

# The "CARE" System Overview: Advanced Control Advice for Power Systems with Large-scale Integration of Renewable Energy Sources

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## ABSTRACT

In this paper, CARE an advanced control system for the optimal operation and management of isolated power systems with increased wind power integration, is presented. This control system minimises the production costs through an on-line optimal scheduling of the power units, which takes into account the technical constraints of the thermal units, as well as short-term forecasts of the load and the renewable resources. The power system security is maximised through on-line security assessment modules, which predict the power system capacity to withstand pre-selected disturbances caused by power variations from both the renewable and thermal power sources or from faults.

## 1. INTRODUCTION

High penetration of renewable energy sources, mainly Wind Power, in isolated electric power systems, as operating on islands, is one way to improve the energy environmental balance and to reduce island dependence on imported fuel. In this case however, it is important to ensure that the power system operation will not be adversely affected by the connection of a large number of Wind Parks to the system. The main problems being identified are related to system security, control of frequency and management of system generation reserves. In consequence, these systems tend to be managed in a conservative way that under-exploits the renewable energy potential or, alternatively, are operated with lower security margins. Advanced control systems can substantially help operators to manage these systems effectively, as demonstrated in the final report of JOULE II project J0U2-CT92-0053 (ARMINES *et al.*, 1996).

The objective of the European Community JOULE III Project (J0R3-CT96-0119), named "CARE" was to develop an advanced control system to help operators achieve a high level of integration of renewable energy plants, while maintaining a high level of security. A pilot installation of CARE has been operating in Crete, the largest Greek island, since May 1999. The developed control system proposes optimal operating schedules for the various power units. It also predicts on-line insecure situations, which might result from pre-selected disturbances. Production costs are minimised through an on-line optimal unit-scheduling module. This takes into account the technical constraints of the thermal-units and short-term forecasts of the load and the renewable resources several hours ahead. The power system security is taken care of by an on-line security assessment module. This supervises the scheduling of the power units and predicts the capability of the system to withstand a number of perturbations caused by the renewable and the conventional power sources without loosing synchronism. Multiple, alternative algorithms for each module have been developed, so CARE can be tailored to the needs of a wide variety of medium and large size islands.

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### 2. THE CRETE POWER SYSTEM

The power system of the island of Crete is the largest autonomous power system in Greece. It has the highest rate of increase in energy and power demand nationwide. The on-line diagram of the Crete power system is shown in Figure 1. The conventional generation system consists of two major power plants, one in Linoperamata and one in Chania, located near the major load points of the island. There are 18 thermal, oil-fired generating units with a total installed capacity of 524 MW installed, including 6 Steam units with total capacity 112 MW, 4 Diesel units with 50 MW, 7 Gas turbines with 227 MW and one Combined Cycle plant with 135 MW. There is no useful heat recovery and so all capacities are for electricity generation only.

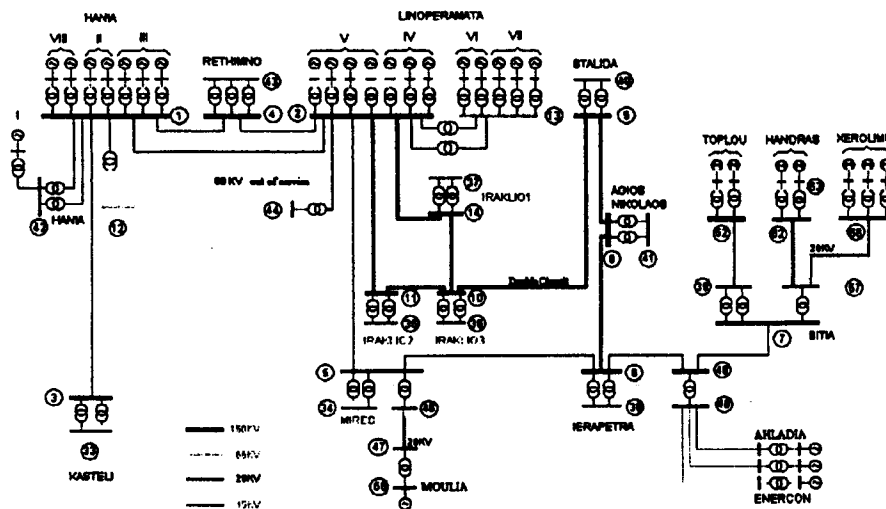


Figure 1. One-line diagram of the Crete network.

