IEEE Transactions on Power Apparatus and Systems, Vol. PAS-104, No. 7, July 1985

PENETRATION OF WIND ELECTRIC CONVERSION SYSTEMS INTO THE UTILITY GRID

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Abstract

This paper is concerned with the development of appropriate models for the interconnected operation of wind generator clusters with an autonomous power system and simulation techniques for the study of the degree of penetration of such wind electric conversion devices when operating in parallel with the utility grid. The quality of the interconnected system performance is specified in terms of operational constraints and the resultant penetration strategy is implemented via a microprocessor-based control scheme. The strategy assures a satisfactory level of system performance while optimizing the available energy transfer from the wind generators to the utility grid.

INTRODUCTION

In recent years there has been growing interest in utilizing wind - electric conversion systems 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." In the case of an autonomous operation of Wind Electric Conversion Systems (WECS), some form of energy storage is required (pumped storage, hydrogen production, battery storage, etc.), thus reducing the economic attractiveness of the overall system.

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.

The optimum utilization of wind generator clusters involves not only those technical considerations mentioned above but also such diverse factors as economy of operation, wind energy availability, proximity of the wind park to the power lines, etc. Various technical, economic, institutional and wind siting aspects relating to the penetration problem have been addressed recently [4-7]. Futhermore, several investigators have reported on theoretical and experimental results relating to fuel displacement in an isolated diesel-powered system supporting a 150 kw wind turbine [8], performance characteristics of a wind farm demostrating concept feasability [9] and analytical methods used in reducing wind generation changes from a wind generator cluster for passage of a thunderstorm [10], to name a few in a growing area of research. Utility protection problems [11] and distribution system automation and control practices [12] 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 with an autonomous power system and simulation techniques for the study of the degree of penetration of such wind electric conversion devices when operating in parallel with the utility grid. In large interconnected systems, problems arising from the interface of WECS to the power grid are usually not as acute. This is due to the fact that the WECS generation capacity is only a small percentage of the load capacity of the interconnected system. It is of course possible that even in this case, problems associated with harmonic distortion or voltage regulation may arise. This is true particularly when WECS clusters are located at the extremities of a radial line. The proposed methodology will be equally applicable to such a configuration. It is nontheless fully justified when applied to more problematic situations (autonomous grid, long transmission lines, etc.). Problematic situations often arise in small islands or isolated communities which operate their own autonomous power system without any ties to other utility lines. The WECS cluster is thought to be centrally located and under direct supervision and control of the utility operators. Dispersed WECS on the residential level are excluded from this study.

THE WIND GENERATOR-POWER GRID INTERFACE

A typical autonomous network is shown in Figure 1, with the generating system consisting of diesel-driven units whereas the distribution system is of the radial type. Such networks, with generating capacities of up to a few megawatts each, are encounteed in the Aegian islands of Greece. A wind generator cluster consisting of small units of the synchronous type with their output rectified and then inverter to AC in synchronism with the utility lines is considered to penetrate the power system. The system design assures a unidirectional power flow from the wind generator units to the power system and suitable protection devices are incorporated to maintain a safe operation in the event of fault conditions either on the side of the WECS or on the side of the power grid. This category of WECS (wind generator - rectifier-inverter) offers, in ad-

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84 SM 608-6 A paper recommended and approved by the IEEE Power System Engineering Committee of the IEEE Power Engineering Society for presentation at the IEEE/PES 1984 Summer Meeting, Seattle, Washington, July 15 - 20, 1984. Manuscript submitted January 31, 1984; made available for printing May 3, 1984.

dition, the advantage of continuous adjustment of output power. This is achieved by modulating the conduction angle of the inverter bridge.

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 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 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.

