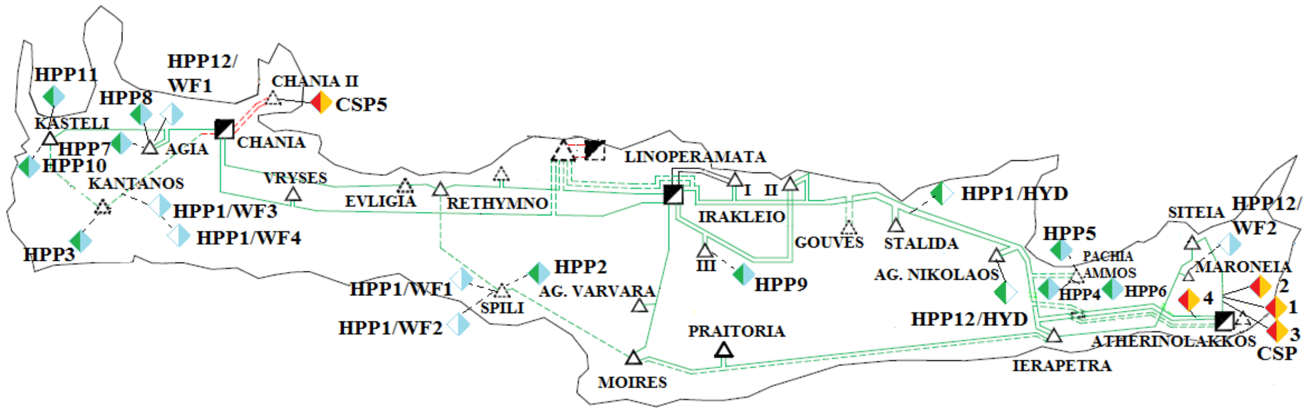

Fig.1. Geographic layout of the power system of Crete including the expected sites of HPPs and CSPs

Chania PS comprises 6 gas turbine units of about 187 MW net capacity (of which one unit of 18 MW is set to cold reserve) and one combined-cycle unit of 105 MW net capacity. Linoperamata PS incorporate 6 steam turbine units (about 101 MW net capacity with one unit of 6 MW set to cold reserve), 5 gas turbine units (105 MW net capacity and 12.8 on cold reserve), and 4 Diesel units of about 40 MW net capacity. Finally, Atherinolakkos PS consists of two steam turbine units of about 100 MW net capacity and two internal combustion units of about 86 MW net capacity.

Renewable Energy Sources Plants

At the time of this study the installed capacity of 31 Wind Farms (WFs) was 173.9 MW. The installed wind capacity in the beginning of 2013 has reached 183.5 MW according to the published data of HEDNO [5]. Most of the WFs are connected through dedicated MV lines. The wind generators used in Crete are of three types [6]:

A. Constant speed wind turbines.
C. Variable speed wind turbines with doubly-fed asynchronous generators.
D. Variable speed wind turbines with full converter.

PVs and other small RES plants are connected at the distribution level because of their small individual size. However, due to attractive financial incentives along with favorable weather conditions, the installed capacity of PVs has radically increased reaching 75 MW in the beginning of 2013 [5]. Therefore their effect to the load level seen by the system is even more prominent (considering that summer peak did not exceed 650 MW for 2012).

Transmission System

The high-voltage transmission system of Crete is operated at 150 kV. Currently in the power system of Crete there are 21 substations. The total length of overhead 150kV lines is about 570 km, and that of HV underground cables is about 7 km.

The capacitor banks, which are installed at the MV side of the substations, cover the requirement for reactive power compensation and local voltage support. Their total installed capacity reaches 225 MVAr and their contribution may be of great importance in periods of heavy loading.

Reference system conditions

The reference year of this study is set to 2017. Despite the fact that the interconnection of Crete to mainland Greece is an on-going issue of debate for several years now, in this study the power system of Crete is considered to be still autonomous, so as to remain on the safe side with respect to the ability of the system to accommodate new renewable sources. The integration of HPPs and CSPs to the power generation mix eliminates the need for addition of new thermal power plants, and therefore in this study no additional conventional thermal power plants are considered.

Regarding RES, 52 MW of new wind farms, which are planned to be installed in the next years are incorporated in the system model making the total installed wind power considered in this paper equal to 225.9 MW. The expected additional PVs effect is integrated in the expected system load of the scenarios considered.

According to available data, there are plans for twelve hydro-wind HPPs to be installed up to 2017 with 166 MW of total guaranteed power. Additionally, five CSP plants are considered of 193 MW total capacity. HPPs are geographically quite dispersed, while four of the CSPs are in the east part and one is in the west part of the island (Fig. 1). A summary of the guaranteed and installed capacities of HPPs and CSPs is given in Table I.

Table 1. Installed capacities of HPPs and CSPs

HPP no.	H: hydro, P: pump, W: wind	Guaranteed Capacity (MW)	Installed Capacity (MW)
1	H	75	100
	P	100	100
	W		39.95
	W		9.35
	W		28.9
	W		11.9
2	H	9	12
	P		12
	W		11.9
3	H	12	16
	P		16
	W		16.15
4	H	15	20
	P		20
	W		19.55
5	H	5.1	6.8
	P		6.8
	W		6.8
6	H	9	12
	P		12
	W		11.9
7	H	1.95	2.6
	P		2.6
	W		2.55
8	H	5	5
	P		5.01
	W		5.1
9	H	12	17.2
	P		20.7
	W		18
10	H	5.1	6.8
	P		6.8
	W		6.8
11	H	1.95	2.6
	P		2.6
	W		2.55
12	H	15	20
	P		20
	W		8.5
	W		11.9
CSP no.			
1	S		60
2	S		70
3	S		25
4	S		38
5	S		50

Definition of scenarios

To evaluate the impact of installing the new HPP and CSP plants on system security, reference scenarios (with different load levels) have been considered without HPPs and CSPs and they are compared to scenarios with HPPs and/or CSPs. At each scenario critical contingencies have been considered, such as transmission line loss for static security analysis, as well as unit tripping and a three-phase-fault for the examination of dynamic security.

