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Methods for evaluating penetration levels of wind generation in autonomous systems

I. D. Margaris[1], J. C. Mantzaris[1], M. E. Karystianos[1], A. I. Tsouchnikas[1], *Student Member IEEE*, C. D. Vournas[1], *Fellow Member IEEE*, N. D. Hatziargyriou[1,2], *Fellow Member IEEE*, I. C. Vitellas[2]

Abstract--During the last decades there has been a continuous growth of wind power generation. This trend, especially in Greek islands, where wind potential is high, raises the issue of acceptable penetration levels of wind generation especially in autonomous systems. This work is part of a research program between PPC S.A. –of Greece and NTUA. The method is applied to two islands, Crete and Rhodes, where wind power penetration is expected to be increased within the next years. The power grid of each island is modeled and speed governors, automatic voltage regulators of conventional plants, as well as wind turbines are modeled in detail. Case studies are formed and simulation results are produced, discussed and eventually the penetration levels are determined, together with proposed measures to increase them.

Index Terms--Wind Generation, Wind Penetration, Autonomous systems, Renewable energy, under frequency load shedding.

I. INTRODUCTION

This paper summarizes the results of a research project between Public Power Corporation (PPC S.A.) of Greece and the National Technical University of Athens (NTUA). In this project a method was developed in order to determine the acceptable level of wind farm penetration in island systems from the viewpoint of system stability. The proposed method was applied to the Greek islands of Crete and Rhodes.

During the last decades there has been a continuous increase in the contribution of renewable energy resources to the total energy production. These changes raise certain issues as power system operation is reformed. Despite the fact that new wind farms (WF) are continuously constructed and are connected to the power grid, there is no general method which determines the acceptable levels of wind farm penetration. These levels are usually determined as a percentage (25-30%) of annual peak load. This percentage is mostly based on operational experience and it does not take into account the topological and electrical characteristics of each autonomous power system.

The paper is structured as follows: In section II some basic characteristics of the autonomous systems on which this method was applied are presented. In section III modeling components of power system such as generators, Automatic Voltage Regulators (AVR), Speed Governors and Wind Farms are analyzed. The dynamic response of these components is critical, as the ability of speed governors to increase power production of power plants and the response of Wind Generators to disturbances determine the overall response of the autonomous system and to what extent underfrequency protection relays are activated to disconnect loads. In section IV, the method developed is presented. In section V simulation results are presented. In section VI discussion of simulation results is being done. In the last section conclusions of this work are presented.

[1] Authors are with National Technical University of Athens School of Electrical and Computer Eng. Electric Energy Systems Lab

[2] Authors are with Public Power Corporation S.A. Athens, Greece

II. SYSTEMS STUDIED

As mentioned above the case studies for this project were two autonomous islands with different size, peak load demand and wind farms, Crete and Rhodes.

TABLE I
BASIC CHARACTERISTICS OF TWO AUTONOMOUS SYSTEMS STUDIED (projected 2012)

	Crete	**Rhodes**
Max Power Demand (MW)	817.8	233.1
Rated Thermal Power (MW)	1055.4	322.9
Rated Wind Power Generation	176.8	48.8

In Crete generation and loads are distributed in the area of the island. Specifically there are four thermal power plants in the scenario of 2012. On the contrary in Rhodes, which is smaller, thermal power generation is concentrated to two thermal plants. However it is very important that most of the rated wind power generation of Crete is on the East side which creates certain difficulties in system operation under heavy disturbances.

III. MODELING POWER SYSTEM COMPONENTS

A variety of software packages, which provide the means for power systems simulations, are available nowadays. For the research project, PSS/E and Matlab models were used for modeling thermal power plants, AVR and wind farms.

Specifically for the wind farms operating in the autonomous systems, three different kinds of wind turbine technologies were considered:

- Fixed speed wind turbines equipped with induction generator, [1].
- Variable speed wind turbines with doubly fed induction generator (DFIG), [2], [3].
- Variable speed wind turbines with synchronous generator and full converter unit (DDSG), [3], [4], [5].

After the comparative study with the user-owned models, the model CIMTR1 from the library of the PSS/E was used to implement the constant speed wind turbines. Accordingly, appropriate models for the variable speed wind turbines were designed and the required adjustments were made to include the fault ride-through capabilities (FRT) of these technologies. Each wind farm operating in the Crete Power System was represented based on the aggregated turbine approach [6].

