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MODELLING OF COMBINED PHOTOVOLTAIC-WIND-DIESEL ENERGY SYSTEMS FOR GRID PENETRATION STUDIES

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Abstract

This paper describes a penetration methodology involving a small conventional power system, supplied in parallel by photovoltaic and wind energy conversion systems. The penetration problem is defined as follows: Quality of system performance is guaranteed when operational parameters, such as voltage and frequency, are maintained within acceptable bounds. The operation of the combined PV-WECS-diesel power plant is sustained within satisfactory limits, with a dynamic penetration strategy. The strategy uses dynamic models of load flow system frequency control and harmonic content, to produce control signals for the operation of the units. The resulting control scheme is implemented via a microprocessor-based system. The proposed methodology is applied to the autonomous power system of the island of Kythnos, where a 100 kW PV plant and a wind park, consisting of five 20kW wind generators, have been in operation since 1982. Simulation results indicate the need for a power supply management tool, which optimizes system performance and maximizes energy derived from renewable sources.

INTRODUCTION

In recent years there has been growing interest in utilizing wind-electric conversion systems and photovoltaic arrays to provide some of the electricity demand on a large scale [1-3]. Such systems are usually interfaced with the existing power grid for "fuel displacement" purposes as well as for earning some "capacity credit". Penetration related problems are acute when considering the installation and parallel operation of WECS and PV with a small autonomous power system. Wind cluster generators and photovoltaic sources 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.

Several investigators have addressed recently various technical, economic and institutional aspects of the penetration problems. Theoretical and experimental results, relating to fuel displacement in an isolated diesel powered system supporting a 150 kW wind turbine [4], performance characteristics of renewable energy farms demostrating concept feasibility [5] and analytical methods used in reducing wind and solar generation changes from climatic conditions [6] have been reported. Utility protection problems [7] and distributed system automation and control practices in the presence of dispersed storage and generation facilities have been extensively treated.

This work involves the development of appropriate models for the interconnected operation of wind generator clusters and photovoltaic arrays with an autonomous power system and simulation techniques for the study of the degree of penetration of such wind electric conversion and PV devices when operating in parallel with the utility grid. The proposed methodology is particularly justified when applied to small autonomous power systems without any ties to other utility lines such as those often arising in small islands or isolated communities. The WECS cluster and PV arrays is thought to be centrally located and under direct supervision and control of the utility operators.

THE WECS/PV-POWER GRID INTERFACE

The normal operation of the power grid-load system presupposes that a number of constraint parameters are maintained within predetermined bounds. The most significant, from an operational and safety viewpoint, constraints 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 should be maintained within ±2 Hz.
3. The maximum value of the time rate of the frequency variation may not exceed ±1.5 Hz/sec.
4. As far as the harmonic distortion introduced by the WECS/PV interface into the utility lines is concerned, the contribution of each

odd harmonic may not exceed 5-6% while each even harmonic may contribute up to 0.5-1%; total harmonic distortion must be maintained approximately within 5%.

5. The WECS/PV power introduced into the grid, at each instant of time, may not exceed the difference between the load power demand at that instant and the minimum amount of power which the conventional generating units are required to provide without an interruption of their operation.

The sizing and siting of WECS/PV farms is studied taking into account bus voltage distributions and line losses in a "static penetration" strategy.

The "dynamic penetration" deals with operational matters of the combined WECS cluster -PV array- utility grid system so that none of the constraints defined above may be violated. The dynamic operational strategy of the WECS -PV- grid interconnected system is implemented via a microprocessor - based control scheme. The microprocessor receives and processes information from both the wind generator cluster and the conventional power system and, taking into account the operational constraints, generates appropriate control signals; the latter determine which ones of the WECS/PV units may be connected to the grid and under what conditions the autonomous power station will operate.

The dynamic penetration characteristics may be studied and implemented with the assistance of appropriate simulation techniques. Brief descriptions of the models are provided below to assist the reader in understanding the overall strategy.

THE SIMULATION APPROACH

See Figure 1. The block diagram illustrates the interaction between the wind generator part, the photovoltaic component and the local utility grid. Move specifically, a synchronous generator - rectifier - line commutated inverter configuration is used to model each one of the WECS in the cluster. On the other hand,the PV plant is modelled as a light-generated current source interfaced to the utility grid via a line commuted inverter. In both cases a maximum power tracker device provides continuously maximum power to the utility lines from the primary sources.

