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A SIMULATION MODEL FOR THE RELIABLE INTEGRATION OF A 4.5 MW WIND FARM INTO THE POWER GRID OF THE CRETE ISLAND

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This paper describes a computer simulation model which has been developed to study the effects of integrating wind energy conversion systems (WECS) into autonomous power systems. The quality of the interconnected system performance is specified in terms of operational constraints. Load-flow and power-system-stability studies were preformed in order to evaluate the penetration impact of a 4.5 MW wind farm on the local grid fo Sitia–Crete. The results show that the above wind energy penetration level will not cause any problem to the existing electric power grid.

1 INTRODUCTION

There is considerable interest in using novel methods to generate electric energy, including wind, tidal and solar sources. The main reason is that the conventional fuels are limited and expensive, whereas the above mentioned new forms, generally known as renewable, are unlimited and cheap to operate, although their first installation is rather expensive. The introduction of a relatively small amount of wind derived electrical power into the utility grid does not normally present any interfacing or operational problems. The situation is completely different though when a substantial amount of power is penetrating a conventional utility system. Penetration related problems are particularly acute when considering the installation and parallel operation of WECS with a small autonomous power system. Wind cluster generators penetrating the utility grid usually tend to disturb such quality performance characteristics of the system as voltage distribution along the power lines, quality of voltage and current waveforms and system frequency stability. Additionally, protection and safety features of the interconnected system relate directly to the overall penetration problem.

Wind power, potentially, is one of the most promising renewable energy sources in Crete, the largest Greek island. The desire to maximize fuel savings arises because the tariff on the islands is the same as the mainland tariff yet the generation costs, being dominated by the price of diesel fuel, are normally much higher. Many parts of the island are identified as high wind potential sites. The region of Sitia, as shown in Figure 1, is estimated to be of the highest wind potential ones. Moreover, it presents a special site interest, because the most windy locations are not situated in complex terrain or at high altitudes. For that reason, the municipality of Sitia–Crete is interested to examine the possibility of installing a 4.5 MW wind farm. The Technical University of Crete was involved to that project. For the purposes of this study, the exact data were used for (a) the

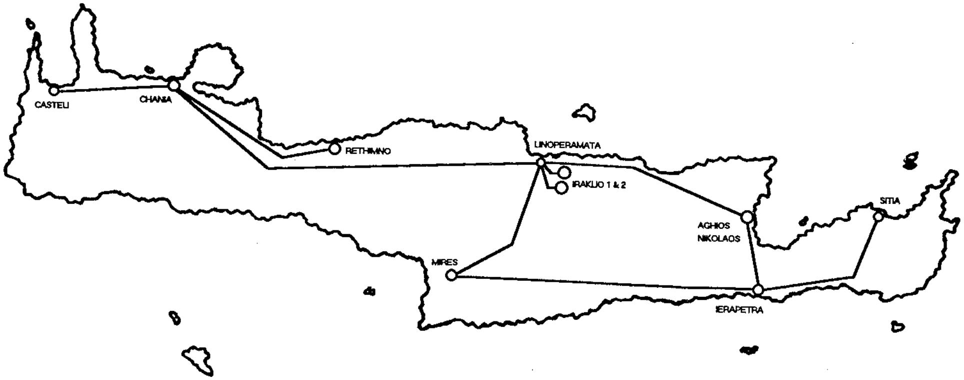

Figure 1 The island of Crete and topography of its high-voltage grid.

high voltage power transmission lines, (b) high voltage grid substations and (c) the electric power production units. All the above consist the electric system of the Public Power Corporation (PPC), currently existing on the island.