As far as speed governor of thermal power plants is concerned, four models were used. GAST2A for gas turbines, GGOV1 for combined cycle plants, DEGOV1 for Diesel Generators and the general model IEEEG1 for Steam Plants. The most crucial part of speed governor modeling was the part of open and combined cycle gas turbine as their response is more complex and accuracy on emergency rate of load pick-up contributes significantly to simulation results. During the study, user-defined models for the wind farms and speed governors were built in the Matlab/Simulink environment [7]-[9] and were compared to the ones available by PSS/E [10], [11].

For AVR modeling, SEXS, EXST1, IEEET2, ESST4B models from PSS/E library were used for the exciters and voltage regulators of conventional units.

IV. Methodology of Penetration Level Estimation

This procedure includes the development of the methodology criteria, which ensure the secure operation of autonomous systems, with emphasis on the evaluation of the dynamic behavior of the system following severe disturbances in the grid. The methodology proposed in this paper for estimating the secure penetration level of wind energy in autonomous systems can be analyzed in the following steps:

A. Operating scenarios

Regarding the first step of the approach, the operating scenarios have to be carefully defined. These scenarios are based on collected operational data of the power system and correspond to the possible severe condition of operation. In this way, it is ensured that their analysis covers the intermediate modes of operation in terms of security. Three reference scenarios were defined as follows:

- The Peak Load Demand scenario – (a).
- The Maximum Wind Power Production scenario (in absolute values of power) – (b).
- The Maximum Wind Power Penetration scenario (in percentage of the load demand) – (c).

The first scenario is the base case scenario and is used to evaluate the operational mode of the system in terms of security without significant wind power production, because annual peak load occurs in a hot summer day with typically very low wind. The second scenario is used to investigate security with large wind power production levels. In this case the levels of wind penetration are quite high going beyond 20% of the total load demand. The third scenario examines a penetration level above the 30% margin, which has been used until now for wind energy as a rule of thumb in autonomous island systems.

B. Selection of critical disturbances

The subsequent step of the methodology defines the critical disturbances, which will be simulated using the developed models of the power system. These disturbances include extreme fault conditions, and are being used to evaluate the dynamic security of the system. According to the grid codes, these disturbances should comply with the N-1 criterion. For the dynamic security analysis, two major categories of grid disturbances were examined:

- Loss of power production and specifically loss of the larger unit in operation. In the case of Crete, this is a combined cycle plant operating in the system. The unit loss includes a gas unit and the corresponding percentage of power produced by the steam turbine.

- Fault in critical areas of the systems (lines that connect power stations, near wind farms). In this case three-phase faults were examined, although they are quite rare in practice. For each fault two different clearing procedures are considered: a fast clearing time of 100 ms (Zone I protection), and delayed clearing time of 500 ms (Zone II protection).

C. Defining acceptable penetration levels of wind farm applications

During the final phase of the methodology, the response of the power system under the defined scenarios and the defined disturbances is analyzed in the simulation platform. The critical variables of the system such as the system frequency, the voltage dips, their time duration and the loads being shed due to under frequency relays are studied. Depending on these results the dynamic security criteria are set. The potential increase in the penetration level is examined and additional measures to support the system are being proposed.

The dynamic security criteria should not be stricter than the ones that correspond to the peak load scenario where wind penetration is quite low. Therefore, the maximum Load Scenario is considered as reference scenario, as the wind power is negligible. However, due to increased interest for renewable integration in the system, the dynamic security criteria are defined lightly looser. For the case study of Crete the dynamic security will be considered if the load shedding is not more than 10% of the total demand, and the minimum frequency during the transient remains above 49 Hz. For the island of Rhodes, load shedding is not acceptable as it does not appear in the Peak Load Demand scenario.

Any method that investigates penetration levels of wind farm application should include a static security analysis.

In order to confirm the secure operation of the system under consideration, the response in steady state operation for the defined scenarios was checked. Both N and N-1 criteria are used to ensure the ability of the system to meet the demands. According to the requirements for secure operation, the loading of the transmission lines should be within the accepted limits, and the bus voltages at the substations should meet the following criteria:

- ±5% of the nominal voltage for normal operation (N)
- ±10% of the nominal voltage for emergency operation (N-1).