The utility grid model is a series of algorithms simulating operational characteristics necessary to verify compliance with the constraints mentioned above. In detail, the main programs are:

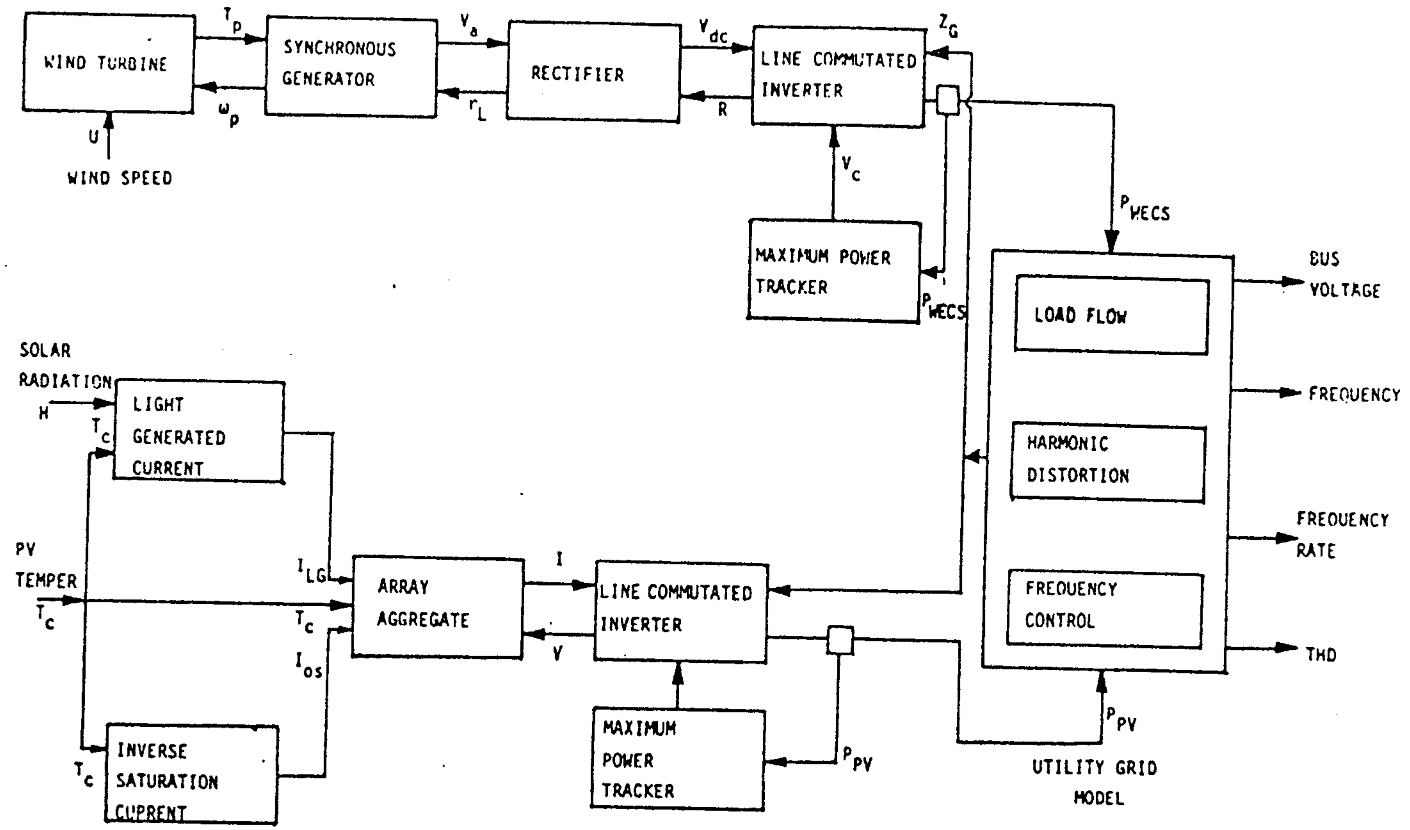


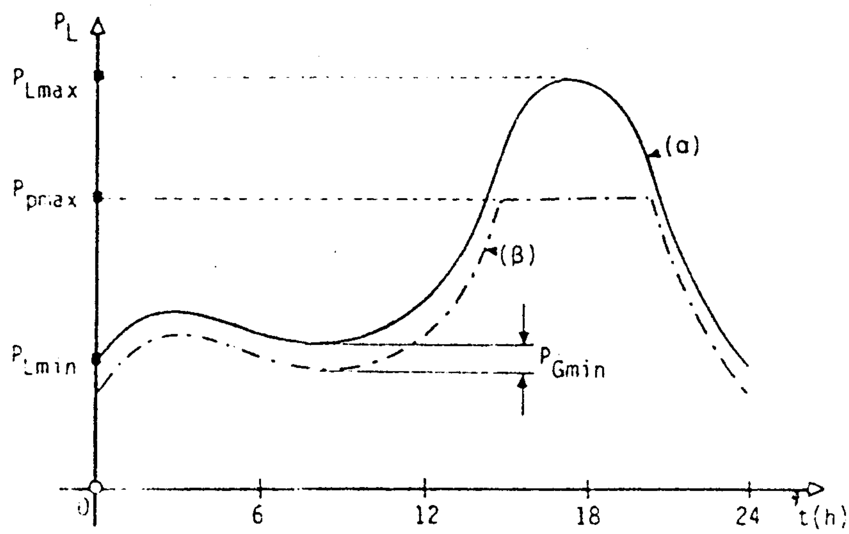
Figure 1. A typical WECS/PV Grid block diagram configuration used in the simulation studies.