2 QUALITY EVALUATION OF THE WECS–POWER GRID INTERFACE

The power grid of Crete is of autonomous type (not interconnected to the rest national power system) and its topology is depicted in Figure 2. The electric power is generated by conventional thermal units. Two types of units are in operation: single stage steam turbine generators and gas turbine generators. The gas units are more expensive but they are faster and they react rapidly during sudden load changes. The Wind Electric Conversion Systems (WECS) of 4.5 MW totally, consisting of small asynchronous units (100–300 kW), is considered to penetrate the power system, interconnected to the high voltage bus of Sitia. The WECS design must assure the unidirectional power flow from the wind generator units to the power system. Also, suitable protection devices have to be incorporated, to maintain safe operation in the event of fault conditions, either on the side of the WECS or the side of the power grid.

The normal operation of the power grid-load system presumes that certain constraint parameters are maintained within predetermined limits. The most significant constraints, from an operational and safety viewpoint, are:

1. The voltage variation, at any point along the grid system, should not exceed ±5% of its nominal value.
2. The maximum permanent system frequency variation may not exceed ±1.5 Hz. In addition, the maximum value of the rate of the frequency variation may not exceed ±1.5 Hz/sec.
3. The WECS power introduced into the grid, at any time instant, may not exceed the difference between the load demand and a minimum permitted power level from the power station, under which the operation of the conventional generators is interrupted.

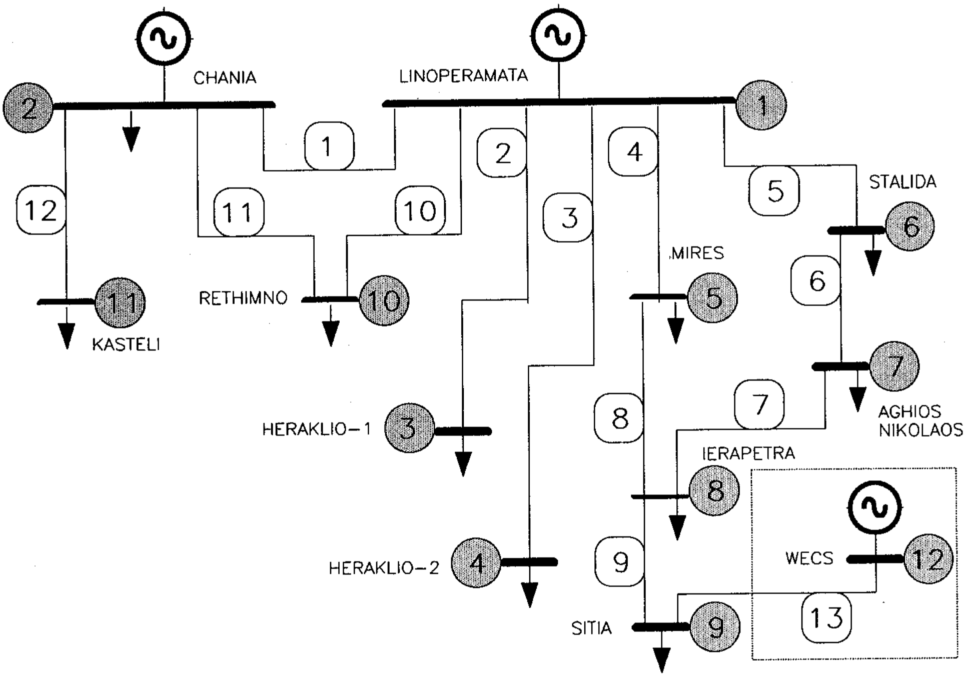

Figure 2 Schematic representation of the power system of Crete.

Load flow and frequency control simulation models were developed, to evaluate the impact of the 4.5 MW WECS penetration to the local grid of Sitia–Crete, under various loading conditions [1, 2, 3]. Brief description of the models is provided below, to clarify the method used.

2.1. *The Load-Flow Procedure* [1, 2]

The load-flow simulation is used to determine the magnitude and the phase angle of the voltage at each bus and the real and reactive power flowing in each line. The net real power into the grid must be specified at each bus except at least one (swing buses). Both, the magnitude and phase angle of the voltage at each swing bus are specified. The power drawn by the bus load is taken as negative, while the generated power input to the bus is taken as positive.