V. Results

A. Wind Parks without FRT capability

In this section results of simulations under different scenarios are analyzed. It should be noted that simulation results for the loss of the biggest unit in Crete are not presented due to the fact that they lead to load shedding within the acceptable limits in all cases. In Figs 1-3 basic responses of Crete system are presented in the case of 3-phase fault on a bus close to wind farms for the Maximum Load demand scenario. Table II summarizes results for this scenario. More specifically, in Fig. 1 voltage at wind farm connection buses is shown, in Fig. 2 system frequency and in Fig. 3 active power generation of a switched-off wind farms. In the case where the wind parks are not equipped with FRT capability, the 3-phase fault results in an extended loss of wind power generation due to voltage dip and produces a second disturbance which is generation loss and can lead to load shedding due to low frequency.

TABLE II
COMPARATIVE RESULTS OF 3 PHASE FAULTS - MAXIMUM LOAD DEMAND SCENARIO (CRETE)

Fault		W/P out of operation	Load shedding		Min Frequency (Hz)
		MW	MW	% system demand	
1	3 phase fault – location Atherinolakkos (t_{cl} = 100 msec)	8.37	0	0	49.88
2	3 phase fault - location Atherinolakkos (t_{cl}=100+400msec)	21.41	40.08	4.97	49.7
3	3 phase fault - location Korakia (t_{cl} = 100 msec)	4.92	0	0	49.92
4	3 phase fault - location Korakia (t_{cl}=100+400msec)	9	40.08	4.97	49.78

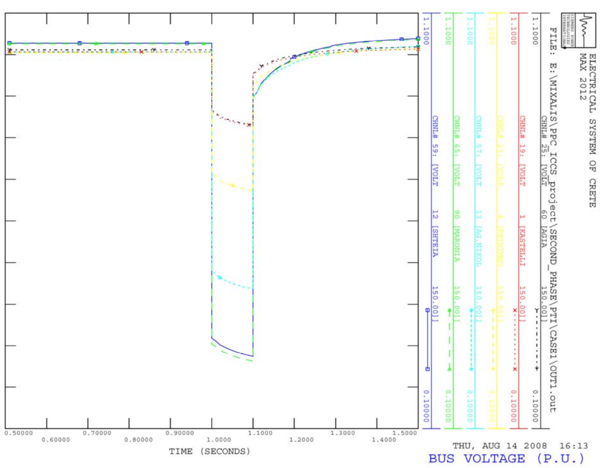

Figure 1: Voltage at wind farm connection High Voltage buses during a 3phase fault in the middle of a High Voltage line - scenario a

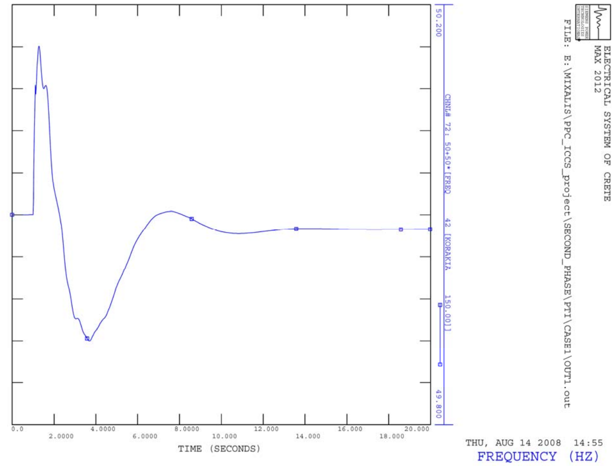

Figure 2: System frequency during a 3phase fault in the middle of a High Voltage line - scenario a

