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Wind Power Impact on Power System Dynamic Performance

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1. Introduction

It is well known that wind power is one of the major sources of renewable energy with a remarkable contribution to the installed capacity of electrical power systems. In this chapter, the impact of large scale wind power generation on the dynamic performance especially of weak and/or islands power systems are presented.

Weak or Autonomous power systems, like the ones operating in idiomorphic areas or in islands, face increased problems related to their operation and control, [Hatziargyriou, N. & Papadopoulos, M. (1997)]. In most of these systems, the real cost of electricity production is much higher than in interconnected systems due to the high operating costs of their thermal generating units, mainly diesel and gas turbines, and the import and transportation costs of the fuel used. Security is also a major concern, since mismatches in generation and load and/or unstable system frequency control might lead to system failures, easier than in interconnected systems, [Hatziargyriou, N. et al. (1997)].

Although under ongoing energy policies wind power exploitation appear particularly attractive, the integration of a substantial amount of wind power in isolated electrical systems needs careful consideration, so as to maintain a high degree of reliability and security of the system operation. The main problems identified concern operational scheduling (mainly unit commitment) due to high production forecasting uncertainties, as well as steady state and dynamic operation disorder, [Dialynas, E. et al. (1998)]. These problems may considerably limit the amount of wind generation that can be connected to the power systems, increasing the complexity of their operation. Thus, next to the more common angle and voltage stability concerns, frequency stability must be ensured, [Hatziargyriou, N. et al. (1998)]. This depends on the ability of the system to restore balance between generation and load in case of a severe system upset with minimum loss of load.

Dynamic simulation studies are the first step in determining the level of wind power penetration in power systems. Analytical studies are required in order to derive security rules and guidelines for the optimal operation of each system [Arrilaga, J. & Arnold, C.P. (1993)]. Simulations of a power system dynamic performance mainly cover voltage and frequency calculations under several abnormal operating conditions, start-up or sudden disconnection of wind generation, wind fluctuations and short circuits on the transmission and distribution network. In order to ensure the maximum exploitation of the available renewable power sources and to operate systems with increased wind power penetration in

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the most economic and secure way, advanced energy management systems (EMS) are needed, [Nogaret, E. et al. (1997)].

Moreover, in order to operate optimally within the new market conditions, the price of providing a given level of security has to be accounted for. This is directly linked to the provision of remedial actions, in case of insecure situations, [La Scala, M. et al. (1998)]. Especially, for Dynamic Security, unlike Steady State security, remedial actions can only be preventive leading to load shedding or generation rescheduling. Consequently, the cost of load shedding has to be balanced with the cost of providing adequate spinning reserves in order to avoid it.

2. Power system dynamic performance

Power system's stability has been recognized as an important problem for secure system operation since the 1920s in [Steinmetz, C. P. (1920)] and in [AIEE Subcommittee on Interconnections and Stability Factors]. Generally, transient stability is the main concern on the majority of the power systems. As power systems have evolved through continuing growth, new operation technologies and controls in highly stressed conditions have emerged. More precisely, voltage stability and frequency stability have become greater concerns than in the past. A clear understanding of different types of stability and how they are interrelated is essential for the satisfactory design and operation of power systems, [Kundur, P. & Morison, G.K. (1997)].

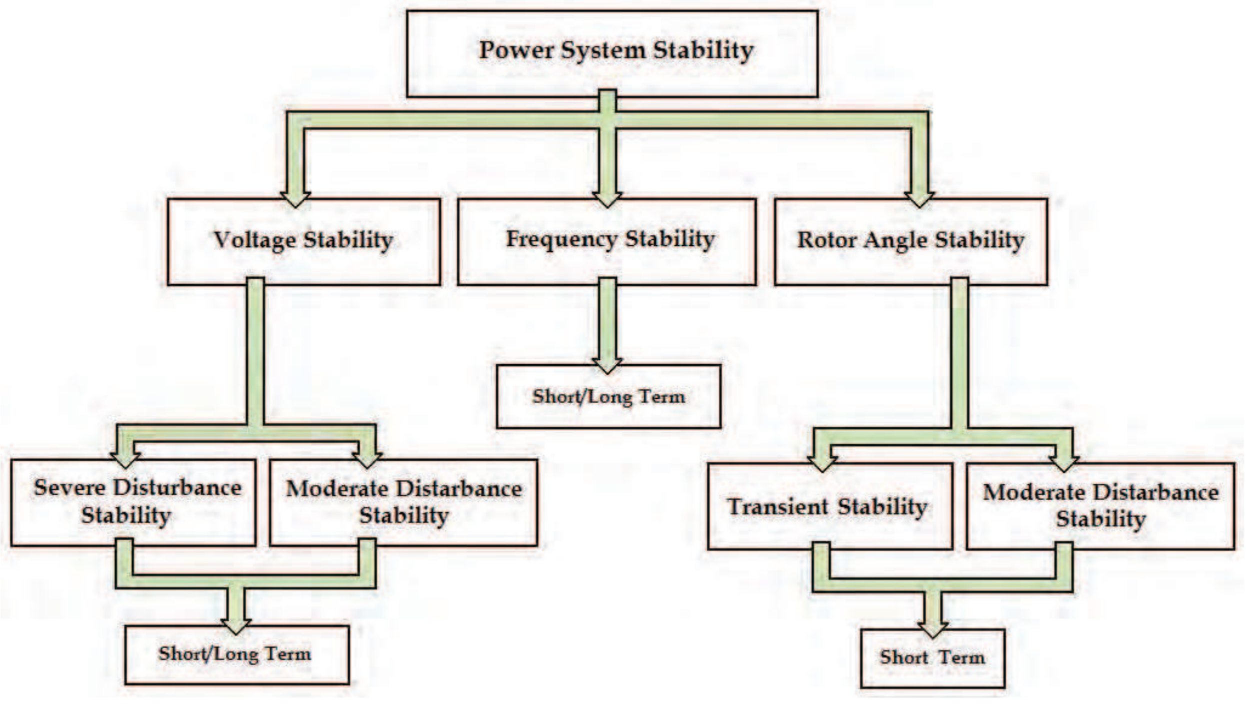

Fig. 1. Categories of power system stability

Power system stability is similar to the stability of any dynamic system, and has fundamental mathematical underpinnings. Precise definitions of stability can be found in the literature dealing with the rigorous mathematical theory of stability of dynamic systems. A circumstantial definition of Power System Dynamic Security and the corresponding types of Power System Stability is provided in [Kundur Prabha, et al. (2004)]. In Fig.1 a concise classification of power system stability is provided. Addionally, another significant issue is the relationship between the concepts of power system reliability, security, and stability of a power system, [Crary, S. B., Herlitz, I., Favez, B. (1948)].

- Power System Reliability: it refers to the probability of a required operation condition achievement, with few interruptions over an extended time period.
- Power System Security: it refers to the risk assessment of system ability to survive disturbances (taking into account the probability of these contingencies) without any power supply interruption.
- Power System Stability: it refers to the dynamic operation after a severe or moderate disturbance, consequently to an initial steady state operating condition.

As it is clearly mentioned in [Kundur Prabha, et al. (2004)], the analysis of security relates to the determination of the power system robustness to imminent disturbances. Assuming that a power system subjected to changes, it is important that when the changes are completed, the system settles to a new operating state where no technical constraints are violated. This implies that, in addition to the next operating conditions being acceptable, the system should survive the transition to these conditions. The above characterization of system security clearly highlights two aspects of its analysis:

- Static Security Analysis: It involves steady-state analysis of post-disturbance system conditions to verify that no voltage constraints are violated.
- Dynamic Security Analysis: It involves examining different categories of system stability described in Section III.