Until 1988, the annual peak load demand always occurred in winter, but from then on it always appears in summer evenings. In 1998 the peak load exceeded 380 MW, while the lowest load was about 100 MW. One characteristic of the load profile is the large variation (low night valleys – high evening peaks). The base-load is mainly supplied by the Combined Cycle. Steam and Diesel units. The Gas turbines normally supply the daily peak load or loads that cannot be supplied by units in outage. Gas turbines have a high operating cost, that significantly increases the average cost of the electricity being supplied. In the pie-chart of Figure 2, the 1998 energy share of each type of unit is shown. The transmission network consists mainly of 150 kV lines and some 66 kV lines.

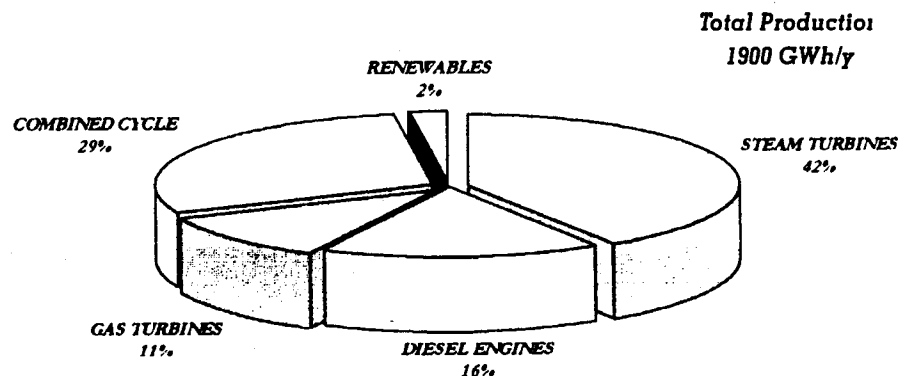


Figure 2. Crete 1998 electric annual energy production.

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The new legal framework introduced in Greece in 1995 dealing and regulating the electricity production from renewable sources has provided a significant stimulus to the installation of Wind Parks in the islands. As a result, 11 Wind Parks were being or were planned to be installed in Crete by the year 2000, as shown in Tables 1 and 2. The Wind Parks (WPs) will be connected to the grid through new HV/MV substations of 20kV/150kV. All the Wind Parks, with a few exceptions, will be installed in the eastern part of the island that presents the most favorable wind conditions. Therefore, in case of faults on some particular lines, the majority of the Wind Parks will be disconnected. Furthermore, protection of the wind turbines might be self-activated in case of frequency variations, decreasing additionally the dynamic stability of the system. Extensive transient-analysis studies have therefore been conducted, to assess the dynamic behavior of the system under various disturbances and with different combinations of the generating units.

The generation system and the transmission network are supervised by a control centre at one of the substations in IRAKLIO. The CARE control system has been installed in the control centre since May 1999. Preliminary evaluation results are presented in the accompanying paper of this Journal Special Issue (Gigantidou *et al.*).

Table 1. WPs in operation (July 1999)

WP	Comm. year	Nr of W/T	Kind of Gear	Manufacturer	Receiving S/S	Ownership	WT Power (KW)	WP Power (MW)
PPC-1	1992	17	Asynchr.	WIND-MASTER	SITIA (Load Bus)	PPC	300	5,10
PPC-2	1993	2	Asynchr.	TACKE	SITIA (Load Bus)	PPC	500	1,50
	1995	1		NORD-TANK				
OAS	1995	1	Asynchr.	TACKE	Sitia (Load Bus)	Local Authority	500	0,50
ROKAS S/A	1998	17	Asynchr.	BONUS	Sitia (W/F Bus)	Private	600	10,20
IWECO	1999	9	Asynchr.	ZONT-40	MOIRES (Load Bus)	Private	550	4,95
AEOLO S	1999	18	Asynchr.	ZONT-40	Sitia (W/F Bus)	Private	550	9,90