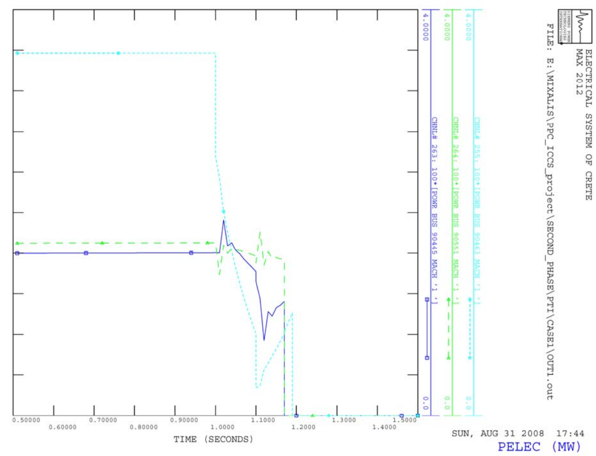

Figure 3: Power production of tripped wind farms during a 3phase fault in the middle of a High Voltage line - scenario a

In scenario A, the fault leads to disconnection of 21.4 MW of wind power due to undervoltage protection at the worst case. The frequency deviation does not violate the frequency protection settings and the minimum frequency after the fault is just 49.7 Hz and load shedding is within acceptable limits (~5%). The wind parks, which were tripped in this case, included fixed speed and variable speed wind turbines, equipped with induction and double fed induction generators respectively. It is worthy noting, that the wind parks in the same area with direct drive synchronous generators remained connected during the fault.

Three phase faults were also examined in the Maximum Wind Power Production scenario (B) and for different fault locations. The following table (III) summarizes the results for various three-phase faults in the system.

The studied faults had a severe impact on the system with the frequency decreasing down to low levels of 48.7 Hz. The load reduction in some cases was 26% of the total load. The underfrequency protection system was activated in these cases, as the spinning reserve was 92.5 MW and therefore less than the wind power being tripped due to the fault. The frequency deviations for these various faults are illustrated in Fig. 4, where the numbers 1-4 refer to the corresponding faults in table (III).

TABLE III
COMPARATIVE RESULTS OF 3 PHASE FAULTS - MAXIMUM WIND POWER PRODUCTION SCENARIO (CRETE)

Fault		W/P out of operation		Load reduction		Min Frequency (Hz)
		MW	% system load	MW	% system demand	
1	3 phase fault – location Atherinolakkos (t_{cl} = 100 msec)	128.2	21.7%	111.1	19.3%	49.24
2	3 phase fault - location Atherinolakkos (t_{cl}=100+400msec)	132.3	22.4%	150.6	26.1%	48.89
3	3 phase fault - location Korakia (t_{cl} = 100 msec)	122.9	20.9%	116.4	20.2%	49.21
4	3 phase fault - location Korakia (t_{cl}=100+400msec)	137.0	23.2%	150.9	26.2%	48.72

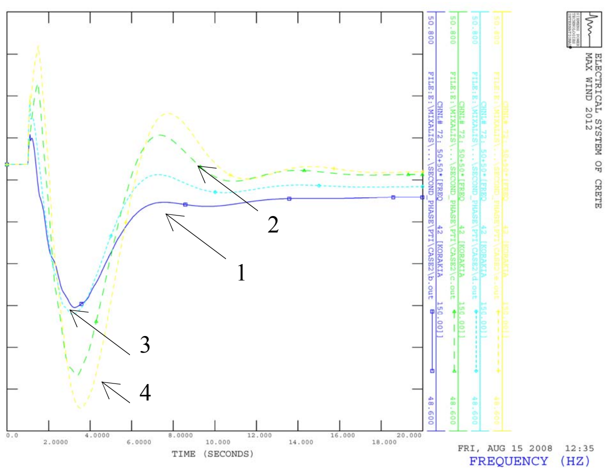

Figure 4: System frequency during 3phase faults in the system – scenario B (Crete)

The same faults were also used to evaluate the system security in the Maximum Wind Power Penetration scenario (C). In this case, the rate of change of frequency was the maximum compared to the previous scenarios and the load reduction increased. Table IV summarizes the results.

Due to the maximum penetration in this case, the impact of undervoltage protection being activated for the wind parks is even more severe compared to the previous scenarios. The wind parks supply a significant percentage of the load, and the resulting load reductions due to the wind farms being tripped reach the level of 35% of the total demand. The frequency deviation for the faults summarized in Table IV is illustrated in Fig. 5.

Simulation results for the autonomous system of Rhodes are summarized in Table V. A difference that should be noted is the fact that in Rhodes, scenario C response does not meet security criteria in case of loss of largest unit. Inertia is low, and few seconds after the disturbance underfrequency relays are activated.