A modified Gauss–Seidel load-flow routine is employed because of the differences between the data specified for the swing and the other buses. The voltage of each bus (except the swing buses) is estimated and a better approximation is computed from the estimated values of the other buses. The iterations are terminated when the changes at each bus voltage are less than an adequate minimum value.

The admittance of each transmission line and the characteristics of the transformers are also fed as input data to the program. Then the program computes the bus impedance levels, the real and the reactive component of the complex power along each line, the line losses, as well as the magnitude and the phase angle of the voltage at each not swing bus. For the swing buses, the program computes the generated real and reactive power.

The load-flow method provides a static view of power flows and voltages of a utility grid, for specified terminal or bus conditions. The results of the method supply information about how voltages of buses are affected by the WECS in long time terms. The numerical solution of the differential equations describing the system dynamic behavior (swing-governor equations and system inertia) and the interative solution of the load-flow equations, to determine the performance of the transmission system, consist a more accurate method for the transient calculations of the power system. Thus, the dynamic performance of the bus voltages and the line currents can be obtained.

The main goal of the present paper is the study of the stability of the power system. The analysis which can be obtained by the above method (system dynamic behavior simultaneously with load-flow) covers, in detail, the stability analysis of the Load-Frequency Control (LFC) system [3, 5]. Additionally, the computer time needed for such simulation runs would be very long. Thus, the power system frequency response (generation units and loads) is simulated by an appropriate transfer function, as described in the next paragraph. The simplification does not degrade the stability considerations and accelerates the model response time.

2.2. *The Frequency Control Procedure* [2, 3]

The operational characteristics of the asynchronous generation units allow for the WECS units to be considered as "negative load", as far as the power system is concerned. This assumption is based on the lack of power regulating mechanisms to control the characteristics of the WECS.

A state space representation, based on the swing equation, of both the drive-generator couple and its power control mechanisms, for each unit of a multiple generation system, can be established [2, 3]. Equations (1) describe the state model of each generation unit:

$$\begin{aligned} \dot{x}_{Gi} &= -\frac{1}{T_{Gi}} x_{Gi} + \left[1 - F_i \frac{T_{Ti}}{T_{Gi}}\right] x_n \\ \dot{x}_{Ti} &= -\frac{1}{T_{Ti}} x_{Ti} + (1 - F_i) x_n \end{aligned} \tag{1}$$

where x_{Gi} and x_{Ti} are the states of the unit i, T_{Ti} and T_{Gi} are the turbine and generator time constant of the unit i respectively, x_n is a global state representing the system frequency change Δf and F_i is the reheat amount of the unit i. The total number of the generation units is n.

Any load disturbance ΔP_L results in a change of system frequency Δf. Each generation unit contributes an output power change ΔP_G, so that the frequency will be brought back to its nominal level. The state equation for the system frequency follows:

$$\dot{x}_n = -\frac{\sum_{i=1}^{n} C_i(x_{Gi} - x_{Ti}) + \Delta P_L}{hpf}$$

$$C_i = \frac{1}{R_i(T_{Gi} - T_{Ti})} \tag{2}$$

$$hpf = \frac{2}{f_N}\sum_{i=1}^{n} H_i P_{Ni}$$

where f_N is the nominal frequency of the system, H_i and P_{Ni} are the inertia and the rated power of the unit i respectively, R_i is the governor constant of the unit i and ΔP_L is the load change to the system. The impact of the rotating loads inertia can be easily included in the summation of the last of the relations (2), if it can be estimated. Generally, the above inertia can be neglected when compared to the generation units inertia [3, 5]. Transmission lines impedances and non-rotating loads do not affect the frequency stability analysis.