The general practice for dynamic security assessment has been to use a deterministic approach. The power system is designed and operated to withstand a set of contingencies selected on the basis that they have a significant possibility of occurrence. In practice, they are usually defined as the loss of any single element in a power system either spontaneously or preceded by a single, double, or three phase fault. This method is generally called as the N-1 criterion because it examines the behavior of an N-component network following the loss of any one of its components. In addition, emergency controls, such as generation tripping, load shedding, and controlled islanding, may be used to withstand such events and prevent widespread blackouts.

Ongoing power systems under deregulated energy markets with a diversity of participants, the deterministic approach may not be appropriate. There is a need to account for the probabilistic nature of system conditions and events, and to quantify and manage risk. The trend will be to expand the use of risk-based security assessment. In this approach, the probability of the system becoming unstable and its consequences are examined, and the degree of exposure to system failure is estimated. This approach is computationally intensive but is possible with today's computing and analysis tools.

3. Wind power penetration

As it is well known, wind is a diffused source of energy and wind parks are mainly a dispersed generation for conventional power system. Thus wind generation is often considered as embedded generation in the power systems with a variable penetration rate. Conventional power systems were designed and developed as centralized networks, where generated power flows unidirectional from higher to lower voltage levels and from large power plants to diverse loads through transmission and distribution systems. Distributed generation and especially dispersed generation of renewable energy sources can provide significant benefits, such as improved system reliability and enhanced power quality, [CIGRE Study Committee (1998)]. Additionally, dispersed generation could increase system efficiency; while under specific conditions could even decrease network operational cost. Generally, the dispersed generation changes distribution networks from passive networks, with power flows from higher to lower voltage levels, into active networks with multi-directional power flows, [Strbac, G. (2002)]. Furthermore, transmission and distribution infrastructures require specific economic regulations, [Stoft, S. (2002)].

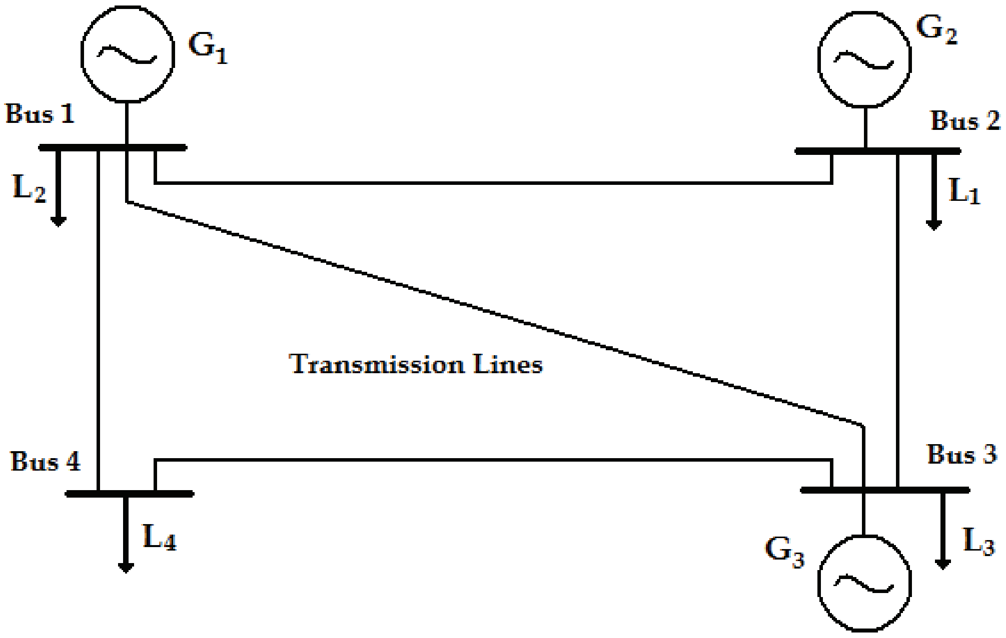

Fig. 2. Power system diagram

In Fig.2 a diagrammatic representation of a common power system is presented. Generating units could be conventional (fossil-fuel, nuclear or hydro installations) or renewables energy sources (wind parks, photovoltaics, biomass or geothermal installations). Generating units are connected to diverse loads mainly through high voltage transmission lines and distribution systems subsequently.

In case of small scale wind power installations where the wind power supplies local loads then the inpact on the grid voltage, frequency and losses is likely to be beneficial, [Burton Tony, et al. (2001)]. However, in case of large scale integrations where significant power should be flow through the trasmiision and/or distribution networks then voltage variations, frequency deviations and losses could became excessive.

For example if a wind generator operates at a power factor equal to one (cosφ=1), then the voltage difference, in a lightly-loaded radial line, is given approximately by:

$$\Delta V = V_E - V_S = \frac{P \cdot R}{V_S} \qquad (1)$$

Operating the generator at a leading power factor (absorbing reactive power) acts to reduce the voltage rise but at the expense of increased network losses. In this case the voltage rise is given by:

$$\Delta V = V_E - V_S = \frac{P \cdot R - X \cdot Q}{V_S} \tag{2}$$

Assuming a typical ratio of inductive reactive X to resistance R equal to 2 and a power factor of 0.89 for a typical uncompensated induction generator at rated output, the apparent voltage difference could be consider as zero. However, real power loss PLosses is given approximately by:

$$P_{Losses} = \left(\frac{P^2 + Q^2}{V_S} \right) \cdot R \tag{3}$$

Though the reactive power absorbed by the generator eliminates the voltage ascent, however higher real power losses are emerged in the line.

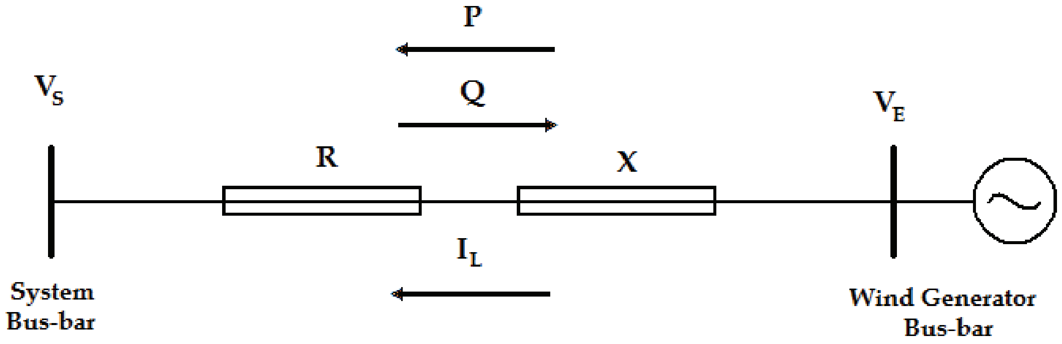

Fig. 3. Wind generator connected to a radial line

Previous equations (1) - (3) are approximate only and they are notaccurate to heavily-loaded systems, where the power factor is rarely unity. A simple but precise calculation for voltage increment in any radial circuit may be carried out using iterative techniques.

$$S_S = P - jQ \tag{4}$$

By definition S = V.I*, where * indicates the complex conjugate. Consequently, the line current is given by:

$$I_L = \left(\frac{S_E^*}{V_E^*} \right) = \left(\frac{P + jQ}{V_E^*} \right) \tag{5}$$

The voltage ascent through the line is given by I_L.Z and the V_E is equal to:

$$V_E = V_S + I_L \cdot Z = V_S + \frac{(R + jX) \cdot (P + jQ)}{V_E^*} \tag{6}$$

Finally, voltage V_E can be defined using a simple iterative expression:

$$V_E^{n+1} = V_S + \frac{(R + jX) \cdot (P + jQ)}{V_E^{n*}} \tag{7}$$

where n is the iteration number.

The previous technique is a simple approach of the conventional Gauss-Seidel load flow algorithm [Weely & Copy, (1998)]. Once the calculation converges an accurate solution is obtained. Additionaly, more complex load flow calculations could be carried out using ad hoc and advanced computer programs, [PowerWorld, (2007)]

4. Wind generation in autonomous power systems

Autonomous or isolated power systems are all the small and medium size power systems where no interconnection exists with conterminous and/or continental systems. These power systems, like the ones operating in large islands, face increased problems related to their operation and control, [Smith, P. (2006)]. In most of these systems, dynamic performance is a major concern, since mismatches in generation and load and/or unstable system frequency control might lead to system failures, easier than in interconnected systems.