TABLE IV
COMPARATIVE RESULTS OF 3 PHASE FAULTS - MAXIMUM WIND POWER PENETRATION SCENARIO

Fault		W/P out of operation		Load shedding		Min Frequency (Hz)
		MW	% system load	MW	% system demand	
1	3 phase fault – location Atherinolakkos (t_{cl} = 100 msec)	82.0	28.4%	67.9	24.0%	49.21
2	3 phase fault - location Atherinolakkos (t_{cl}=100+400msec)	97.3	33.7%	98.1	34.6%	48.52
3	3 phase fault - location Korakia (t_{cl} = 100 msec)	77.1	26.7%	79.0	27.9%	49.26
4	3 phase fault - location Korakia (t_{cl}=100+400msec)	97.3	33.7%	98.1	34.6%	48.53

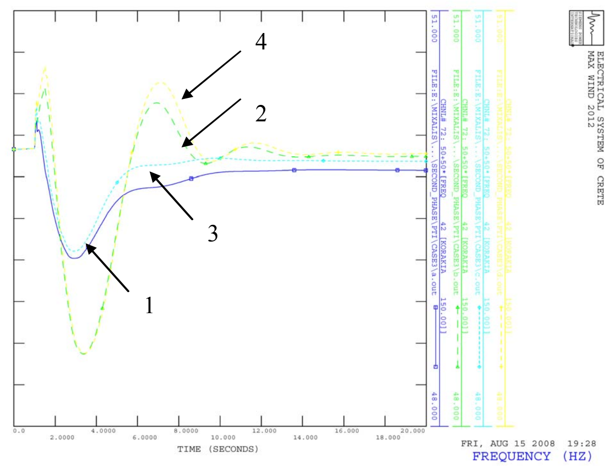

Figure 5: System frequency during 3phase faults in the system – scenario C

TABLE V
SIMULATION RESULTS OF RHODES

Scenarios/Fault		W/P out of operation		Load shedding		Min Frequency (Hz)
		MW	% system load	MW	% system demand	
a	Loss of largest unit (19.78MW)	0.0	0.0	0.0	0.0	49.75
b	Loss of largest unit (13.36MW)	0.0	0.0	0.0	0.0	49.86
c	Loss of largest unit (12.75MW)	0.0	0.0	15.45	18.6%	48.34
a	Fault at transmission line (t_{cl} = 200 msec)	4.29	1.8%	0.0	0.0	49.5
b		45.23	26.8%	59.75	35%	47.9
c		28.24	34%	56.22	67.7%	47.73

B. Wind Parks with FRT capability

The acceptable levels of wind power penetration are highly affected on the response of wind farms during a fault. In the previous section, 3-phase fault triggered undervoltage relays and caused loss of power production, frequency dips and the activation of underfrequency relays. In this section the simulations are repeated for the three scenarios, considering that wind farms (apart from those with asynchronous machine) have Fault Ride Through capability. This capability maintains wind farms connected to the network during a fault, so power production loss after a disturbance decreases. Fig. 6 illustrates typical voltage and time limits that the fault ride through is subjected to. It should be noted that system response in case of loss of largest unit is not improved with FRT capability, as discussed before.

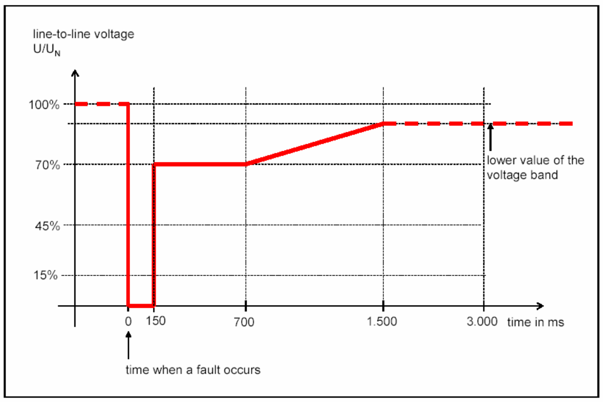

Figure 6: Typical Voltage-Time diagram of FRT for wind turbines

In Maximum Load Demand scenario, the presence of FRT capability of variable speed wind turbines, both doubly fed and direct drive, do not result in any particular improvement, as system response includes low wind power penetration. The number of wind parks out of operation reduces to those equipped with induction generator and the load shedding is not significant (2-5% of the total demand). Table VI summarizes the results for this scenario.