The definition of the considered scenarios is based on the combination of load level, wind generation, hydro production/pumping and solar power generation. The scenarios correspond to extreme operation points, so that their analysis can cover all possible operation conditions in terms of security.

For the reference year 2017 maximum load of 735 MW, minimum daytime load of 300 MW, and minimum night load of 200 MW are considered.

The following constraints are taken into account:

- Technical constraints of conventional units: due to the characteristics of the units (shut-down/start-up time, technical minima, ramp-up/down load rates), some units must operate even at the minimum load.
- Penetration limit of non-dispatchable units: according to operation experience of the system of Crete, a maximum penetration level is adopted in terms of power. A corresponding value of 30% of load is set in this study for total wind generation by standard (non HPP) wind farms.
- Generation/pumping scheme of HPPs: hydro generation takes place during daytime and pumping at night.
- CSP generation is only scheduled during daytime and due to their similar nature and reduced storage capacity they all operate together.

Due to the above constraints and the size of the new planned units, a preliminary conclusion is that simultaneous operation of HPPs and CSPs is not always possible. Thus, the HPPs and the CSPs need to operate at different hours, defined by the system dispatch centre. It is thus assumed that only units of the same type (CSPs or HPPs) will operate simultaneously during low daytime load hours.

The following four cases are examined with respect to load level and wind generation:

A. No wind and maximum load (735 MW), hydro generation of HPPs and generation of CSPs. In Crete maximum load occurs during daytime, with intense sunlight and no wind. In this situation operation of HPPs and CSPs is required to satisfy system load.

B. Typical wind generation (70 MW), minimum daytime load (300 MW), wind and hydro generation of HPPs equal to their guaranteed power. In this situation HPPs substitute conventional thermal plants and should maintain the normal operation of the system.

C. Typical wind generation (70 MW), minimum daytime load (300 MW), generation by CSPs. This time the CSPs are substituting conventional thermal plants and their performance is checked.

D. Wind generation close to the penetration limit (60 MW), minimum night load (200 MW), pumping operation of HPPs. The production of standard WFs (excluding HPPs) reaches the considered penetration limit of 30%, while generation by WFs of HPPs is at 80% of their installed capacity and is absorbed for pumping. In this case the effect of heavy pumping load is examined.

The above cases A-D are combined with different degrees of integration of HPPs and CSPs corresponding to the following conditions:

0. No HPPs and CSPs considered. This is used as a reference case for judging the effects of HPP and CSP integration.
1. 166 MW of HPPs (maximum guaranteed capacity of the 12 plants) and 214 MW of CSPs (89% of the installed capacity of the five CSPs), assuming Chania PS shut down.
2. 166 MW of HPPs, or 170 MW of CSPs (70% of the installed capacity of the five CSPs with Chania PS in operation.

Combination of A-D with 0-2 gives rise to 9 meaningful scenarios A0-D1 (in D there are no CSPs and only HPP pumps are in operation, while B0 and C0 are the same, as are A1 and A2).

For the reference scenario A0 (maximum load) it is necessary to assume another 100 MW of generation in Atherinolakkos PS, meaning that if no HPPs or CSPs materialize a new generating unit is necessary. Also, in order to maintain sufficient spinning reserve, the three units which have been set in cold reserve, as mentioned above, are considered to be back in service.

Static security assessment

System Modeling

The network modeling of the high-voltage power system of Crete and the relative load flow studies have been realized in Siemens PSS/E^{TM} [7]. All HV circuits have been included, along with some dedicated MV circuits for the connection of WFs. The loads are connected to MV buses of substations and the generators are connected through step-up transformers. For constant speed wind generators appropriate reactive compensation is assumed at low voltage, so that they operate at 0.95 power factor lagging. Variable speed wind generators are assumed to operate at unity power factor. Capacitor banks are connected to the MV buses of the substations and are represented through the switched shunt data record of Siemens PSS/E^{TM}.

The system model includes 270 buses, 151 branches, 167 transformers, 115 machines (30 thermal units, 12 hydro generators of HPPs, 5 CSP generators, 49 WFs, and 19 pump motors), 34 capacitor banks, and 34 aggregate loads.

Problems and proposed countermeasures

Static security assessment includes the examination of voltage levels and circuit loadings at a specific operational snapshot (scenario) through the execution of load flow analysis for normal (N) and all single outages (N-1 contingency analysis) excluding the loss of radial connections. The typical security limits adopted are:

For bus voltages:
- ± 5% of the nominal value for normal operating conditions (N)
- ± 10% of the nominal value for N-1 conditions

For branches:
- Thermal limit corresponding to each conductor type

For the power system of Crete the conductor types for 150 kV overhead lines are: Aluminum Conductor Steel Reinforced (ACSR) light type (E), ACSR heavy type (B), Aluminum Conductor Steel Supported (ACSS) (Z). Also there are some underground connections using 150kV XLPE cables. The thermal limits of these conductors are shown in Table 2 [8]

Table 2. Thermal limits of electrical conductors

Conductor Type	**Thermal limit 1[(1)] (MVA)**	**Thermal limit 2[(2)] (MVA)**
E/150 kV	117	90
B/ 150 kV	169	140
Z//150 kV	200	166
XLPE/150 kV	200	200

(1) Nominal operating conditions
(2) Extreme operating conditions (42°C, no wind)

As will be seen in detail below, static security analysis showed that in order to accommodate the proposed HPPs and CSPs a few reinforcements of the existing transmission system are required. Also, the installation of an automatic system for connecting/disconnecting capacitor banks at certain substations is proposed as an alternative to maintaining must-run operating practices for some units.

More specifically, in the analysis it is assumed that special controllers are installed at certain HV/MV substations, which monitor the local transmission voltage (HV) and order the connection of a capacitor bank if the voltage is less than 95%. It is also assumed that this connection of capacitor banks is based on inverse time logic, so that the capacitor banks at the substations with the lower voltage are connected first. The voltage correction by means of the automated capacitor banks has been considered only if the voltage does not reach levels below 80% after the contingency, as lower voltages cannot be tolerated even for the limited time required to automatically connect the capacitors.