The total number of the state equations describing the system is $2n + 1$. The change of power of the unit i is given by the relation:

$$\Delta P_{Gi} = -C_i(x_{Gi} - x_{Ti}) \tag{3}$$

The rate of the power change at the output of each generation unit is limited to a maximum value MR. This is expressed in the terms of the following relations:

$$\dot{x}_{Ti} < \frac{MR_i}{C_i} + \dot{x}_{Gi} \quad \text{and} \quad \dot{x}_{Ti} > -\frac{MR_i}{C_i} + \dot{x}_{Gi} \tag{4}$$

The power rate limits for the steam units are very tight, because large deviations of steam pressure from its nominal level must be avoided. The rate limits for the gass units are wider enough, resulting in a much faster response during sudden load deviations.

The speed controller performs two functions: (a) a primary control function, which brings the system to an equilibrium state with a permanent frequency error ΔF_{stat} and (b) a secondary control, which establishes eventually nominal rotational speed, thus eliminating the static frequency error. A fourth-order Runge–Kutta routine are employed leading to a determination of the maximum frequency variation for a given load disturbance, the permanent frequency variation following primary frequency control as well as the rate of the frequency variation.

The schematic representation of the state space model of the system is shown in Figure 3. The block enclosed in the dotted line is the model of each generation unit. The lower portion of the figure illustrates the frequency model of the system. Each matrix $\mathbf{A}_i$ is of the form:

$$\mathbf{A}_i = \begin{bmatrix} -\frac{1}{T_{Gi}} & 0 & 1 - F_i\frac{T_{Ti}}{T_{Gi}} \\ 0 & -\frac{1}{T_{Ti}} & 1 - F_i \end{bmatrix} \tag{5}$$

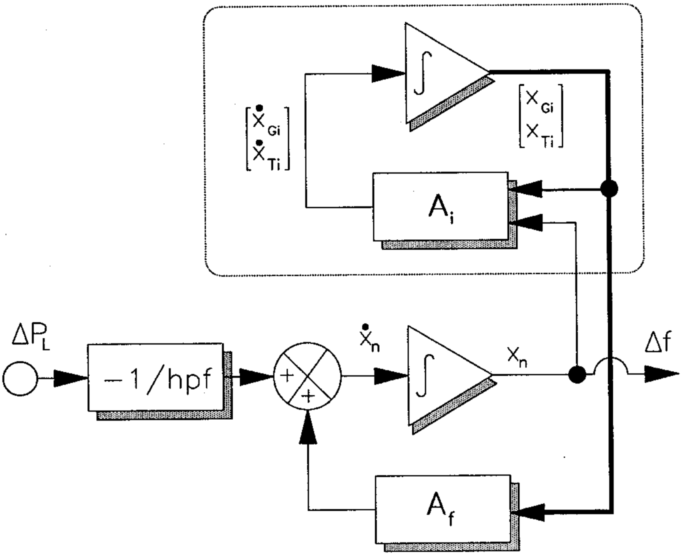

Figure 3 Schematic representation of the state space model of the power system.

Matrix $\mathbf{A}_f$ is given by the relation:

$$\mathbf{A}_f = -\frac{1}{hpf}[C_1 \; -C_1 \; C_2 \; -C_2 \; \cdots \; C_n \; -C_n] \tag{6}$$

The above method is of general use. The only limitation concerns the model used to simulate the power network transient response. As has been mentioned before, one can use the combination of the load-flow representation with the rest simulation of the power system. However, in the literature, a first order model, with estimated parameters using the inertia values of the generating units, is considered to represent well the power network dynamic response [3].

2.3. *The Penetration Strategy* [2, 4]

The first step in this procedure is to determine the absolute maximum penetrating power from the WECS cluster to the grid, so that the operating constraints are not violated. The second step involves the selection of the most appropriate bus for connecting the WECS cluster. One criterion for the interface bus selection is the minimization of the bus voltage deviation for each grid bus, from its nominal value and the total line losses. The siting process must also consider such other factors as wind potential, availability, proximity, economics, etc.

The third step in the penetration procedure is based upon the constraint that, at each instant of time, the difference between the load demand and the power introduced by the WECS, should remain above a minimum value. This assures a minimum spinning reserve, necessary to retain the stability of the system during sudden wind changes or WECS failures.