TABLE VI
COMPARATIVE RESULTS OF 3 PHASE FAULTS - MAXIMUM LOAD DEMAND SCENARIO

	Fault	W/P out of operation	Load reduction		Min Frequency (Hz)
		MW	MW	% system demand	
1	3 phase fault – location Atherinolakkos (t_{cl} = 100 msec)	1	0.0	0.0	49.93
2	3 phase fault - location Atherinolakkos (t_{cl}=100+400msec)	5.67	40.08	4.97	49.81
3	3 phase fault - location Korakia (t_{cl} = 100 msec)	0.0	0.0	0.0	49.94
4	3 phase fault - location Korakia (t_{cl}=100+400msec)	2.1	15.61	1.94	49.79

In the Maximum Wind Power Production scenario, the significant improvement in the dynamic security of the system due to FRT of the wind farms is summarized in Table VII. The results are compared to the ones from Table III (numbers in brackets). In addition, in Table VIII results of scenario c are presented, while in Table IX the results for Rhodes.

TABLE VII
COMPARATIVE RESULTS OF 3 PHASE FAULTS - MAXIMUM WIND POWER PRODUCTION SCENARIO

	Fault	W/P out of Operation		Load reduction		Min Frequency (Hz)
		MW	% system load	MW	% system demand	
1	3 phase fault(t_{cl} = 100 msec)	12.22 (*128.2*)	2.07% (*21.7%*)	34.86 (*111.1*)	6.1% (*19.3%*)	49.87 (*49.24*)
2	3 phase fault (tcl=100+400msec)	50.2 (*132.3*)	8.52% (*22.4%*)	87.2 (*150.6*)	15.1% (*26.1%*)	49.59 (*48.89*)
3	3 phase fault(t_{cl} = 100 msec)	0.21 (*122.9*)	0.04% (*20.9%*)	0.21 (*116.4*)	0.0% (*20.2%*)	49.92 (*49.21*)
4	3 phase fault (tcl=100+400msec)	47.60 (*137.0*)	8.08% (*23.2%*)	70.86 (*150.9*)	12.31% (*26.2%*)	49.56 (*48.72*)

The number and the total capacity of wind farms which are cut off due to voltage dip are significantly reduced. As a result, the number of the underfrequency relays being activated is also reduced and therefore the load shedding is kept to considerably lower values. The important impact FRT has on the dynamic security of the system is illustrated in Fig. 7, where the frequency response is shown for both cases, with and without FRT.

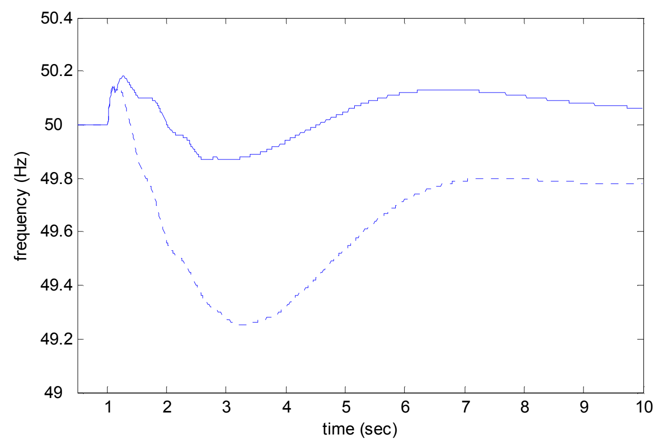

Figure 7: System frequency for 3 phase fault (solid line: FRT included, dashed line: FRT not included)

The active and reactive power production of wind farms during the 3 phase faults, with and without FRT, are shown in Fig. 8 and Fig. 9. When FRT is included, the power output is smoother and, especially in the case of direct drive synchronous generators, the reactive power injection supporting the system voltage during the fault is illustrated.