Scenarios A

Scenarios A correspond to maximum loading conditions, during summer period, and therefore thermal limit 2 is considered for static security assessment.

In the reference scenario A0 the load of 735 MW is served without HPPs and CSPs. Generation is 257.3 MW at Chania PS, 223.5 MW at Linoperamata PS, and 264 MW at Atherinolakkos PS. Because of the stressed loading conditions it has been assumed that capacitor banks are switched on, so as to maintain a lagging power factor close to unity. Under these assumptions the studies have shown that secure operation is achieved at normal and all N-1 conditions considered.

In scenario A1 the operation of HPPs (166 MW) and CSPs (214 MW) is introduced. The generation of thermal plants is then is then restricted to 169.4 MW at Chania PS, 36 MW at Linoperamata PS, and 172.8 MW at Atherinolakkos PS. Undervoltage problems did not appear at normal operating condition. However, upon the loss of some critical circuits security violations were observed.

In particular, the loss of any circuit of the transmission line Linoperamata, Gouves, Pachia Ammos, Atherinolakkos leads to overloading of the circuit Stalida-Koutralia (Koutralia is the substation where the hydro plant of HPP1 is connected). This is partially due to the fact that the restrictive thermal limit 2 has been assumed. Additionally, the loss of the circuit Stalida – Koutralia incurs severe undervoltage (<0.9 pu) at the HV bus of substation Stalida, while there is reactive power shortage (the reactive power output of the slack bus exceeds its limits by about 12 MVAr). Therefore the actual voltage levels will be even lower. This situation is shown in the one-line diagram of Fig. 2, which corresponds to the area close to Stalida substation. The production of the hydro plant of HPP1 is also shown in this figure.

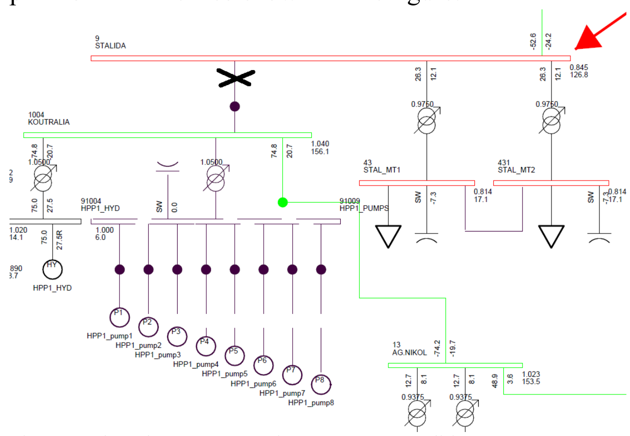

Fig. 2. Undervoltages at scenario A1, “N-1” Condition

If an automatic capacitor switching system is utilized according to the above voltages are restored and the system is N-1 secure.

As an alternative to the automatic capacitor scheme, another connection of Koutralia substation (HPP1) has been investigated and in particular a direct connection with a double circuit line to the Stalida substation as in Fig. 3. With this configuration the system is secure under all N-1 contingencies without the need for capacitor switching.

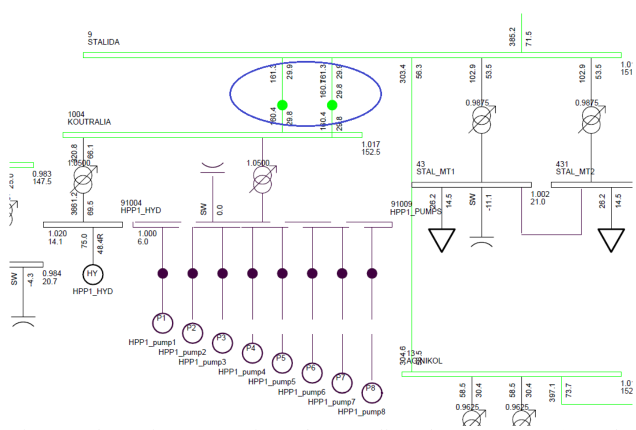

Fig. 3. Alternative connection of Koutralia substation (HPP1) to the System

Scenarios B

In scenarios B the effect of the hydro generation of HPPs at low daytime load conditions is examined. The static security analysis of the system for scenario BC0 (reference scenario – no HPPs) showed that the system is N and N-1 secure.

In scenario B1 the Chania PS (west part of the island) is considered out of service to investigate if this operation pattern is feasible. The load of 300 MW is fed by generation of 73 MW at Atherinolakkos PS, 70 MW of standard wind farms and 166 MW of HPPs (total guaranteed capacity of 12 HPPs coming from both hydro and wind). Because of the low load conditions no capacitor banks are switched on.

The system is N secure for this scenario. However, voltages are relatively low, especially in the west part of the island, e.g. at Chania substation where transmission voltages are close to 0.96 pu. This is due to the fact that production is mostly located in the eastern part of the system.

In this case N-1 security analysis resulted in three critical contingencies with security violations:

1. Loss of Rethymno - Evligia circuit
2. Loss of Linoperamata - Stalida circuit
3. Loss of Stalida - Koutralia (HPP1) circuit.

The common characteristic of all the above contingencies is the severe voltage drops in the western part of the island and below acceptable limits, because the weakening of the main East-West electrical corridor results in lack of reactive power in the western part.

The simulation of these contingencies showed that the required reactive generation at the slack bus exceeded the upper limits of the unit: by 11 MVAr for contingency 1 and 30 MVAr for contingency 2, while for contingency 3 the load flow did not converge. The low-voltage situation for contingency 1 in the western part of the system is shown in Fig. 4.