(a) The Load Flow Program.

A modified "load flow" routine is employed in order to simulate efficiently the steady-state behavior of the power system. With input data the characteristics of the transmission and distribution networks and the loading conditions of each bus, the program calculates the admittances of power lines, the real and reactive components of power along the same line as well as the voltage level of each bus. The network impedance at any point along the grid may also be computed.

(b) The Frequency Control Program.

The operational characteristics of the particular type of inverter employed allow for the WECS-PV units to be considered as "negative loads", as far as the power system is concerned. The dynamics of the power control mechanism employed and those associated with the conventional diesel-generator units are described via a state variable formulation. A fourth-order Runge-Kutta routine is called upon to solve the resulting system equations. Solutions lead 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 time rate of the frequency variation. 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.



(a) Load demand profile

(b) Maximum permissible penetrating power from WECS.

Figure 2. The dynamic penetration strategy.

(c) Harmonic Distortion Program.

The introduction of the WECS-PV electrical power into the utility grid via a line-commutated inverter results in the presence of harmonic frequencies along the power lines. The harmonic distortion program accepts as input data information relating to the power level penetrating into the grid, the line impedance at the point of interconnection as well as the inverter operational characteristics and determines the Fourier coefficients of the line voltage waveform and the total harmonic distortion at the point of interconnection. Under "worst case" conditions, the