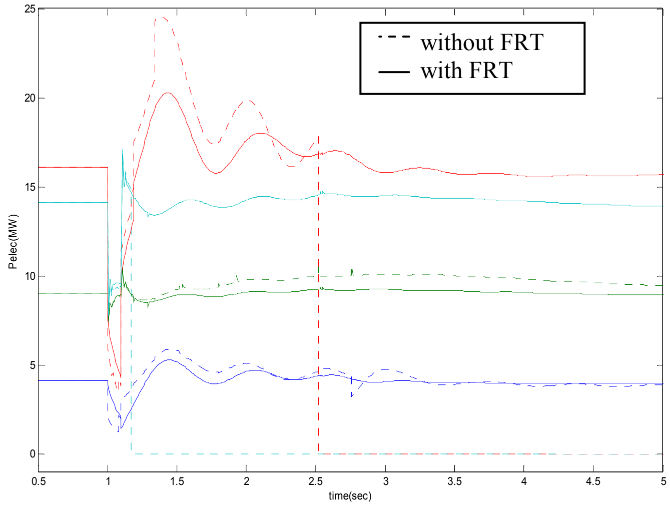

Figure 8: Active power for wind farms equipped with DFIGs and DDSGs

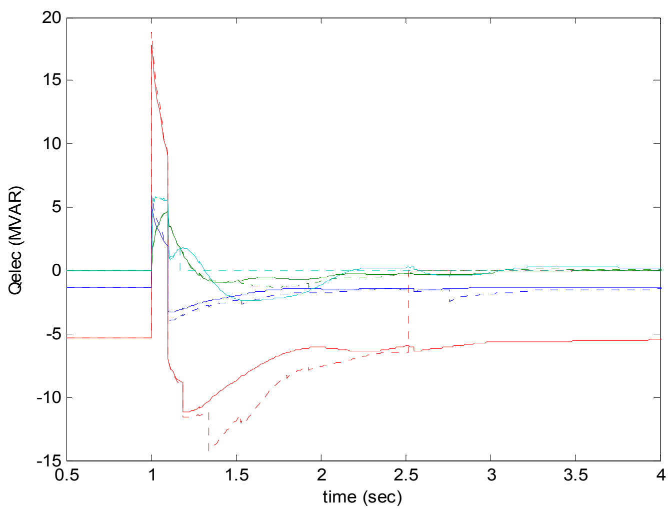

Figure 9: Reactive power for wind farms equipped with DFIGs and DDSGs

For Maximum Wind Power Penetration scenario, the improvement in terms of dynamic security is obvious when looking the number of wind farms out of operation as well as the load reduction and the minimum frequency.

TABLE VIII
COMPARATIVE RESULTS OF 3 PHASE FAULTS - MAXIMUM WIND POWER PENETRATION SCENARIO

	Fault	W/P out of Operation		Load reduction		Min Frequency (Hz)
		MW	MW	MW	% load demand	
1	3 phase fault (t_{cl} = 100 msec)	7.79 *(82.0)*	2.69% *(28.4%)*	0.0 *(67.9)*	0.0% *(24.0%)*	49.72 *(49.21)*
2	3 phase fault (tcl=100+400msec)	30.78 *(97.3)*	10.65% *(33.7%)*	60.44 *(98.1)*	21.33% *(34.6%)*	48.62 *(48.52)*
3	3 phase fault (t_{cl} = 100 msec)	0.3 *(77.1)*	0.1% *(26.7%)*	0.0 *(79.0)*	0.0% *(27.9%)*	49.89 *(49.26)*
4	3 phase fault (tcl=100+400msec)	12.2 *(97.3)*	4.22% *(33.7%)*	35.74 *(98.1)*	12.61% *(34.6%)*	48.64 *(48.53)*

As shown above, in some cases the criteria set for the dynamic security of the system of Crete are violated. In these cases, the installation of an SVC or STATCOM is necessary in order to ensure the uninterrupted operation of the wind farms equipped with induction generators.

Simulation of the other case study (Rhodes) gives results similar to the previous ones. Tripping of wind farms is reduced as shown in Table IX and system improves its response to the disturbance.

However it should be noted that in scenario c, in the case of unit loss, the implementation of FRT capability will not improve system response. Increased penetration of wind farms decreases thermal power production. This not only reduces the capability of the system to increase quickly power production after a disturbance but also decreases system inertia, so frequency dips are increased and load shedding is more common. As a result FRT capability of wind generators cannot solve this problem in Rhodes, where some solution to the inertia problem has to be provided so that the considered scenario c becomes acceptable.