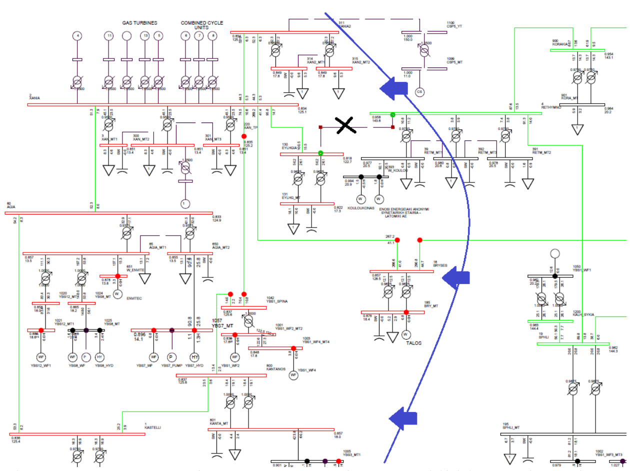

Fig. 4. Western part of power system of Crete exhibiting under-voltages – Scenario B1, Contingency 1

Clearly for scenario B1 (where Chania PS is not in operation) new capacitor installation is necessary. For instance, introducing new capacitive compensation in Chania 2 substation is sufficient to restore security for contingency 1, since voltages remain above 0.9 pu (Fig. 5).

For contingencies 2 and 3 besides the new capacitors installed at Chania 2 substation, the operation of an automatic capacitor switching scheme is necessary to restore security. In particular the switching of capacitors at Chania and Agia substations is sufficient for restoration of security for contingency 2, while switching of capacitors at Chania, Agia, and Kasteli substations is required for contingency 3.

In conclusion, if the combined cycle units of Chania PS are allowed to shut down in the considered low daytime load conditions, new capacitive compensation and an appropriately designed automatic switched capacitor system are required for the secure operation of the system.

In scenario B2, Chania PS is considered in service producing 36 MW, while the generation of HPPs is 166 MW and that of WFs 70 MW. The remaining 37.2 MW come from Atherinolakkos PS. As expected, static security analysis did not detect any problems for normal and N-1 conditions, as now the generation is balanced between East and West.

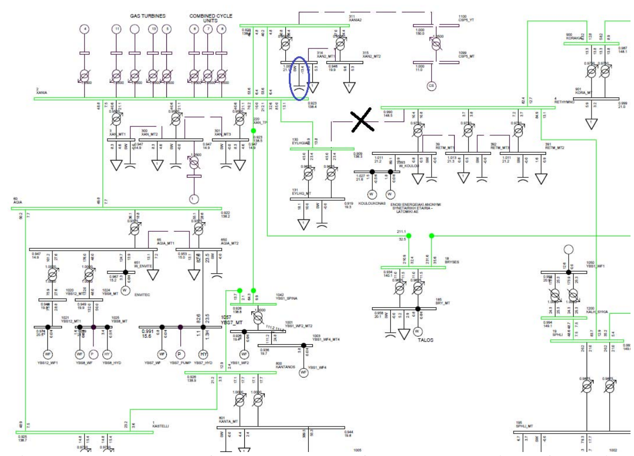

Fig. 5. Western part of power system of Crete, restoration of security. Installed capacitors at Chania 2– Scenario B1, Contingency 1

Scenarios C

In scenarios C the effect of CSPs is examined. In scenario C1 generation is dispatched as follows: 214 MW is CSPs production, 70 MW come from WFs, and 28.2 MW from conventional units (25.2 MW from Atherinolakkos PS and 3 MW from a small unit at Linoperamata PS).

Again the absence of generation in the western part is expected to raise security issues. In fact even in the normal operating condition, the reactive power output of CSP 5 has reached its upper limit. Additionally, in Table 3 the critical contingencies for this scenario are shown, along with the shortage of reactive power induced by each of them.

Table 3. Critical contingencies for scenario C1

No.	Critical contingency	Reactive power deficit (MVAr)
1	Stalida - Koutralia (HPP1)	2
2	Agios Nikolaos – CSP4	11.5
3	Agios Nikolaos - Koutralia (HPP1)	3
4	Pachia Ammos – Gouves	3.5
5	Atherinolakkos – Pachia Ammos	8
6	Atherinolakkos – CSP3	26
7	Chania 2 – CSP5	voltage collapse

The first six critical contingencies of Table 3 correspond to loss of a power transfer path from the eastern to the western part. For instance, as can be seen in Fig. 1, CSPs 1, 2, and 3 are connected to the single-circuit line Atherinolakkos-Siteia. When a part of this line is tripped (e.g contingency 6) the generation of the three CSPs (134 MW) is transferred through the remaining part towards Siteia substation. This weak connection deteriorates the reactive power deficit (violation of 26 MVAr at the slack bus). On the other hand the loss of the underground cable connecting CSP 5, leads to a voltage collapse, meaning that an additional parallel cable is required.

It is clear that, in order for scenario C1 to be secure, more capacitors should be in service even in normal N operation condition. With the addition of capacitors at Chania 2 substation normal operation (no reactive power deficit) is restored in N condition and for all the contingencies except for contingency 6, where a deficit of 14 MVar persists (see Fig. 6). In addition, there are still undervoltage problems for contingencies 2 (see Fig. 7) and 5. Use of the automatic capacitor switching scheme can alleviate voltage drops and restore security. For instance, switching of capacitors at Ag. Nikolaos substation after contingency 2 restores voltages and security (Fig. 8).

Another important issue is the appropriate regulation of the excitation of generators during normal operating conditions. Generators with weak connection to the system should be excited close to their limits, while others should maintain excitation at relatively lower levels. For instance, Atherinolakkos PS should have enough reactive reserve to provide in case of contingency, since it is closely connected to the transmission system and can greatly increase transfer capability to the western part of the island.