Renewable sources and especially wind power exploitation appear particularly attractive, [Doherty, R. & O'Malley, M.J. (2006)]. However, the integration of a substantial amount of wind power in isolated systems needs careful consideration, so as to maintain a high degree of reliability and security of the system operation. The main problems identified concern operational scheduling (mainly unit commitment) due to high production forecasting uncertainties, as well as steady state and dynamic operating problems. These problems may considerably limit the amount of wind generation that can be connected to the island systems, increasing the complexity of their operation. Thus, next to the more common angle and voltage stability concerns, frequency stability [Karapidakis, E.S. & Thalassinakis, M. (2006)] must be ensured. This depends on the ability of the system to restore balance between generation and load following a severe system upset with minimum loss of load.

4.1 Autonomous power system of Crete

Grete is the largest Greek island with approximately 8.500 Km^2 and one of the largest in Mediterranean region. Its population is more than 600,000 inhabitants that triple in summer period. As well, it features a considerable annual increase of electricity demand approaching the 7% during the last decade. As a result, the annual energy consumption during 2008 surpassed the 3TWh in comparison with the modest 280 GWh of year 1975. Additionally, comparing the mean hourly load demand variation all year round, there is a considerable electricity generation diversification between months and seasons, as it is shown in Fig. 4.

However, even during the low consumption periods, minimum load demand is greater than current system technical minimum (approximately 100 MW). Island's electricity generation system is based mainly on three (3) oil-fired thermal power units, located as it is shown in Fig. 5. The official capacity of the local power plants is 742.9 MW, although the real power of the system is 693 MW for winter and 652 MW for summer operation. Additionally, there are 25 wind parks installed with nominal power of 124,85MW in appropriate regions of the island. These WPs are connected to the grid through MV/HV substations of 20kV/150kV. The annual peak load demand occurs on a winter day and overnight loads can be assumed to be approximately equal to 25% of the corresponding daily peak loads. The steam and diesel units mainly supply the base-load. The Gas turbines normally supply the daily peak load or the load that cannot be supplied by the other units in outage conditions. These units have a high running cost that increases significantly the average cost of the electricity being supplied.

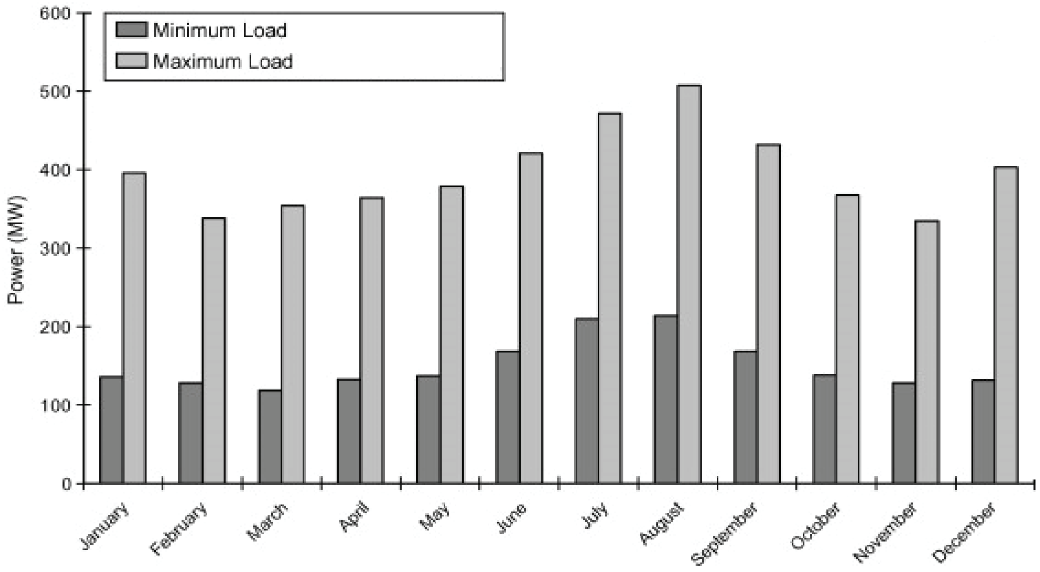

Fig. 4. Monthly variation of min and max load demand

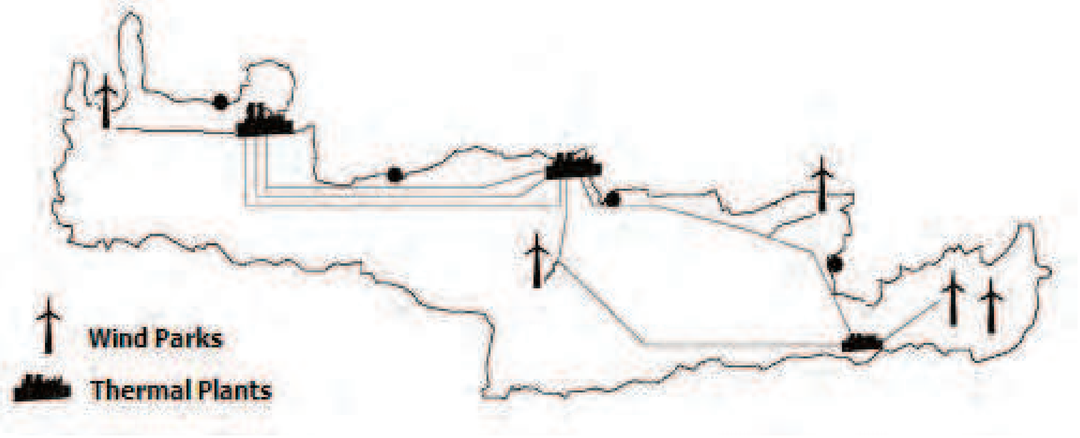

Fig. 5. Power plants and wind parks locations

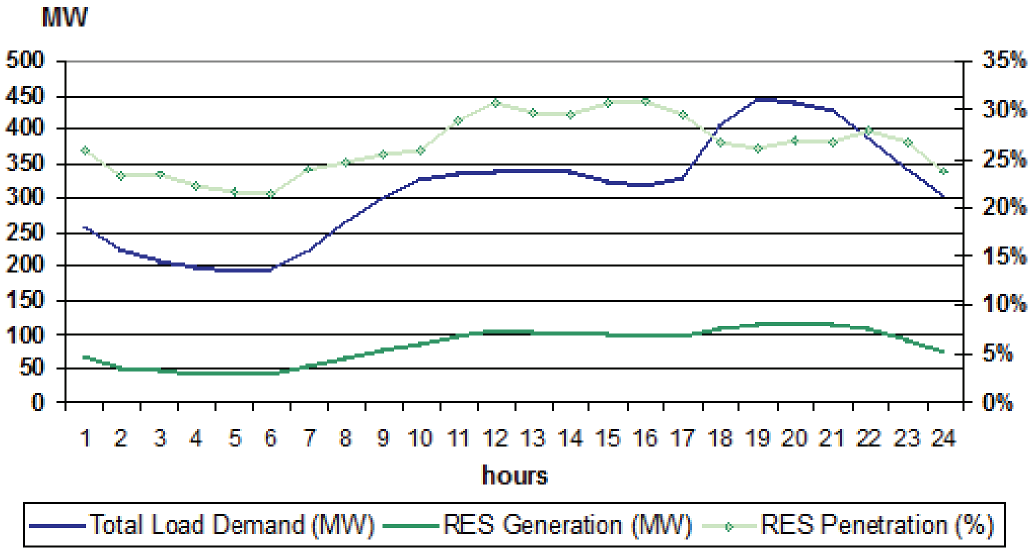

Fig. 6. Wind power penetration in power system of Crete

In Fig.6 the wind power production in parallel with the overall production in a specific day within 2008 is presented. In this case the portion of the corresponding wind generation varies between 22% and 32% of the total power supply that is considered as a significant high penetration for an autonomous system such as Crete's network. Wind energy exploitation activities in Crete started since mid eighties. As a result, a remarkable wind park installation activity has started since 1992, leading by 2008 to the existence of 25 wind power stations of rated power 124.85 MW. While a licensed capacity of additional 95 MW nominal power is planned to be installed till 2012.
Assuming the current wind parks and the prospect of many PV installations (104 MW till 2012) Crete deals even now with a significant dispersed generation and high RES penetration. Thus autonomous power system of Crete is an excellent represenative for dynamic performance estimations.