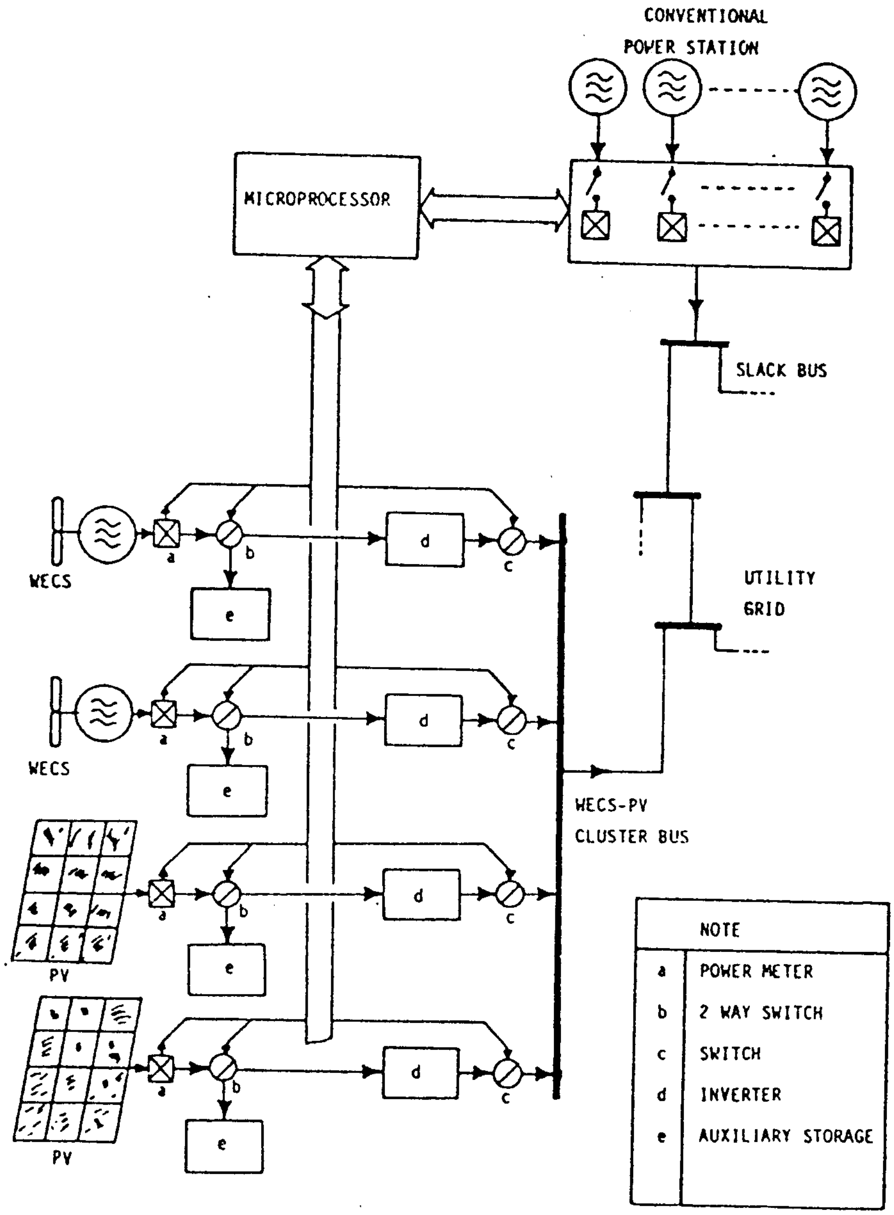


Figure 3. Block diagram of the dynamic penetration implementation scheme.

degree of penetration may be determined so that the wind-PV generator cluster does not severely degrade the quality of the power line voltage waveform.

THE PENETRATION STRATEGY

The dynamic penetration methodology is based upon the assumption that, at each instant of time, the difference between the load demand P_L and the power introduced by the WECS and PV, P_p, should remain above a minimum value, P_{Gmin}, so that at least one unit of the conventional power station is always in operation. If P_{pmax} is the maximum permissible penetrating power from the WECS/PV, then:

$$P_{pmax} = P_L + P_{Gmin} \tag{1}$$

and the penetrating power, at each instant of time (P_p) must remain below P_{pmax}, that is:

$$P_p \leq P_{pmax} \tag{2}$$

The maximum value for the penetrating power is the WECS/PV cluster power, P_{wmax}. This is expressed as:

$$P_{pmax} \leq P_{wmax} \tag{3}$$

A systematic organization of the procedural steps outlined above leads to an overall dynamic penetration strategy which allows for the normal operation of the interconnected system. To simplify matters, let us assume that the loading characteristic, for some given period of time, is as shown in Figure 2. A penetration curve is also shown in the same figure. Up to a load value of P_L, the total WECS/PV power penetrating the system is smaller than the load by Pg_{min} . For penetrating power greater than P_{wmax}, one of the specified constraints is violated and the penetrating cluster power is kept at the maximum value of P_{wmax}.

Next, the frequency control program is used to determine the loading conditions for which the system frequency variations are kept within the specified limits. The results of these program runs establish, as part of the dynamic penetration strategy, the time sequencing for the introduction or removal of cluster units in a way that assures a satisfactory system performance.

Figure 3 shows in block-diagram form the main features of the dynamic penetration implementation scheme. The diagram highlights the philosophy of the penetration strategy omitting such details as protection devices, transformers, communication links, etc. Central to the scheme is a microprocessor - based system with programmed instructions relating to the operational constraints on the voltage, frequency and harmonic distortion introduced by the WECS into the power grid.

EXAMPLE AND CONCLUSIONS

For the dynamic penetration characteristics, load flow simulation studies show that the voltage variation is always maintained within the constrained values under extreme penetrating conditions. The constraint that may be violated first in this particular example is the total harmonic distortion. Harmonic distortion results dictate a dynamic penetration characteristic which follows the load curve from $P_{Lmin} = 50KW$ to $P_L = P_{wmax} + P_{Gmin} = 120kW$. At a level which is always below the load curve. For load values from $P_L = 120W$ to $P_{Lmax} = 440kW$, the maximum possible penetrating power is fixed at $P_{wmax} = 110kW$ since the resulting total harmonic distortion reaches the constraint value of 5 %.

Finally, using the frequency control program with a minimum system load $P_{Lmin} = 50kW$ (one diesel unit in operation) and a maximum load of 440kW (up to three diesel units in operation), the maximum allowable load variation is computed. The results are shown in Table 1.

Table 1

Generator Units	Nominal Power (KVA)	Maximum Permissible Load Change
A or B	125/UNIT	± 35 kW
C	250	± 80 kW
A + B	125 + 125	± 75 kW
A + C	125 + 250	± 90 kW
A + B + C	125 + 125 + 250	±110 kW

Each entry specifies the maximum allowable load power variation exceeding the frequency and rate of frequency variation constraints.

The proposed strategy optimizes system performance on the basis of quality constraints for the power system. Its implementation, using a microprocessor based controller programmed with the assistance of appropriate algorithms, assures maximum system reliability and component protection.

The constraints stipulated relate only to those technical aspects of the penetration problem that refer to such system variables as voltage, frequency and harmonic distortion. In a more general perspective of the same problem, other significant parameters of an economic, social, climatological and topographical nature should also be jointly considered in deciding upon the optimum interfacing of wind -PV generator clusters.

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