3 SIMULATION RESULTS

The rated capacity of the WECS under consideration is 4500 kW. This power level represents the 2.45% of the maximum total load demand of the island, or the 15·7% of the minimum total load demand. For the transmission lines and the transformers of the grid and the parameters in relations (1) through (4) as well, are used values available by the PPC of Crete island. It has been considered that the PPC policy guarantees a spinning reserve, when the WECS are connected to the grid, at least equal to the rated capacity of the WECS. As stated before, the response of steam turbine generators is much slower than that of gas turbine units. Thus, it is recommended that the spinning reserve capacity to rely upon gas turbines. A discussion of the sytem performance follows.

3.1. Load-Flow Study of the Interconnected System

First, a load-flow simulation study is performed, under maximum and miminum loading conditions for the power grid, with the total WECS capacity removed. The results of this simulation are listed in Table 1 for maximum loading and Table 2 for minimum loading conditions.

Then, the load-flow simulation study for the maximum and minimum loading conditions of the power grid, with the total WECS capacity interconnected, is performed. The results of this simulation are shown in Table 3 for maximum loading and Table 4 for minimum loading conditions.

A comparison for the bus voltage levels both, between Tables 1–3 and 2–4, proves that the voltage variation, at any point along the power grid, due to the WECS penetration, is around ±1% for maximum and around ±1.5% for minimum loading conditions.

3.2. Frequency Stability Study of the Interconnected System

For the frequency stability study, it is assumed that the instantaneous introduction or removal of the total WECS cluster capacity, constitutes the "worst case"

Table 1. Load-flow bus results under maximum loading conditions with the WECS disconnected.

Bus		*Bus results*					
	Type	*V_mag (kV)*	θ *(rad)*	*Ps (kW)*	*Qs (kVAr)*	*Pg (kW)*	*Qg (kVAr)*
1	slack	150.000	0.000	126635.949	75467.989	0.000	0.000
2		151.720	0·002	58500.000	43875.000	36600.000	22683.000
3		65.068	−0.009	0.000	0.000	37700.000	23364.000
4		148.765	−0.008	0.000	0.000	28100.000	17415.000
5		146.911	−0.014	0.000	0.000	12200.000	7561.000
6		145.598	−0.020	0.000	0.000	13400.000	8305.000
7		144.057	−0.027	0.000	0.000	11400.000	7605.000
8		143.528	−0.029	0.000	0.000	12000.000	7436.000
9		142.392	−0.034	0.000	0.000	7400.000	5486.000
10		149.877	−0.006	0.000	0.000	17600.000	10907.000
11		151.170	−0.002	0.000	0.000	7100.000	4400.000
12		142.392	−0.034	0.000	0.000	0.000	0.000

Table 2. Load-flow bus results under minimum loading conditions with the WECS disconnected.

Bus		*Bus results*					
	Type	*V_mag (kV)*	θ *(rad)*	*Ps (kW)*	*Qs (kVAr)*	*Pg (kW)*	*Qg (kVAr)*
1	slack	150.000	0.000	15597.975	8026.478	0.000	0.000
2		150.584	0.001	13135.000	9851.000	7400.000	4586.000
3		65.876	−0.001	0.000	0.000	5100.000	3161.000
4		149.835	−0.001	0.000	0.000	3800.000	2355.000
5		149.613	−0.002	0.000	0.000	1600.000	991.000
6		149.454	−0.003	0.000	0.000	1600.000	991.000
7		149.252	−0.004	0.000	0.000	1800.000	1116.000
8		149.195	−0.004	0.000	0.000	1500.000	930.000
9		149.064	−0.005	0.000	0.000	1000.000	620.000
10		150.082	−0.001	0.000	0.000	3900.000	2417.000
11		150.506	−0.001	0.000	0.000	1000.000	620.000
12		149.064	−0.005	0.000	0.000	0.000	0.000

Table 3. Load-flow bus results of the interconnected system (WECS connected) under maximum loading conditions.