4.2 Power system dynamic performance

Regarding security, a large number of wind parks are installed at the eastern part of the island, which presents the most favorable wind conditions. As a result, in case of faults on some particular lines, these wind parks are disconnected. Frequency oscillations might easily trigger the under-frequency protection relays of the wind parks, thus causing further imbalance in the system. Fig. 7 depicts a real situation when short-circuit occured at 12:10 p.m. leading the frequency, in spite of the fast load shedding to drop till 49 Hz. The frequency oscillations are the main characteristics of an autonomous power system as Crete's.

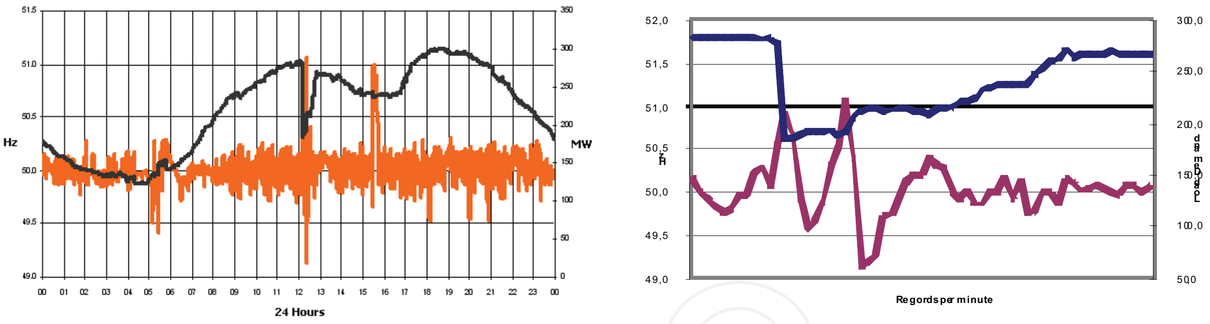

Fig. 7. Frequency fluctuations and load disconnection

In order to investigate and assess the dynamic behaviour of an examined power system, accurate simulationa are needed. So that the models, which are used for the presentation of the system components were chosen taking into account that the duration of the transient phenomena under study are between 0.1 and 10 sec approximately. The formulas for the main components of the system are as follow:

a. Diesel motors and Gas turbines

The generic model, illustrated in Fig. 8, is used for the simulation of the diesel engines and the gas turbines speed governors.

Input is the frequency change and output is the produced mechanical power, while the diesel engine or the gas turbine is represented by a first order lag with a time constant T_D. T_G is the time constant of the hydraulic actuator of the governor mechanism.

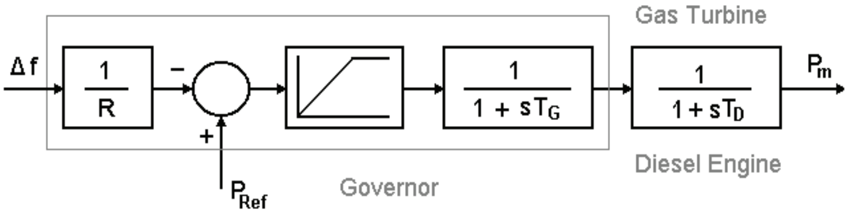

Fig. 8. Diesel-Gas speed control system

Δf, is the per unit frequency change (f_o=50Hz).
P_m, is the mechanical power of the diesel motor.
R, is the droop of the speed governor.

b. Steam unit

The block diagram of Fig. 9 represents the speed governor system considered for each steam unit.

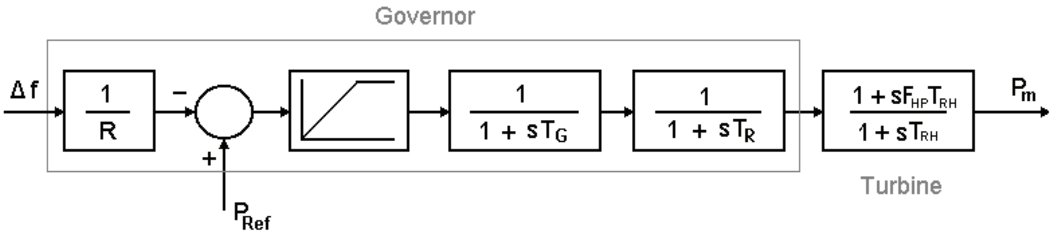

Fig. 9. Steam speed control system

Δf, is the per unit frequency change (f_o=50Hz)
P_m, is the mechanical power of the steam turbine.

The transfer function for the governor includes speed relay and transient droop. The steam turbine is represented as single reheat type whose transfer function is:

$$G_T(s) = \frac{1+F_{HP} \cdot T_{RH} \cdot s}{1+T_{RH} \cdot s} \tag{8}$$

F_{HP}, is the fraction of total turbine power generated.
T_{RH}, is the time constant of reheater.

For the simulation procedure, an integrating control parallel to machine droop is added to the speed controllers of Fig. 8 and Fig. 9, as shown in next Fig. 10.

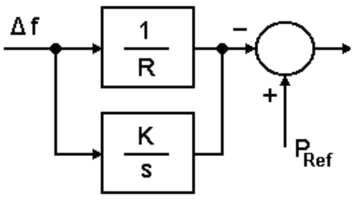

Fig. 10. Addition of integrating control block

c. Voltage regulator

The standard DC1 model of IEEE, is considered for the voltage regulator of each generator of the system.

d. Asynchronous generator equations

Wind generators are simulated mainly as induction machines with a sort-circuited double cage rotor. These induction machines are derived from synchronous machines, with the excitation winding short-circuited. Besides this, the machines are assumed to be perfectly symmetrical. The initial slip corresponds to the intersection of the electrical torque curve and the opposing mechanical torque, as shown in Fig. 11. The mechanical power is a linear function of the asynchronous wind generator speed:

$$P_m = T_m.\omega_r \tag{9}$$

In steady state conditions and in case of a disturbance where the wind remains stable, the mechanical power is assumed to be constant, therefore:

$$T_m.\omega_r = \text{constant} \tag{10}$$

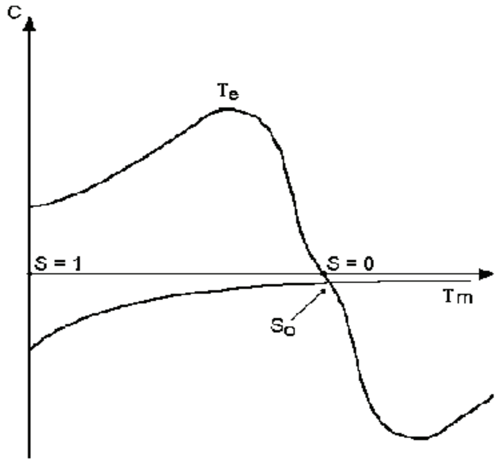

Fig. 11. Intersection of electrical and mechanical torque

e. Load equations

In general, power system loads are composed of a variety of electrical devices. For resistive loads, such as lighting and heating loads, the electrical power is independent of frequency. In case of motor loads, the electrical power changes with the frequency due to changes in motor speed. The overall frequency dependent characteristic of a composite load may be expressed as:

$$\Delta P_e = \Delta P_L + D\Delta f \tag{11}$$

ΔP_L, is the non frequency sensitive load change
$D\Delta f$, is the frequency sensitive load change
D, is the load damping constant

In the absence of a speed governor, the system response to a load change is determined by the inertia constant and the damping constant. The steady state speed deviation is such that the change in load is compensated by the variation in load due to frequency sensitivity.