TABLE IX
RESULTS OF RHODES WITH FRT

Scenarios/Fault		W/P out of operation		Load reduction		Min Frequency (Hz)
		MW	% system load	MW	% system demand	
A	Fault at transmission line (t_{cl} = 200 msec)	1.75 (4.29)	0.8% (1.8%)	0.0 (0.0)	0.0 (0.0)	49.67 (49.5)
b		10.61 (45.23)	6.3% (26.8)	0.0 (59.75)	0.0 (35.0)	49.18 (47.9)
C		6.63 (28.24)	8.0% (34%)	0.0 (56.22)	0.0 (67.7))	48.65 (47.73)

VI. DISCUSSION

As illustrated in the previous results, for both Maximum Wind Power Production and Maximum Wind Power Penetration scenarios, the system response in Crete and Rhodes is not considered acceptable. In some of these cases, the load shedding reaches levels of 20%-35% and the frequency falls beneath 49 Hz. Simulation provided the following conclusions:

1. Apart from the type of wind generator used, there are certain parameters (inertia, type of thermal plants, distribution of power production, under-frequency relays settings) that are crucial for system response.
2. Generally, the rule of thumb of 30% penetration does not seem to be confirmed. In Crete and Rhodes, when WFs operate without FRT capability, penetration levels above 25% (scenarios B, C) do not meet the security criteria.
3. Wind turbine-generators should be equipped with FRT capability. This refers not only to the future wind farms but also to the ones already installed in the system except wind farms with fixed speed induction generators, which need separate fast reactive support.
4. The implementation of FRT improves system response to fast-cleared faults within acceptable limits of load shedding and frequency dips for both case studies. However faults that are cleared in second protection zone demand further improvements to be made in the electrical system of

Crete, in order to maintain the studied penetration levels.

5. Increased wind power penetration does not only limit the ability of thermal plants to undertake power, but also limits inertia. System inertia has to be increased in Rhodes in cases of increased wind penetration to maintain security standards.

These conclusions led to proposed measures beyond the ones mentioned above (additional inertia, fast thermal units, implementation of FRT) in order to increase acceptable wind power penetration levels in the autonomous systems studied.

- A factor that can be used in order to optimize electrical systems performance is the review of under frequency protection system settings. The protection settings are quite sensitive and large amounts of load is shed due to settings of Rate Of Change Of Frequency relays (ROCOF) just after the fault incident. Having ensured that the dynamic security criteria are fulfilled through the FRT capability of the wind parks, the protection settings could be revised. Additionally, a time delay in the cut off action due to ROCOF would allow for use of the spinning reserve of the units online and especially of the gas turbines during the primary frequency control period.
- Dispersion of wind power plants among different substations in the system increases the percentage of reliable wind power penetration. Especially in Crete, where most of the WF are concentrated in the East part of the system, certain disturbances in the East part, affect most of the wind farms and limit the acceptable penetration levels.
- Installation of SVC or STATCOM for fast voltage control in the most critical areas of the system. These systems, can guaranty the uninterrupted operation of wind parks, especially those equipped with induction generators, during severe fault situations. For instance, the substation where most of these wind parks are connected could be considered as the most appropriate for this installation.

The implementation of the above suggestions can allow wind power penetration to overcome the boundary of 30% of the load, keeping the dynamic security of the system in the desired levels.

VII. Conclusions

Conclusions of the work presented in this paper are summarized as follows:

- The rule which defines maximum wind power penetration at 30% does not apply to every power system. Nevertheless it can be achieved by modifying certain parameters of the system.
- The main characteristic affecting stability in high wind power penetration is the sensitivity of these units to disturbances, especially those related to voltage. Wind farms interruption produces a second disturbance of power production loss that provokes load shedding and frequency deviation.
- The acceptable percentage of wind power penetration especially in autonomous systems depends on a wide variety of parameters. It does not only rely on internal parameters of wind turbines (type, existence of FRT) but also on system and grid parameters (inertia, thermal power production, protection relays, reactive compensation etc).

The procedure proposed may be complex, and demands quite detailed modeling of autonomous system, but it takes into account the particular characteristics of every system and leads to accurate results.

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