Total wind power (MW): 32.15

Table 2. WPs under construction (July 1999)

WP	Comm. month	Nr of W/T	Kind of Gens	Manufacturer	Receiving S/S	Ownership	WT Power (KW)	WP Power (MW)
CRETAN W/F	Jul 1999	20	Syn-chronous	ENERCON	MARONIA (Private S/S)	Private	500	10
		20					500	10
		10					500	5
PPC-3	Dec 1999	8	Syn-chronous	MICON	SITIA (W/F Bus)	PPC	600	4,80
PPC-4		9					600	5,40

Total wind power (MW): 35,20

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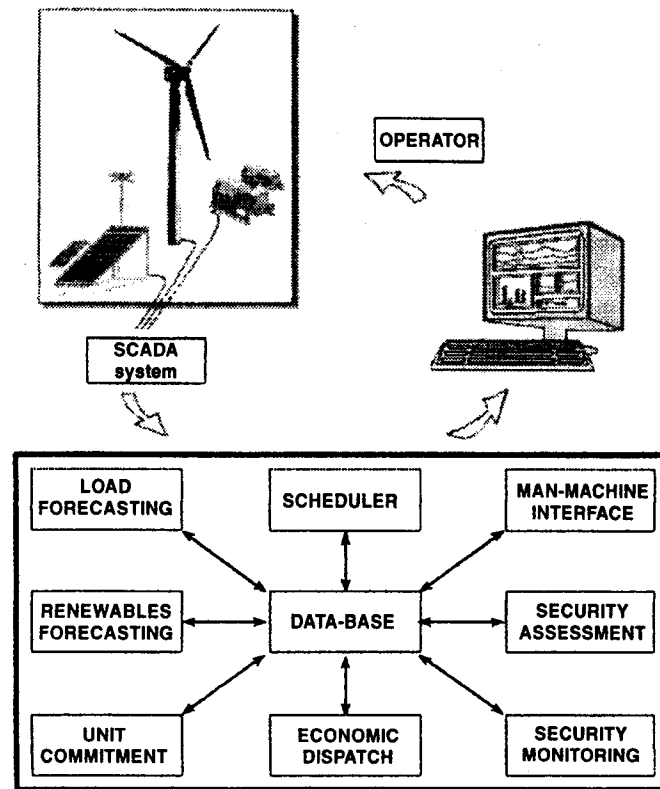


Figure 3. The CARE system architecture.

### 3. THE CARE SYSTEM ARCHITECTURE

The CARE control system is designed to produce optimal scenarios, both from the economic and security point of view, for the power system operation. For this purpose, various functions have been developed and integrated in the control system structure, which is shown in **Error! Reference source not found.** After extensive testing and evaluation of the calculation burden of each module, the basic time step for Crete was fixed on 20 min for all the activities (forecasting, security assessment, unit commitment and economic dispatch), as shown in Figure 4.

Unit commitment has a horizon of 8 hours ahead (moving window) but tests showed that an outer cycle of 48 hours was needed to define guidelines that take into account the daily cycle of the load.

Security assessment follows the unit commitment and dispatch modules, leaving to the operators the decision whether or not they activate the module for validation of the proposed dispatch (or pre-dispatch resulting from the unit commitment).

In the next Sections, the main modules of the system are described.

### 4. LOAD AND RENEWABLE POWER FORECASTING

For the economic and reliable operation of the power system, it is necessary to have accurate forecasts of the power demand, as well as the production of the renewables (Kariniotakis, Matos and Miranda, 1999). The following types of models have been developed within the CARE project:

#### 4.1 Load Forecasting

- (i) Same time as the previous day (scaled for errors between days) (RAL);
- (ii) Same time as the previous week (scaled for errors between days) (RAL);
- (iii) Winter method (NTUA);
- (iv) Autoregressive model (RAL);
- (v) Fuzzy neural network (ARMINES).