4.3 Wind measurements

Although, many wind farms are under operation in the island of Crete, there is a lack of sufficient data from different wind farms. The data (time series of 10 minute time step) that are used in this study are derived by a wind farm of 20MW located in the east part of the island. The capacity factor of the wind farm is defined:

$$C.F = \frac{\overline{P}}{P_R} = \frac{E}{8760 \cdot P_R} \tag{12}$$

where, $\overline{P}$ is the mean power of a measured power time series, P_R the rated power of the wind farm, E is the annual energy production and 8760 the hours of a year.

The calculated annual capacity factor of the wind farm is 41.5%. The annual mean wind speed of the wind farm is defined by the annual series of data:

$$\overline{v} = \frac{1}{N} \cdot \sum_{1}^{N} v_n \tag{13}$$

where, v_n is the wind speed at data point n, and n=1,2,…,N is the number of measurement data.

The calculated annual mean wind speed is approximately 9.0 m/sec. The main wind direction is the North West. Then, standard deviation σ is calculated:

$$\sigma = \sqrt{\frac{1}{N-1} \cdot \sum_{1}^{N} \left(v_n - \overline{v}\right)^2} \tag{14}$$

The calculated value of standard deviation is 4.58. The power curve of the wind farm for the sixteen various wind directions was formulated given the collected data. The power curve of one wind direction is presented in Fig. 12.

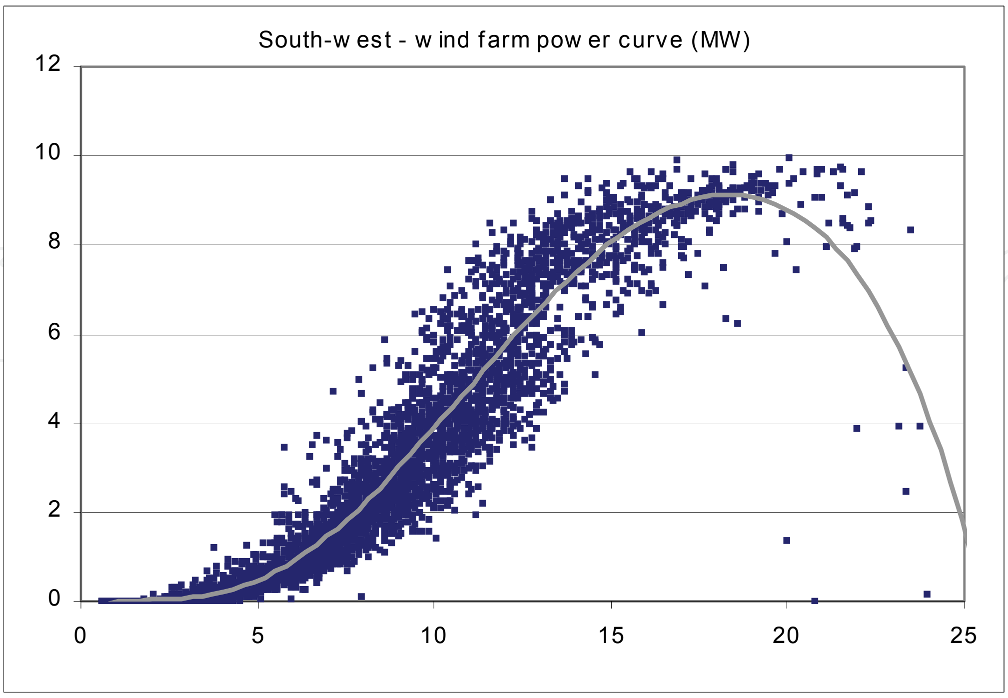

Fig. 12. Wind farm power curve and measures

The aim of this analysis was to record any sudden variation of the wind speed and of the power production of the wind farm. Two kinds of sudden variations were distinguished: "sudden loss" and "sudden blow" of the wind.

In the Fig. 13 and Fig. 14, the variation of the wind speed causes different variation of the produced power (case of power rejection and case of a sudden wind increase).

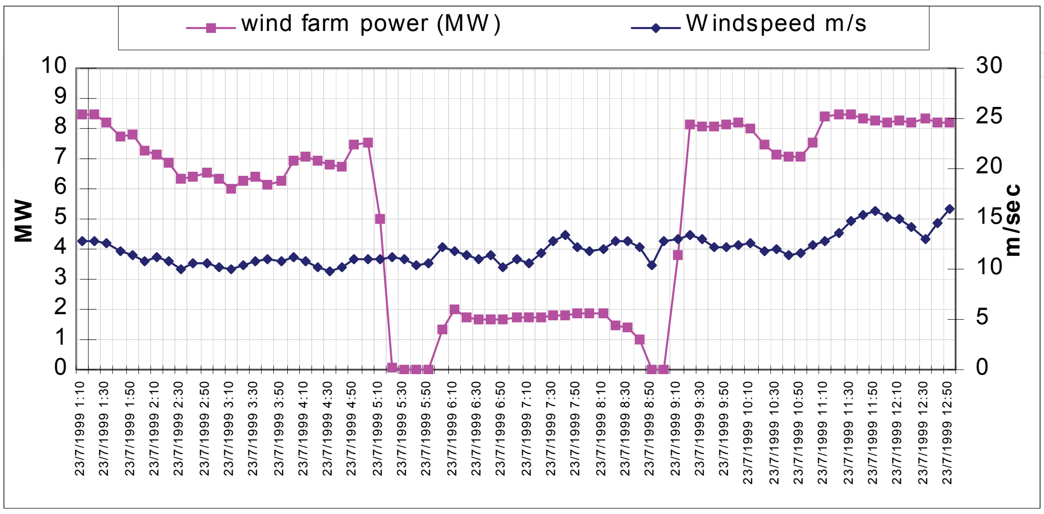

Fig. 13. Sudden power rejection

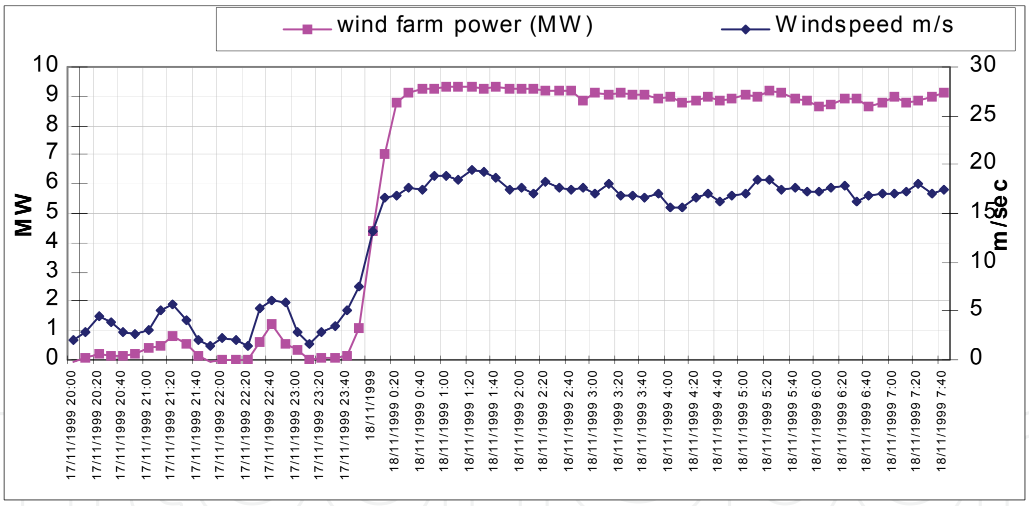

Fig. 14. Sudden increase of the produced wind power

It is obvious, that we are interested in variations of the produced power, which are caused by variations of the wind speed. The moving average of the wind farm power and the wind speed were calculated for short term (3 data points - half an hour) and medium term (12 data points - 2 hours) and then compared. When a significant deviation between the short term and the medium term moving average of the power was recorded and caused by a deviation of the wind speed, a "sudden variation" is occurred. During a "sudden blow" of the wind the short term moving average is bigger than the medium term, since the short term follows the wind speed closely. During a "sudden loss" of the wind the moving average of the short term is smaller than the medium term.