Bus		*Bus results*					
	Type	*V_mag (kV)*	θ *(rad)*	*Ps (kW)*	*Qs (kVAr)*	*Pg (kW)*	*Qg (kVAr)*
1	slack	150.000	0.000	121887.552	71488.268	0.000	0.000
2		151.720	0.002	58500.000	43875.000	36600.000	22683.000
3		65.068	−0.009	0.000	0.000	37700.000	23364.000
4		148.765	−0.008	0.000	0.000	28100.000	17415.000
5		147.198	−0.013	0.000	0.000	12200.000	7561.000
6		146.018	−0.018	0.000	0.000	13400.000	8305.000
7		144.719	−0.024	0.000	0.000	11400.000	7605.000
8		144.404	−0.026	0.000	0.000	12000.000	7436.000
9		143.967	−0.028	0.000	0.000	7400.000	5486.000
10		149.877	−0.006	0.000	0.000	17600.000	10907.000
11		151.170	−0.002	0.000	0.000	7100.000	4400.000
12		144.290	−0.027	4500.000	3375.000	0.000	0.000

Table 4. Load-flow bus results of the interconnected system (WECS connected) under minimum loading conditions.

Bus		*Bus results*					
	Type	*V_mag (kV)*	θ *(rad)*	*Ps (kW)*	*Qs (kVAr)*	*Pg (kW)*	*Qg (kVAr)*
1	slack	150.000	0.000	11095.769	4643.844	0.000	0.000
2		150.584	0.001	13135.000	9851.000	7400.000	4586.000
3		65.876	−0.001	0.000	0.000	5100.000	3161.000
4		149.835	−0.001	0.000	0.000	3800.000	2355.000
5		149.869	−0.001	0.000	0.000	1600.000	991.000
6		149.826	−0.001	0.000	0.000	1600.000	991.000
7		149.846	−0.001	0.000	0.000	1800.000	1116.000
8		149.987	−0.001	0.000	0.000	1500.000	930.000
9		150.513	0.001	0.000	0.000	1000.000	620.000
10		150.082	−0.001	0.000	0.000	3900.000	2417.000
11		150.506	0.001	0.000	0.000	1000.000	620.000
12		150.821	0.003	4500.000	3375.000	0.000	0.000