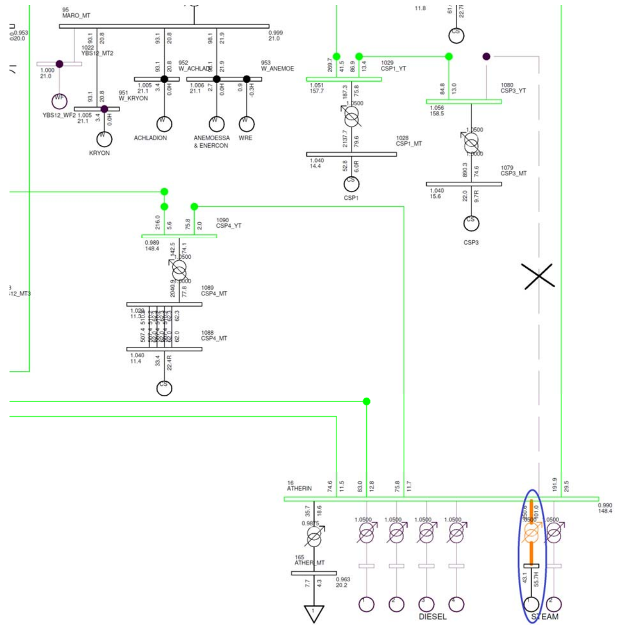

Fig. 6. Reactive power shortage for contingency 6 after the addition of capacitors at Chania 2 substation – Scenario C1.

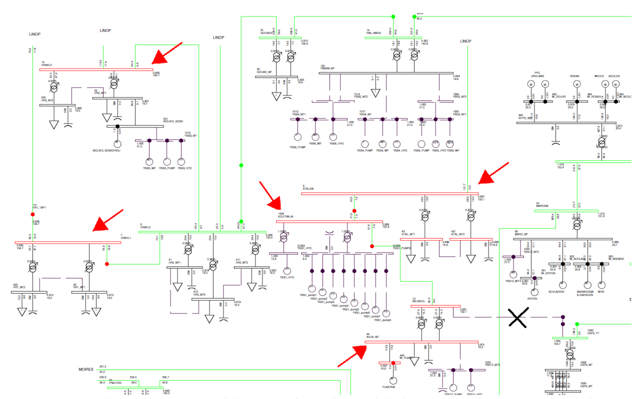

Fig. 7. Undervoltage problems after the addition of capacitors at Chania 2 substation – Scenario C1, Contingency 2

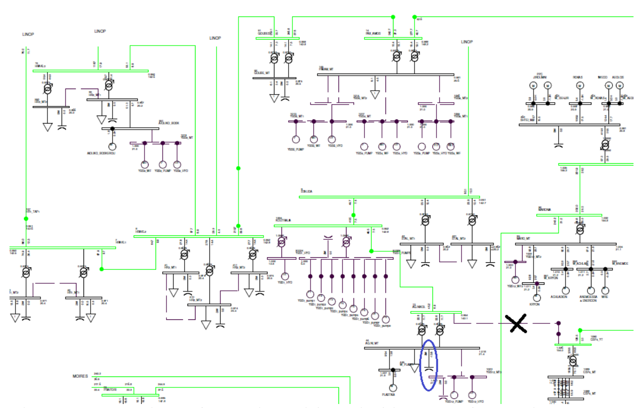

Fig. 8. Restoration of security with switching-on of capacitors at Ag. Nikolaos substation after Contingency 2 – Scenario C1

Again, security conditions are much better in scenario C2, where Chania PS is in operation and CSPs generation is reduced to 170 MW (70% of their installed capacity). The geographic distribution of generation is now more balanced, which results in more efficient voltage support at transmission level. As a consequence, the system is secure under normal and N-1 conditions, even for severe contingencies, such as 6 and 7 of Table 3.

Scenarios D

The effect of extensive pumping load of HPPs is studied in scenarios D. Reference scenario D0 refers to minimum night load where the wind generation of conventional WFs is restricted to 60 MW (corresponding to the dynamic penetration limit of 30%). The thermal plants power output is 35 MW at Chania PS and 105 MW at Atherinolakkos PS. Static security analysis showed no problems for normal operating conditions and all N-1 contingencies.

In scenario D1 the WFs of HPPs are generating about 170 MW, which are consumed by the corresponding pumps. At normal operating conditions no violations occur in the transmission system. However, switching of capacitors at the MV buses of pumps of HPPs 1, 4, and 12 is required for maintaining voltage values. Also in WFs 1 and 2 of HPP 12, the long MV line connection induces some local overvoltages. These issues in the MV level should be corrected either with an appropriate compensation scheme, or the connection with more MV circuits in parallel.

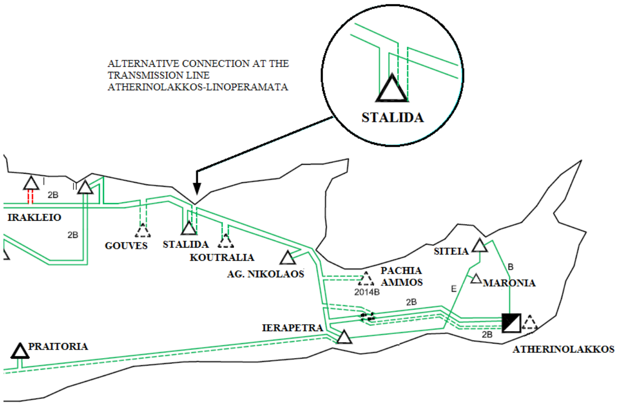

Fig. 9. Reinforcement of connection of Stalida substation for restoration of security – Scenario D1

The N-1 analysis showed that the loss of the circuit Atherinolakkos-Ag. Nikolaos is a critical contingency since it results in voltage collapse, as the remaining path to the heavy pumping load becomes too long. For this reason an alternative connection of HPP1 to the system should be adopted. For instance the connection of Stalida substation could be reinforced with the addition of another double-circuit line connecting through a two-port configuration to the transmission line Atherinolakkos-Linoperamata which in the present configuration bypasses Stalida substation (Fig. 9). Equivalently, Koutralia (HPP1) substation could be directly connected to Stalida substation with a double-circuit line. With any of the above upgrades, no security violations were observed for all N-1 contingencies.

Dynamic security assessment

The dynamic security analysis presented in this section is indicative, rather than exhaustive. In the power system of Crete, dynamic security mainly refers to frequency stability due to the autonomous system nature and the low inertia, especially at light load. This issue is aggravated when many wind parks are in operation, as they substitute conventional plants, while variable-speed wind turbines do not usually provide inertia [9], even though modern wind turbines have the capability to provide inertia emulation on demand [10]. Frequency stability of the system of Crete is protected by an appropriately tuned system of underfrequency and Rate of Change of Frequency (RoCof) relays.