4.4 Dynamic security assessment

EUROSTAG program [Meyer; B & Stubbe, M. (1992)], PowerWorld Simulator [PowerWorld, (2007)] and Matlab [Power System Toolbox, (2006)] have been used for the simulation of the transient operation of the examined power system, under several operating conditions. Disconnection of conventional machines and wind generators as well as wind velocity fluctuations are the main disturbances under investigation. Especially, the following cases are presented:

a. Generator Trip

The system was examined for a case of power unit disconnection (Gas Turbine), which was producing 20MW. In Fig. 15 the change of the frequency and the diesel machine power in three different operating conditions, are shown. At first, the system is considered to operate without wind turbines and it seems to be quite stable. Secondly, the system is considered to operate with 28% of wind power, equal to 46MW and with the fast conventional units such as diesel machines and gas turbines to be in operation (fast spinning reserve). In this case, the system seems to be stable again. The lower value of the frequency is almost the same as in the previous case.

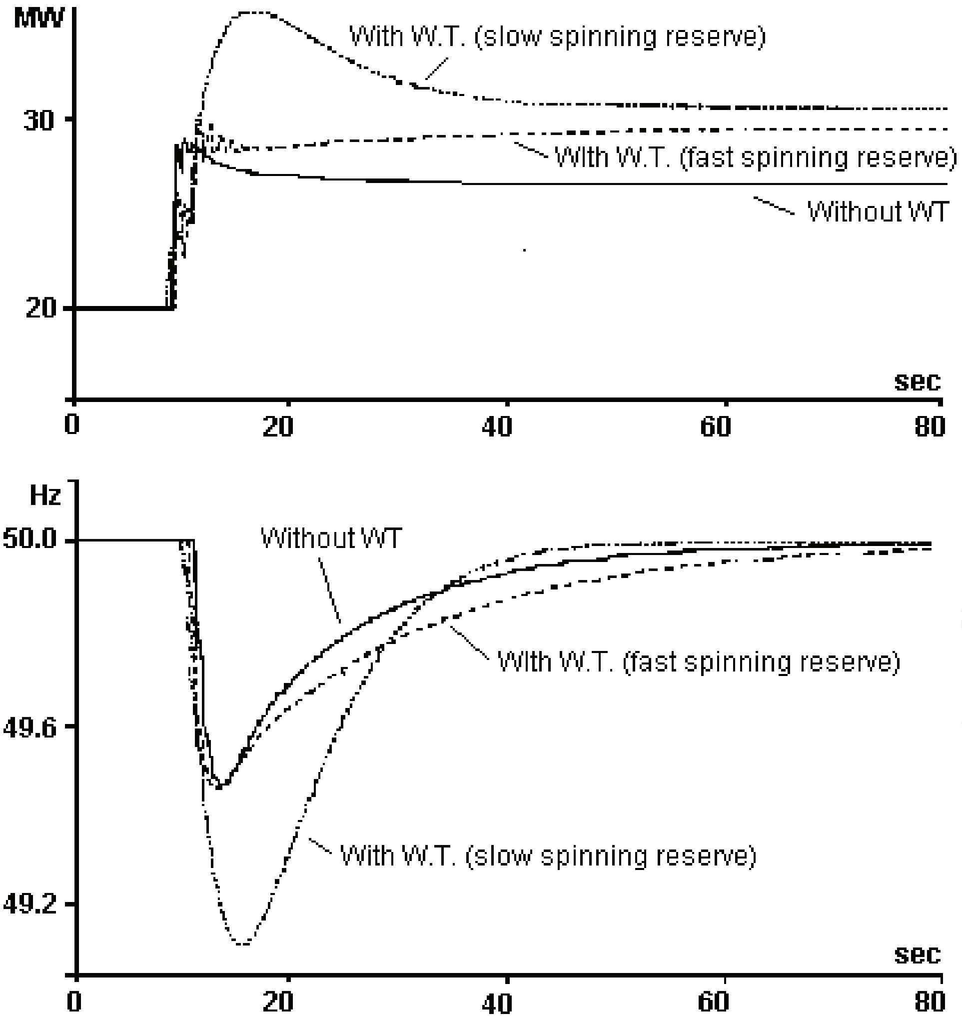

Fig. 15. Frequency and power change

Thirdly, the system is again considered to operate with the same high percent of wind power but with the slow machines, such as steam turbines, to cover the main spinning reserve (slow spinning reserve). In this case, the lower frequency value, which is equal to 49.14Hz, surely causes the operation of wind parks protection devices, leading the system to collapse after the total wind power disconnection. Therefore, it is obvious that in case of large wind power penetration, the operation of the diesel machines and the gas turbines is necessary for the dynamic security of the system.

b. Wind Power Change

In Fig. 16 the variation of the frequency and the voltage at the main wind park substation, are shown. The frequency follows the wind power changes, while the voltage profile follows an opposite trend. It can be seen that in case of normal wind power fluctuation, when the wind parks are not suddenly disconnected, and with sufficient spinning reserve, the power system remains satisfactorily stable.

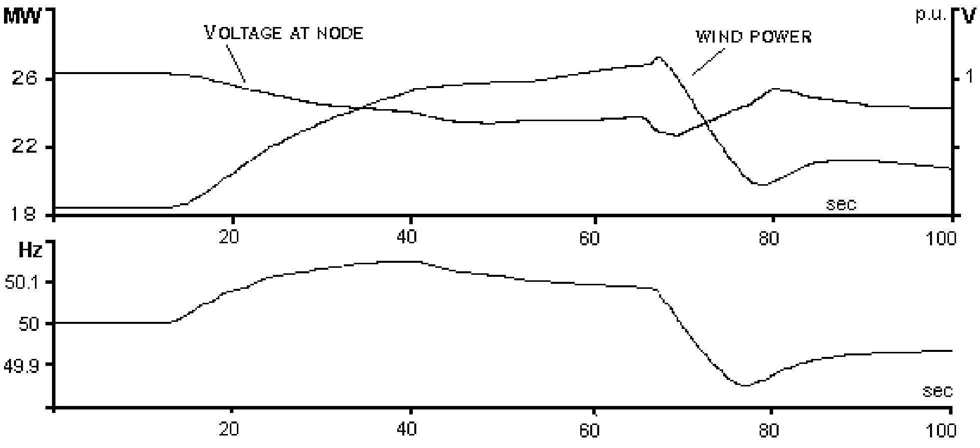

Fig. 16. Frequency and voltage variation

c. Unit Commitment Change

A maximum wind power penetration of 30% has been used by the system operators as the respective security margin. However, extensive transient analysis studies are conducted in order to assess the dynamic behavior of the system under various disturbances. Different combinations of the generating units have shown that a fixed security margin does not guarantee the system security and it distorts its economical operation. Thus, under the same contingency the system is shown to collapse with lower than 30% of wind power penetration, while survives with higher penetrations.