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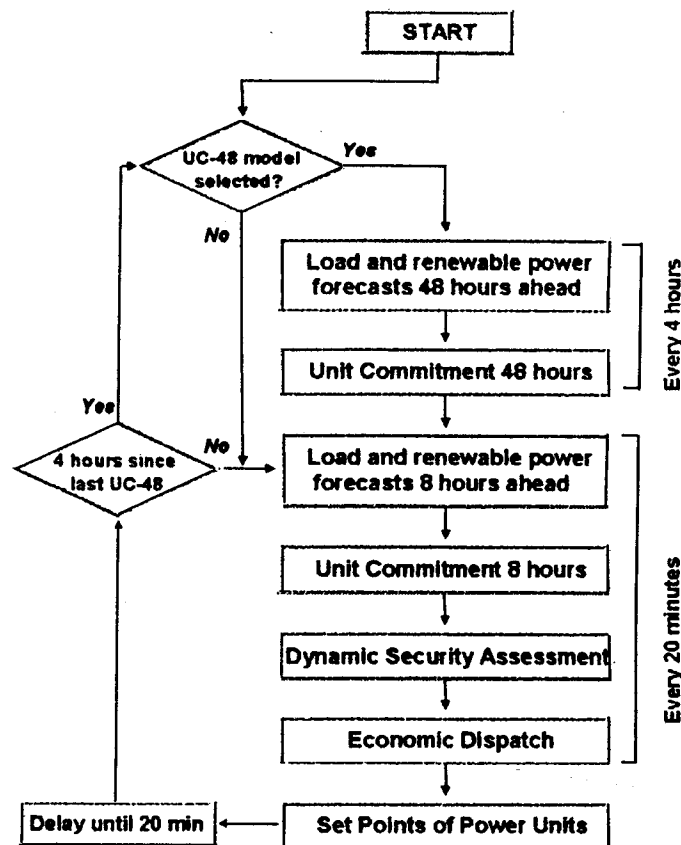


Figure 4. Main operations of the CARE system algorithm.

The name of the partner responsible for each model is shown in parentheses. The two last methods are clearly superior, as shown by comparative tests, and have been incorporated in the CARE software. Load forecasts are required on both short-time (several minutes up to several hours ahead) and long-time scales (of the order of several hours ahead up to several days ahead). These forecasts provide input to the economic dispatch and unit commitment algorithms. ARMINES has analysed the performance of simple methods for load and wind forecasting (persistence, moving averages, predictors based on the load of the previous day or week etc.) with the performance of models based on fuzzy autoregressive modelling, ARMA modelling and neural networks (Kariniotakis *et al.*, 1999).

### 4.2 Wind Power Forecasting

Three basic methods have been incorporated in the CARE software:

- (i) linear ARMA models (RAL);
- (ii) linear ARMA and fuzzy-neural network models (ARMINES);
- (iii) fuzzy neural network based on geographically distributed wind data (AUTH).

Various model configurations for the wind-forecasting problem for different horizons (8h, 24h ...) and with different time steps (20 min, 1 hour) have been examined. The fuzzy logic and ARMA methods have been applied and compared. For the implementation of the wind forecasting models, a generic architecture was proposed so that CARE becomes able to integrate meteorological-based forecasts in a future stage.

Details of the CARE forecasting models can be found in the accompanying paper in this Journal Special Issue (Dutton *et al.*).

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### 5. UNIT COMMITMENT

The Unit Commitment (UC) module suggests to the operator of the power system a number of optimised operating schedules for the next hours. These schedules are characterised by:

- switch on-off decisions regarding the thermal units. The time step for these decisions is 20 minutes;
- a pre-dispatch (operating schedule) for conventional and renewable units;
- maximum power limits for renewable power units.

Two modules are developed within this project for the UC task:

- INESC's module based on Genetic Algorithms (GAs), both for the 8-hour and the 48-hour horizons. This approach provides a relatively short computation time, while constraints of the various kinds of generators and security spinning reserve restrictions can be included easily. Short computation time is crucial for this function. Several techniques and genetic operators have therefore been used to limit the length of the chromosome;
- NTUA's combinatorial Unit Commitment module that provides switch on-off commands every 10–20 minutes (Androutsos and Papadopoulos, 1999). Following the current PPC operating practice, the Steam Units are considered to operate continuously either with a fixed or a variable output. Temperature forecasts are used to determine the maximum available power of the gas turbines.