The simulation of the power system dynamic behavior requires detailed modeling of its components. These include generators, loads, and protection devices. In this project, the simulations were performed using Siemens PSS/E^{TM}. Modeling of the power system components follows [2] and is not repeated in detail here. Dynamic models of the PSS/E^{TM} model library are used for: synchronous generators (conventional thermal plants, hydro and CSPs), induction generators (type A wind generators), induction motors (pumps), control systems of synchronous generators (excitation systems and governors), type C and D wind generators. Note that for CSPs a steam turbine model is used (IEEEG1).

Following common practice, wind farms are represented by one equivalent machine (assuming wind generators of each farm are identical and subject to the same average wind conditions). Wind farms of the planned HPPs are assumed to be equipped with type C wind generators. Reactive power control of variable speed wind generators is assumed to keep constant power factor (p.f. = 1) with no explicit voltage support programmed during voltage drops [11]. Also, in order to remain on the safe side, no inertia emulation is assumed for variable-speed wind turbines.

Relays that disconnect the wind farms if voltage or frequency exceeds certain limits are incorporated in the dynamic mode. Type – A wind generators are not equipped with Low Voltage Ride Through (LVRT) capability, as they are older installations. All variable speed wind generators are modeled to remain in operation as long as the voltage remains above the solid line of Fig. 10, which is a stepwise approximation of a typical LVRT curve.

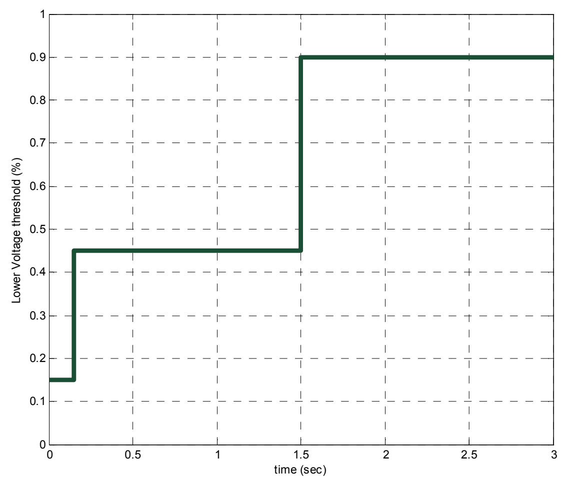

Fig. 10. Low Voltage Ride Through capability of variable-speed wind generators

It is noted that, as in [2], all HPPs pumping installations are modeled as one equivalent pump, except of the largest one (75 MW guaranteed capacity, HPP 1), where 8 individual pumps are modeled.

Simulations of disturbance

The examined critical disturbances are the loss of the largest unit and a three-phase fault in a critical location.

Loss of the largest unit

The loss of the largest unit (CSP 2, producing 49 MW) is first simulated for scenario C2. The disturbance occurs at t = 1 s. The corresponding system frequency response is depicted in Fig. 11, while Fig. 12 shows the active power consumption of indicative loads. A total load shedding of 39 MW occurs in this case. At the moment of frequency minimum (about t = 4 s) the largest load shedding of about 17 MW from Irakleio 3 substation is taking place, due to underfrequency.

Primary frequency control is mainly provided by the gas turbine of the combined cycle unit of Chania PS, as the rest of the generators are driven by slow steam turbines (conventional or CSP). It is noted that in this scenario the only conventional units in operation are the combined cycle in Chania PS (producing a total of 36 MW) and one steam turbine in Atherinolakkos PS (producing another 36 MW).