Fig. 17 depicts the change of frequency caused by the outage of a Gas turbine, providing 23 MW under two different operating conditions. Case 1 corresponds to a total load of 207.2 MW supplied as follows: 27 MW by Combined Cycle (18 MW of spinning reserve), 56.8 MW by the new Steam turbines (18.2 MW spinning reserve), 21.3 MW by Diesel (27.9 MW spinning reserve), 10.1 MW by the remaining Gas turbine (6.1 MW spinning reserve of maximum 16.2 MW), while the Wind power is 69 MW, corresponding to 33.3% penetration. It can be seen that the frequency undergoes a severe transient reaching a lowest value of 49.1 Hz, however the system restores its balance in about 50 seconds. Case 2 corresponds to a lower load of 199 MW supplied by 27.57 MW of Combined Cycle (17.43 MW spinning reserve), 69.3 MW of new Steam Turbines (5.7 MW of spinning reserve), 23.4 MW of Diesel (25.8 MW of spinning reserve), and 55.73 MW of Wind corresponding to 28% penetration.

Although the wind power penetration is lower than the security margin adopted the system does not manage to regain its stability and is led to frequency collapse. The difference is attributed to the fact that in the first case the spinning reserve is higher (70.2MW) and provided by faster units (Gas Turbines), while in the second case by slower units (48.93MW). The need for spinning reserve optimization can be clearly seen.

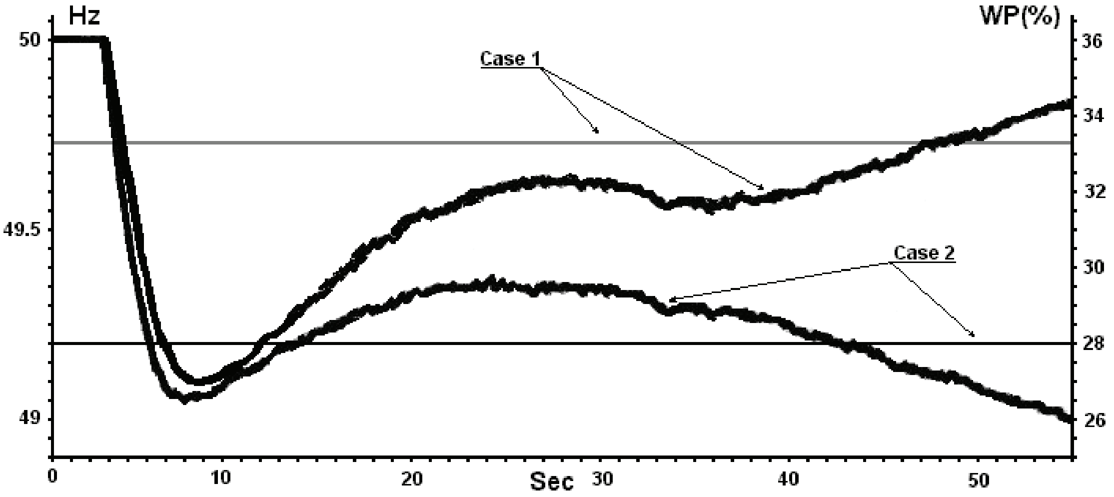

Fig. 17. Simulation results of Crete power system

5. Preventive dynamic security

In this paragraph a method for on-line preventive dynamic security of isolated power systems is presented, [Karapidakis, E.S. & Hatziargyriou, N.D. (2001)]. The method is based on Decision Trees which provide the necessary computational speed for on-line performance and the flexibility of providing preventive control. Emphasis is placed on the on-line use of the method to test the dynamic security of each generation dispatch scenario and thus to provide corrective advice via generation re-dispatch. Moreover, the algorithm implemented provides the flexibility of displaying the cost of each re-dispatch. In this way, the method can help in objective decision-making. Results from the application of the system on actual load series from the island of Crete, where the proposed system is in trial operation, are presented.

A dispatch algorithm approximating actual operating practices followed in the Control system of Crete is applied next in order to complete the pre-disturbance Operating Points (OPs). For a given load demand P_L and wind power P_W, the total conventional generation P_C is equal to:

$$P_C = P_L + P_{Losses} - P_W \tag{15}$$

P_C is dispatched to the units in operation, depending on their type and their nominal power. The various thermal units are grouped according to their type. The attributes characterizing each Operating Point comprise the active power and spinning reserve of all conventional power units. Ten variables are selected as initial attributes. Five attributes correspond to the active production of the conventional unit groups and five attributes to the spinning reserves, respectively. For each of the Operating Points produced, two characteristic disturbances have been simulated using:

- Outage of a major gas turbine
- Three-phases short-circuit at a critical bus near the Wind Parks.

The first of these disturbances happens very frequently, while the second is particularly severe leading to the disconnection of most wind parks. For each Operating Point the maximum frequency deviation and the rate of change of frequency are recorded. Both of these parameters are checked against the values activating the under-frequency relays used for load shedding and the OPs are labeled accordingly. The security criteria were:

If fmin < 49 Hz **And** df/dt > 0.4 **then**
The system is insecure **else** is secure

5.1 Secure economic dispatch

Economic dispatch analysis determines the power setpoints of the online generating units (15), so as to meet the system load and losses at least cost.

$$P_C = P_1 + P_2 + ... + P_i + ... + P_n \tag{16}$$

where P_C is the total conventional generation,
P_i is the generation of the i-th unit.
n is the number of units

Traditional dispatch algorithms tackle this problem as a constrained optimization problem and base its solution on the concept of equal incremental cost, also known as the Lambda Iteration algorithm: The total production cost of a set of generators is minimized, when all the units operate at the same incremental cost. In order to ensure that the operating setpoints proposed by the Economic Dispatch algorithm will provide a dynamically secure operating state of the system following pre-specified disturbances, the rules extracted by the relevant Decision Trees (if-then-else rules) can be used as additional constraints in the above constrained optimization problem.

5.2 Cost analysis

The presented approach provides the flexibility of displaying the cost of security, i.e. the cost associated with each re-dispatch. This is easily provided as the difference between the operating cost of the original dispatch and the operating cost of the secure re-dispatch. These costs can be calculated from the cost functions of the generating units, once the unit productions have been determined.

In addition, the security cost can be compared to the cost of load shedding. The unsupplied electric energy can be easily calculated from the operating settings of the under-frequency relays and the load forecasted at each bus affected. Alternatively, it can be estimated from the pre-disturbance load and the forecasted load as a whole, however its cost is more difficult to determine. For the dispatcher the cost of load shedding can be the price the regulator imposes for energy not served. In the traditional monopoly operation this cost can be the revenue lost due to the unsupplied electric energy, although this by no means reflects the true cost of load shedding. In any case, the total cost can be calculated from:

$$S_L = C * \int_{t=0}^{T} P_L(t)dt \tag{17}$$

where: P_L is the load shed.
C is the cost of kWh in Euros (€).
T is the time of load disconnection.

5.3 Cost of security

In this paragraph results from the application of the secure economic dispatch algorithm on actual load series of Crete are presented. In Fig. 19, the total load, the corresponding security classification (1 for secure and 0 for insecure) for the machine outage contingency and the operating cost in Euros of a characteristic day are plotted. In the upper diagram, it is shown that, approximately between 9:00 and 10:30, the system is insecure, i.e. at least a significant load shedding will take place. In the lower diagram, the effects of the secure economic dispatch algorithm on the security classification and the system operating costs are shown. The increase of costs during the previously insecure period, provided by the increased and probably faster (more expensive) spinning reserve, is notable. The effect of the two dispatch scenaria on the system frequency deviation, in the case of the machine outage, as obtained by simulation programs, is shown in Fig. 20. It is clearly shown that the proposed re-dispatch will not cause load-shedding. The probability of the contingency occurrence however is not considered in this study.