The above models are able to simulate systems with Steam units, Gas turbines, Diesel and Combined Cycle power units. Various types of renewable supplies can be considered, i.e. wind farms, photovoltaic plant, and small hydro stations. To generate the operating scenarios, the power system operation is simulated in detail by taking into account the characteristics of the various power units (start-up time, power limits, production costs etc.). Appropriate spinning reserve criteria are developed able to account for the uncertainty of the forecasts. In addition, contractual aspects are taken into account, related to generation from independent producers.

### 6. ECONOMIC DISPATCH

The aim of the Economic Dispatch (ED) module is to define the set points, i.e. the production values for all the generators in the system, for the next time step (20 minutes ahead). The module receives the output of the Unit Commitment for the next time-step. This output is optimised by rescheduling generating units, so the operating cost of the system is the minimum possible. Security constraints for both the generation system and the transmission network are considered.

Three different ED models have been integrated in the CARE system:

- The INESC module based on Evolutionary Programming. The model follows the usual steps in an Evolutionary Programming algorithm, where the solutions are not coded in chromosomes (as in Genetic Algorithms). The fitness function assesses the quality of the proposed solution setting the basis for the selection process. It proposes a penalty for constraint violations (voltage levels and line thermal limits) that increases with the number of generations, in order to allow the digression of the algorithm through unfeasible parts of the solution universe. It also contains processes of auto-correction of power losses and voltage levels. The fitness values for a given solution will include generation costs as well as cost of losses;
- The AUTH module based on Genetic Algorithms (GAs) (Kazarlis, Bakirtzis and Petridis, 1996). The module incorporates all the features of a standard GA implementation, such as: Roulette Wheel Parent Selection, Crossover, Mutation, Adaptation of Crossover and Mutation Probabilities, Fitness Scaling and Elitism, as well as advanced features like Adaptation of Crossover and Mutation Probabilities and the Consecutive Variable Swapping Operator;
- The NTUA model (Optimal Power Flow Program) based on constrained linear programming (Contaxis and Vlachos, 1999). The module utilises a linearised model of the system, which relates the generation production rescheduling and the other control resetting to the

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operating cost and the transmission network constraints. Particular emphasis is given to the feasibility and deficiencies concerning a large penetration of wind power and the operation of Independent Power Producers (IPPs) under three alternative operation modes, i.e. fixed schedule, fixed penetration and economic schedule.

Details of the CARE operational planning models can be found in the accompanying paper in this Journal Special Issue (Matos *et al.*).

### 7. DYNAMIC SECURITY ASSESSMENT

In isolated power systems, with increased wind power penetration, sudden changes of system operating conditions must be compensated quickly and efficiently. This is to avoid large voltage and frequency excursions or high frequency rates of change. These may trigger the operation of protection relays provoking unwanted load shedding, Wind Park or conventional unit disconnections, or even system collapse (Hatziaargyriou, Karapidakis and Hatzifotis, 1998). This means that for some probable disturbances, expected system frequency excursions must be assessed in a fast way to help operators adopt secure operating strategies. On-line analysis of system behaviour for the specified disturbances is practically impossible using conventional tools. Therefore, machine learning techniques have been used to provide accurate and fast evaluation of system stability, relative to pre-selected disturbances (Hatziaargyriou, 1998; Pecos Lopes, 1998).

For Crete, a unified Learning Set has been developed for three pre-selected disturbances, specified after discussions with PPC. A large number of Operating Points covering various loading conditions (low-, medium- and high-load) were simulated and labelled as secure or insecure according to the frequency variations calculated. Based on this Learning Set, NTUA has produced a number of "if . . . then . . . else" security rules using the Decision Trees (DTs) methodology. INESC has also provided rules and, in addition, the degree of robustness of each OP (new) using Kernel Regression Trees (KRTs) (Hatziaargyriou *et al.*, 1999). In this classification structure one can assign a given degree of security to each leaf accordingly to the mean value of the OPs that belong to that node. INESC has also developed Artificial Neural Networks with one output layer having two security indices as outputs, namely the maximum absolute frequency variation and the rate of variation.

The security modules are available on call to provide on-line security assessment of the present or scheduled operating points. Details of the CARE dynamic security models can be found in the accompanying paper in this Journal Special Issue (Pecos Lopes *et al.*).