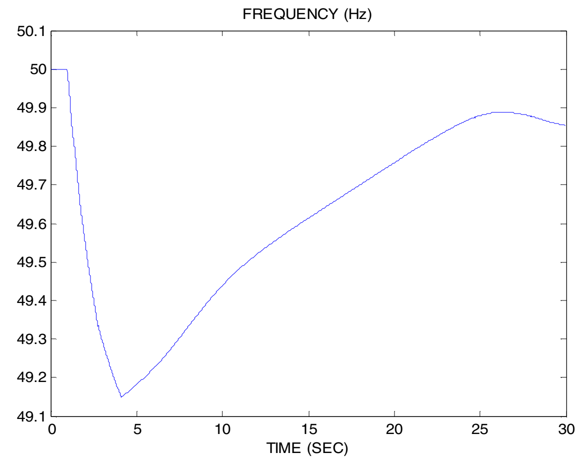

Fig. 11. System frequency response - loss of CSP 2, scenario C2

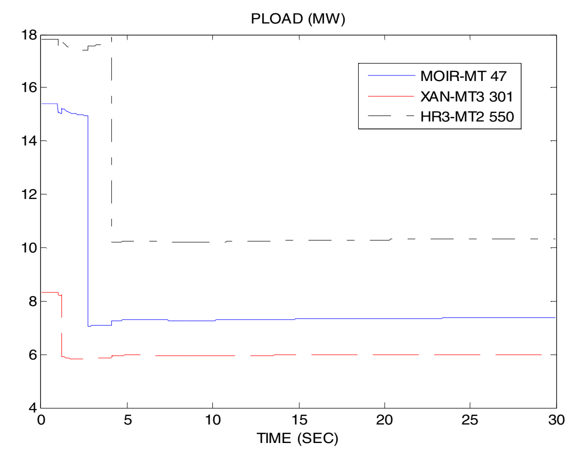

Fig. 12. Load active power consumption - loss of CSP 2, scenario C2

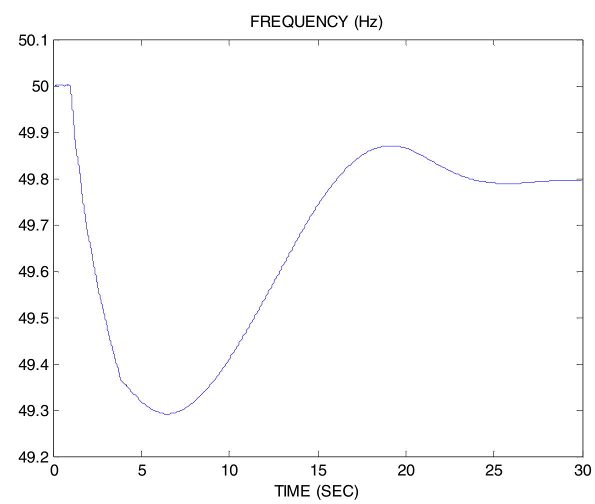

Fig. 13. System frequency - loss of Chania CC unit, scenario BC0

To estimate the effect of CSPs on the system security level, the corresponding disturbance is simulated for scenario BC0, where there is only conventional generation: 4 steam turbines in Linoperamata PS, the combined cycle in

Chania PS, two steam turbines and one Diesel unit in Atherinolakkos PS. In this case, the largest unit is the combined cycle at Chania PS (producing a total of 50 MW). Its loss results to load shedding of about 21 MW, i.e. it is lower comparing to scenario C2. The system frequency response in this case is shown in Fig. 13.

In this case, even though the gas turbine of the combined cycle is lost, the Diesel unit response is significantly faster comparing to the steam turbines. It can thus be deduced that the substitution of the Diesel units by CSPs (which due to the steam turbines have slower transient response to frequency deviations) reduces the system dynamic security.

Three-phase fault

A three-phase fault is first simulated for scenario D1. It is assumed that Koutralia (HPP1) substation is directly connected to Stalida substation, as proposed by the static security analysis in the previous section, so that the scenario is statically safe. In this scenario it is assumed that the pumps of the HPPs are in operation. The fault is assumed to occur at a middle point of the circuit Atherinolakkos PS – Ag. Nikolaos, lasts for 120 ms and is cleared with simultaneous opening at both ends of the circuit. The voltage at some 150 kV buses is shown in Fig. 14.

Note that for the dynamic modeling it is assumed that the pumps are driven by induction motors directly connected to the grid [2]. Therefore the voltage drop due to the fault causes deceleration of nearby pumps (of HPP 1 and 12), which results to instability and stalling.

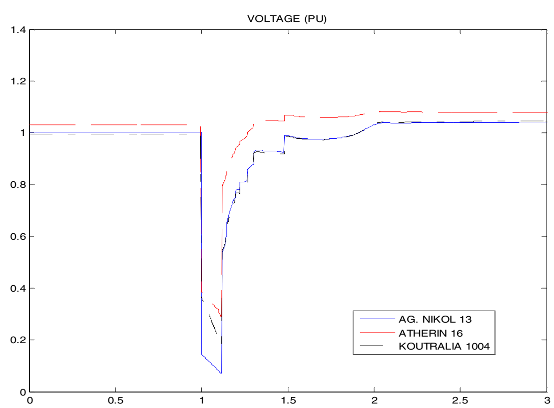

Fig. 14. Voltage of indicative buses – three-phase fault, scenario D1

In the simulation a deceleration protection is assumed for the pump motors. This protection is activated and disconnects the pump of HPP 12 when the motor slip reaches 14%. The pumps of HPP 1 are assumed to be disconnected gradually, i.e. the 1st at 14% slip, 2nd at 15% slip, etc. up to the 5th which is disconnected at 18% slip. Fig. 15 shows the rotor speed deviation of pumps 1, 5, and 6 of HPP 1 (pumps 7 and 8 of HPP 1 are not in operation).

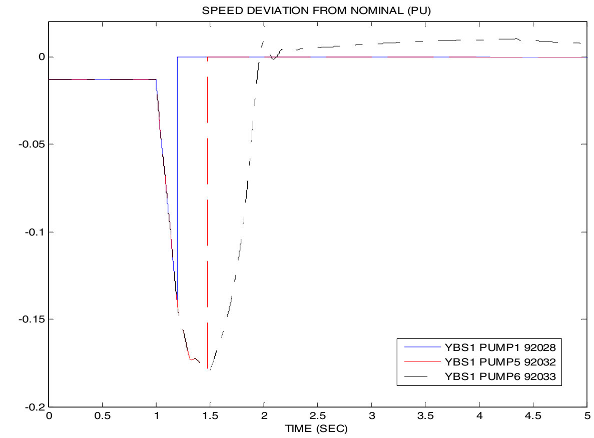

Fig. 15. Rotor speed of HPP 1 pumps – three-phase fault, scenario D1

Figure 16 shows the system frequency response. It can be seen that the frequency continues to increase after the fault clearance because of the loss of the pumps (76 MW total load loss).

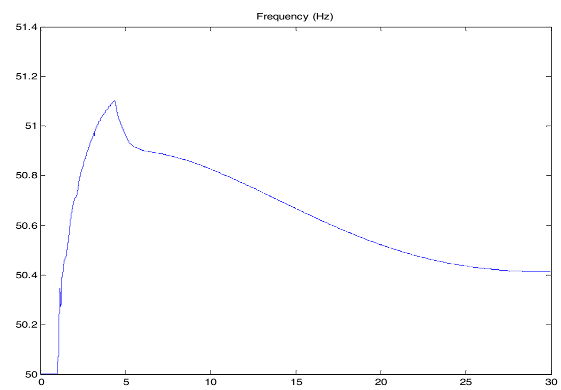

Fig. 16. System frequency response – three phase fault, scenario D1

As shown in Fig. 17, the thermal units reduce their production, to prevent frequency increase. However, the frequency transiently exceeds 51 Hz, which results to disconnection of some wind parks due to operation of overfrequency relays, as shown in Fig. 18.

As a conclusion, the system is marginally insecure at the considered high level of pumping, because the overfrequency beyond 51 Hz may cause disconnection of conventional units (their overfrequency protection is not explicitly simulated) and system black out. It is again noted that, as HPPs are in planning phase, pumps are simulated as driven by directly connected induction motors, which are prone to instability in case of voltage drop (worst case scenario).