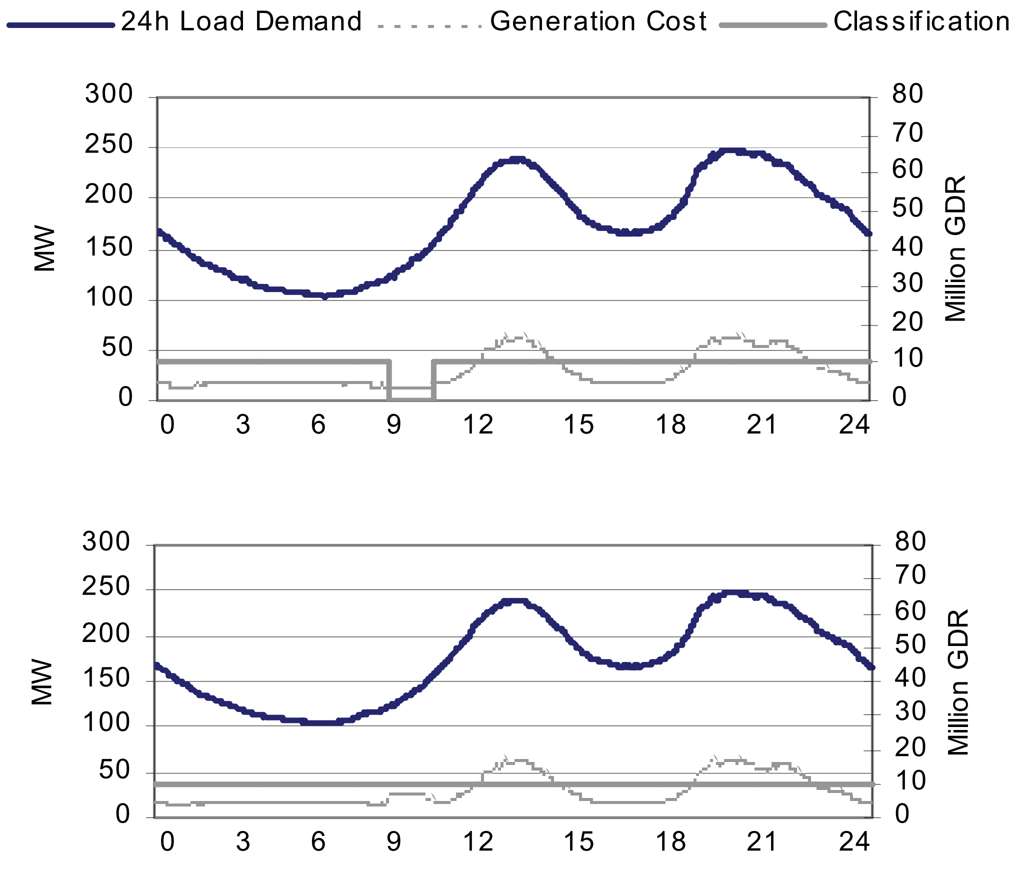

Fig. 19. 24-hour diagrams illustrating load, security classification and operating cost

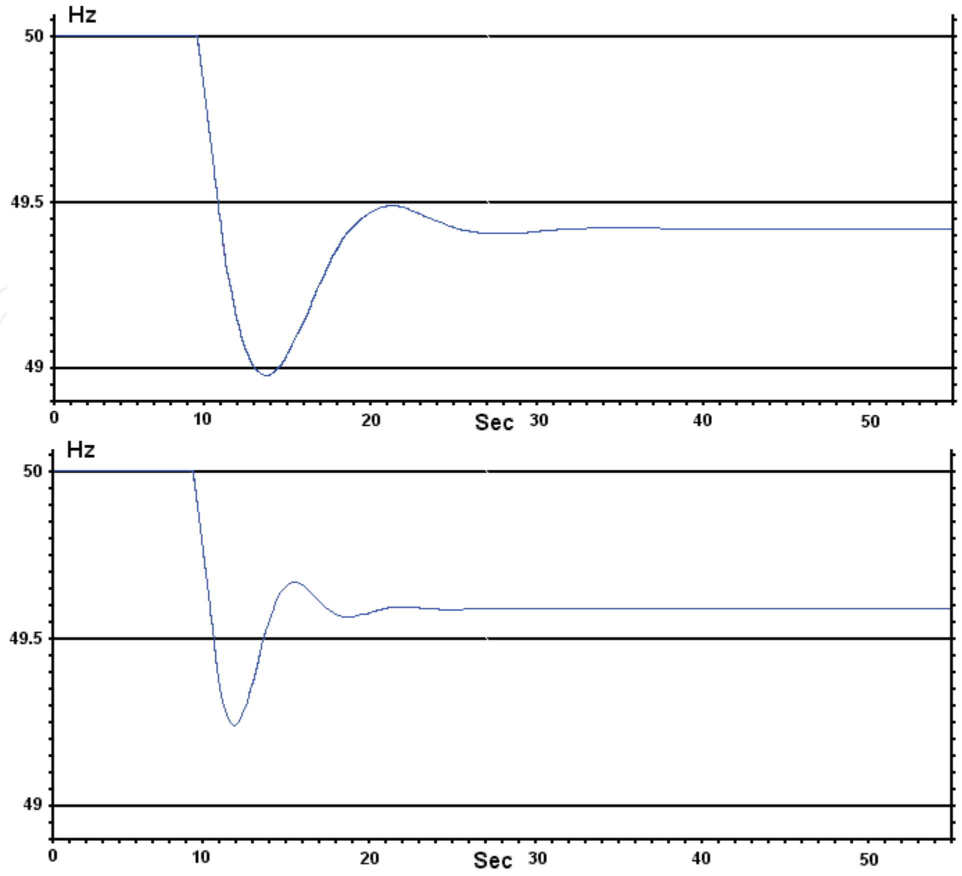

Fig. 20. Effect of dispatch on system frequency deviation

7. Conclusion

In this chapter the dynamic behavior of a power system with high percentage of wind power penetration (up to 40%) was studied with emphasis given to the modeling of the system, in order to examine the probable impacts. More precisely, several simulations were performed to study the impact of the wind park on the dynamic behavior of a representative autonomous power system as Crete's power system. The most considerable disturbances that were invastigated are the short circuit, the sudden disconnection of conventional power units as well as wind parks and the strong wind velocity fluctuations. Simulations have shown that the deviations of the power system voltage and frequency remain acceptable under most examined perturbations. However, the situation depends on the scheduling of the power units and the amount of allocated spinning reserve.

Cause to significant replacement of conventional power generation that was supplied by synchronous generators, with wind turbines that operate either asynchronous or variable-speed generators, the dynamic performance of the power system will indeed be affected. Thus, although wind turbines affect the transient stability of a power system, they are not a principal obstacle to an adequate secure and reliable operation. The stability of a power system can be maintained even if high penetration of wind power exist by additional system measures, control enhancement and preventive actions.

Finally, a method for on-line preventive dynamic security is proposed, in order to determine optimal reserves and to provide corrective advice considering dynamic security. Based on the Decision Trees classification new unit dispatch is calculated on-line, until a dynamically secure operating state is reached. This technique provides the flexibility of displaying the cost of each proposed solution weighted against the cost of load shedding; it forms therefore the basis for valuable decision-making aid. Results from the application of the method on actual load series from the island of Crete show the accuracy and versatility of the method. Moreover, the fast execution times required for on-line classification of the current operating state make the method suitable for large systems, as well.

Therefore, there is a considerabe impact of wind parks generation to the power system that they are embeded. This impact is generally propotional to the wind power penetration percentage (running active power injection and/or reactive power absorbedness). Furthermore most of the perturbations exclusively due to the operation of the wind generators do not affect significantly the operation of the power system. Concluded it should be noted that it is possible to operate a power system with a high level of wind penetration maintaining a high level of security. This is possible, if adequate spinning reserve of the conventional units is available. The issue of spinning reserve is particularly important; therefore it must be further investigated.

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This book is the result of inspirations and contributions from many researchers of different fields. A wide verity of research results are merged together to make this book useful for students and researchers who will take contribution for further development of the existing technology. I hope you will enjoy the book, so that my effort to bringing it together for you will be successful. In my capacity, as the Editor of this book, I would like to thanks and appreciate the chapter authors, who ensured the quality of the material as well as submitting their best works. Most of the results presented in to the book have already been published on international journals and appreciated in many international conferences.

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