### 8. INTEGRATION

The modules described in the previous sections have been integrated into CARE, an advanced software having real-time performance and interfaced according to the two execution cycles defined in Figure 4. In this way, a highly modular package has been developed. The various modules exchange their inputs and outputs via the CARE database, which is updated from the SCADA database every minute.

Particular emphasis has been given to the provision of a user-friendly man-machine interface, to ensure acceptability by the system operators. Its basic philosophy is to provide all the essential information graphically on a single screen, with a number of "windows" available on call to provide explanatory information or other results. The permanently displayed information provides the present state of the system, i.e. active load demand at the 12 load buses, production of the 5 Wind Parks and generation of the conventional units at Linoperamata and Chania power stations. The central window provides forecasting information for the system, together with its recent history. This window spans a period of 24 hours and is divided by a hypothetical vertical line in the middle of the screen. Half of the screen shows the total load and wind power production for the past 12 hours. The other half displays the wind power and load forecasts. The latter is contrasted to the respective load values 24 hours before or any other day selected by the operator (Figure 5). Finally, in the right part of the screen the commands and options for the easy adaptation and parameterisation of the CARE software are shown. These commands allow the consideration of thermal units available for dispatch or out of action e.g. for maintenance, as well details of the units in operation. The

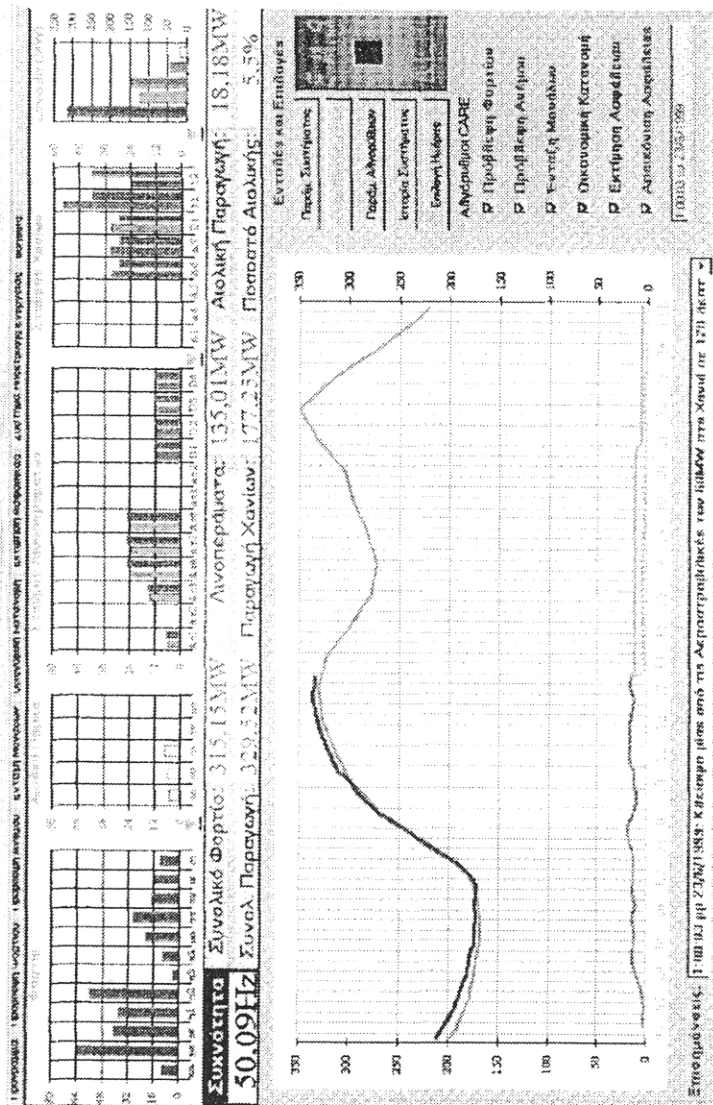


Figure 5. CARE basic screen.