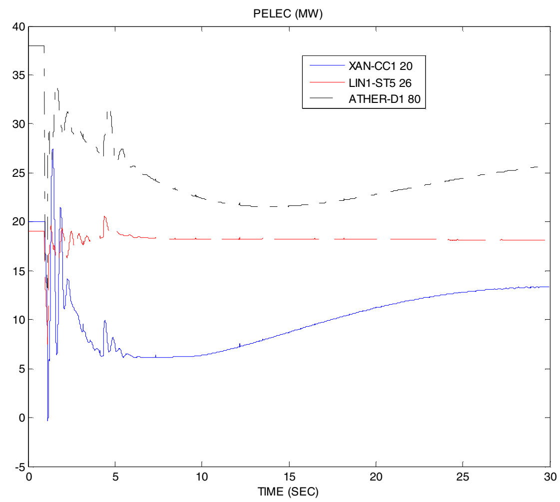

Fig. 17. Active power of conventional units: gas turbine (blue), steam turbine (red), Diesel unit (black) – three-phase fault, scenario D1

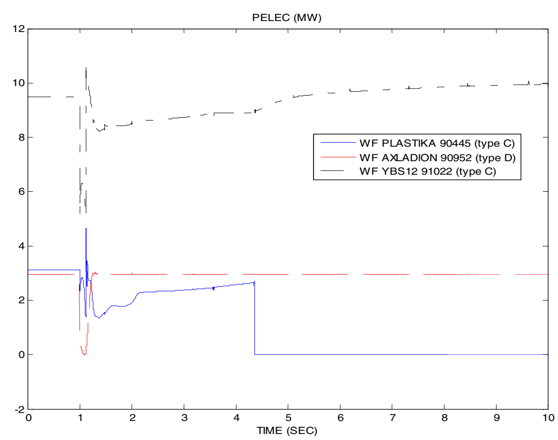

Fig. 18. Active power of wind farms – three-phase fault, scenario D1

Conclusions

According to the findings of the study presented in this paper the power system of Crete for year 2017 can maintain static security with the presence of the proposed HPPS and CSPs provided that the following conditions are fulfiled:

- Reinforcement of the connection scheme of large power plants in potentially weak points of the transmission system (e.g. HPP1, CSP 5).
- Introduction of an automatic switched capacitor scheme, following inverse-time logic for the maintenance of voltages within acceptable levels. Detailed design of this system requires special studies.

Alternatively, if the Chania PS is considered as must-run in all cases, the automatic capacitor switching scheme is not necessary.

The indicative studies conducted for the dynamic response of the system resulted in two basic preliminary conclusions:

- The incorporation of 170 MW CSPs (scenario C2) increases total load shedding, in case of loss of the largest unit, comparing to the reference scenario BC0. Therefore, the operation of the system with this penetration level of CSP is considered insecure and CSP penetration limits should be set lower than 170 MW.
- In the case of three-phase faults when pumping operation is significant, the power system may encounter overfreqency problems due to stalling and subsequent disconnection of pumps.

An alternative to setting a lower penetration limit to CSPs is to adopt an operational practice that will always have fast Diesel units with adequate spinning reserve in operation, so as to improve frequency control.

Pump disconnection phenomena may be avoided if pumps are driven by variable speed motors or if they incorporate power electronics controls. Alternatively, a combined protection scheme could be introduced that will automatically trip pumps and wind farms of equal capacity belonging to the same HPP.

Clearly further studies will be required as the first HPP and CSP will start being realized in the system, but so far it is safe to assume that they can be smoothly integrated when appropriate care is taken.

References

[1] S. Papaefthimiou, E. Karamanou, S. Papathanassiou, and M. Papadopoulos, "Operating policies for wind-pumped storage hybrid power stations in island grids," Renewable Power Generation, IET, vol. 3, no. 3, pp. 293-307, 2009.

[2] N.G. Sakellaridis, J.C. Mantzaris, S.A. Papathanassiou, I. Vitellas, C.D Vournas, "Security assessment of an autonomous system with increased wind penetration and pumped storage hybrid plants", Power and Energy Society General Meeting, 2012 IEEE , vol., no., pp.1,8, 22-26 July 2012

[3] I. Margaris, J. Mantzaris, M. Karystianos, A. Tsouchnikas, C. Vournas, N. Hatziargyriou, and I. Vitellas, "Methods for evaluating penetration levels of wind generation in autonomous systems," in PowerTech, 2009, IEEE Bucharest. IEEE, 2009, pp. 1–7.

[4] E. Karapidakis, "Transient analysis of Crete's power system with increased wind power penetration," in Power Engineering, Energy and Electrical Drives, 2007. POWERENG 2007. International Conference on. IEEE, 2007, pp. 18–22.

[5] Hellenic Electricity Distribution Network Operator SA. Available at http://www.deddie.gr/Default.aspx?id=12294&nt=105&lang=1

[6] P. Pourbeik (convener), "Modeling and dynamic behavior of wind generation as it relates to power system control and dynamic performance", CIGRE, WG C4.601, Paris, France, Tech. Brochure 328, Aug. 2007

[7] PSS/E-32 Program Operation Manual, Siemens Power Technologies Inc

[8] Public Power Corporation (PPC) S.A., "Transmission System Development Plan of Non-Interconnected Islands 2010-2014," Oct. 2010.

[9] G. Lalor, A. Mullane, M.J. O' Malley, "Frequency Control and wind turbine technologies", IEEE Transactions on Power Systems, Vol. 20, No. 4, Nov. 2005.

[10] N. W. Miller, K. Clark, M. Shao, "Impact of frequency responsive wind plant controls on grid performance", 9th Int. Workshop on Large-Scale Integration of Wind Power, Quebec, Canada, Oct. 18-19, 2010.

[11] A. Ellis, Y. Kazachkov, E. Muljadi, P. Pourbeik, J.J. Sanchez-Gasca, "Description and technical specifications for generic WTG models - A status report", IEEE PSCE, 2011.