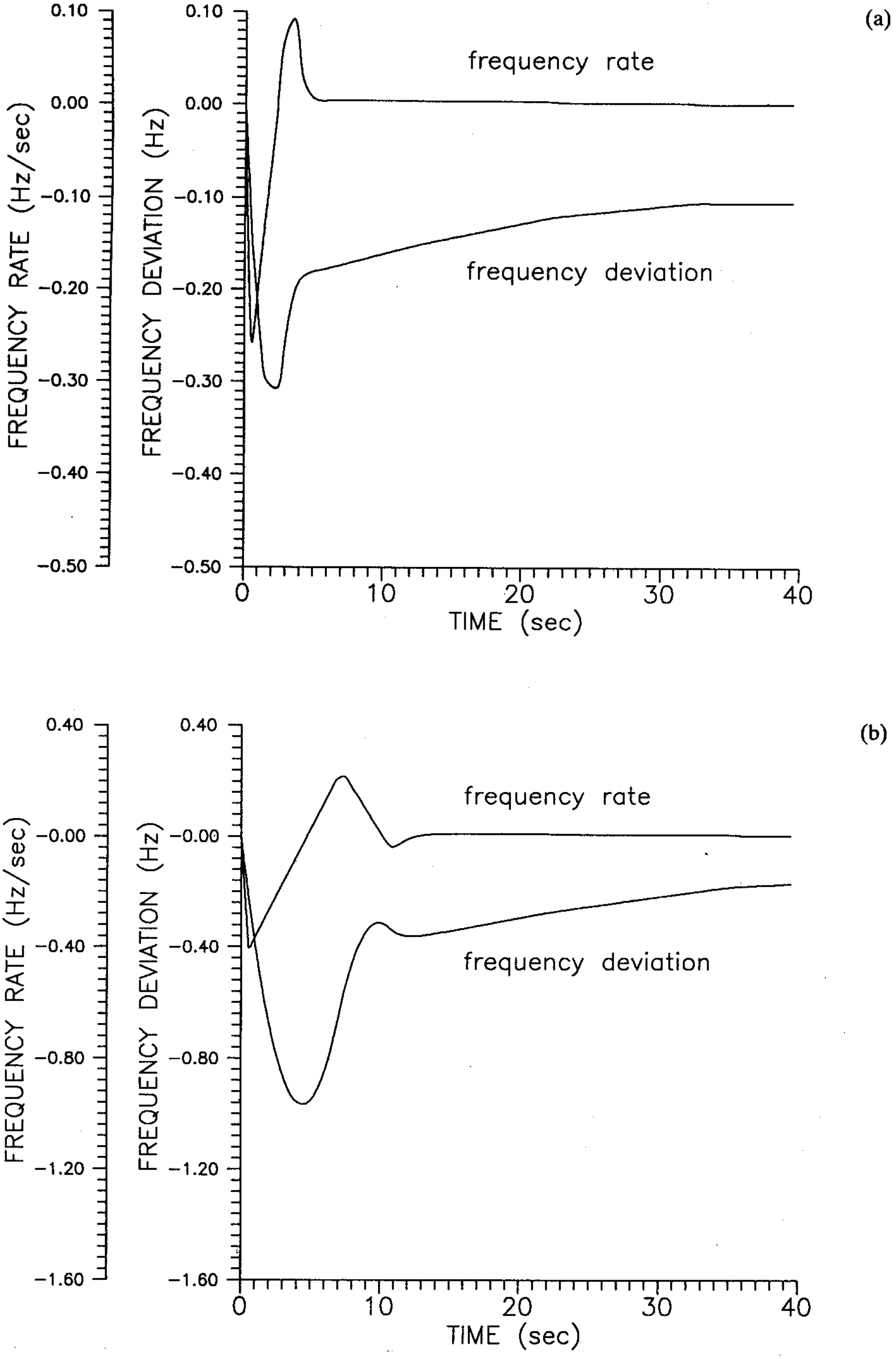

Figure 4 (a) Sudden rejection of the total WECS capacity under maximum loading conditions. (b) Sudden rejection of the total WECS capacity under minimum loading conditions.

conditions for the frequency control calculations. The program results are compared with the specified frequency constraints and the degree of dynamic penetration is determined for an acceptable, from a frequency control point of view, performance.

The simulation results from the frequency control model, when the total WECS capacity is suddenly disconnected, are depicted in Figure 4. The case (a) corresponds to maximum, whereas the case (b) to minimum loading conditions, when total WECS capacity was disconnected.

Under maximum and minimum loading conditions, the maximum frequency deviations are −0.307 Hz and −0.965 Hz, while the rate of the frequency variations are −0.258 Hz/sec and −0.406 Hz/sec, respectively.

The results above show that the bus voltage variations at any point along the power grid, the maximum permanent system frequency variation and the maximum frequency rate variation are maintained well within the predetermined limits. Therefore, even under the worst conditions, i.e during wind gusts or abrupt changes in WECS output power, the 4.5 MW wind farm can penetrate the power grid of Sitia–Crete without degrading of the normal operation of the power grid. Thus the project seems to be attractive, from the power grid reliability point of view.

4 CONCLUSIONS

The work reported in this paper is concerned with the development and application of a simulation model for the study of the interconnected operation of wind generation clusters with isolated power grids. The described simulation procedures are flexible and not purely a model of the island of Crete power system. Therefore, they can be used for any similar study. The application of the model shows clearly that a 4.5 MW wind farm can be installed at the local grid of Sitia–Crete without any preoccupation for the power system quality performance.

A penetration strategy is briefly described, in order to take into account the most important aspects related to wind penetration problem.

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