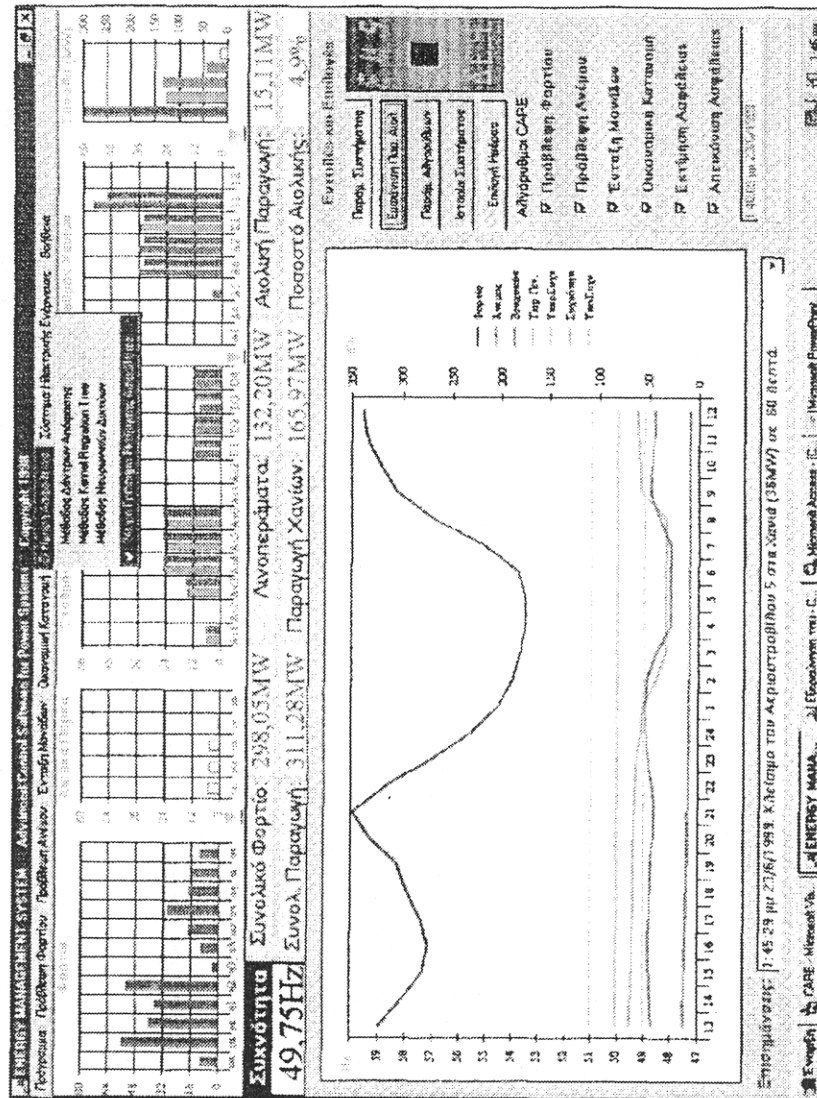


Figure 7. Dynamic security assessment for 48 hours ahead.

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privileged user has the ability to specify which of the modules will be executed every 20 minutes or 1 hour, and even decide which of the available modules will take care of each activity.

Under the central window, the output of some modules and warning messages are displayed, in the form of commands and information to the operators. Additionally, two main windows are available "on call". These are:

- The Unit Commitment results for 48 hours ahead, which are displayed in a form of coloured chart (Figure 6);
- The Dynamic Security Assessment results for 48 hours ahead, which are displayed in a form of lines that represent the frequency that is expected in case of the considered disturbances under the predicted load demand and wind production (Figure 7).

## 9. CONCLUSIONS

This paper presents the main features of CARE. This is an advanced control system, providing advice to power system operators for the optimal operation and management of isolated power systems with large integration from renewable power sources. A number of different models for performing each main task have been integrated, so the operator can choose which models will run on-line. A pilot CARE system has been installed on the Greek island of Crete, since May 1999. The modular configuration of the control system software, and the standard hardware used, enables application in other isolated networks, e.g. in Europe and in developing countries.

## 10. ACKNOWLEDGEMENT

The authors express their gratitude to the European Union, Directorate General XII, for funding the project CARE: "Advanced Control Advice for Power Systems with Large Scale Integration of Renewable Energy Sources" within the JOULE III framework and especially Mr K. Diamantaras for his help and guidance. The support of the PPC is particularly acknowledged.

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