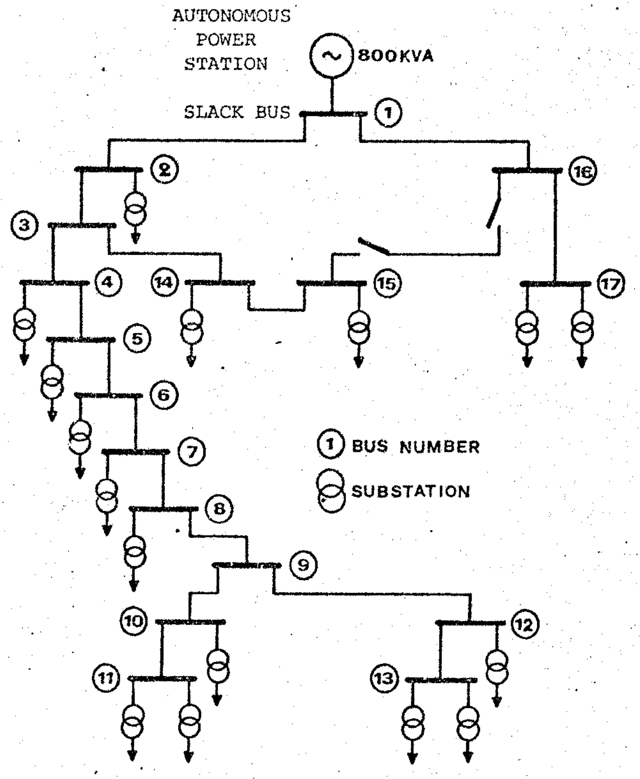


Figure 1. Typical topology of an autonomous power system.

The penetration problem may be thought of as consisting of two main parts: The first one, defined as "static penetration," is conserned with (a) the determination of the maximum possible WECS power allowed to penetrate the given autonomous system at the specific grid location. If the WECS type to be employed is known, then the number of wind generators in the cluster may determined and (b) the determination of the specified grid location where the WECS cluster may be connected resulting in minimum line losses and optimum voltage level distributions.

The second part, known as "dynamic penetration," deals with operational matters of the combined WECS cluster-utility grid system so that none of the constraints defined above may be violated. The dynamic operational strategy of the WECS - 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 cluster units may be connected to the grid and under what conditions the autonomous power station will operate.

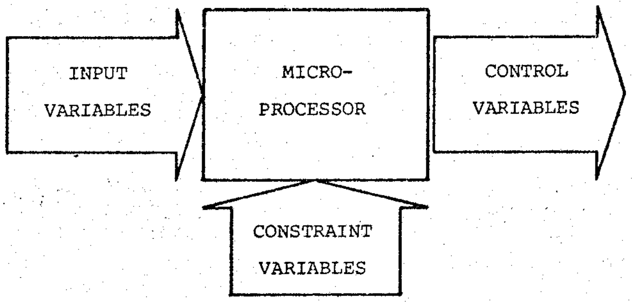


Figure 2. Schematic of the μP input - output configuration.

Figure 2 shows a schematic representation of the μP input-output configuration. The constraint variables, in the form of a "dynamic penetration" strategy, are stored in the memory unit of the μP. The control variables are determined at each instant of time, so that, for any input conditions, they maintain an acceptable level of system performance.

Both the static and dynamic penetration characteristics may be studied and implemented with the assistance of appropriate simulation techniques. Load flow, frequency control and harmonic distortion models are used to determine the degree of penetration, under various loading conditions. Brief descriptions of the models are provided below to assist the reader in understanding the overall strategy.

THE SIMULATION APPROACH

(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. The load flow program determines the maximum bus voltage from its nominal value under various loading conditions, the line losses and the bus impedance levels.

(b). The Frequency Control Program.

The operational characteristics of the particular type of inverter employed allow for the WECS units to be considered as "negative loads," as far as the power system is concerned. Figure 3 shows the transfer function representation of power control mechanisms for a multiple generator system [13]. Any load disturbance ΔP_L results in a change of system frequency Δf. Each generating unit contributes an output power change ΔP_G so that the frequency will be brought back to its nominal level. The speed controller performs two functions: a primary control function which brings the system to an equilibrium state with a permanent frequency error Δf_{stat} and a secondary control which establishes eventually nominal rotational speed thus, eliminating the static frequency error. The speed controller is, therefore, part of an overall feedback mechanism as shown in Figure 3. For an autonomous system, without interties, we may write for the transfer function of the i^{th} generator:

$$\Delta P_{Gi} = \frac{1}{(1 + sT_{Gi})\,(1 + sT_i)} \cdot \frac{-\Delta f}{R_{ri}} \qquad (1)$$

where, R_{ri} is the second regulation parameter due to governor action, T_{Gi} and T_{Ti} are the time constants for the speed governing mechanism and the turbine-generator set, respectively.

The system input - output relationship is given by:

$$\Delta f = -\frac{G_p}{1 + \sum\limits_n \frac{1}{R_{ri}}\, G_p\, G_{GTi}} \qquad (2)$$

where G_p is the transfer function of the grid - load combination expressed as:

$$G_p = \frac{k_p}{1 + sT_p} \qquad (3)$$

and G_{GTi} is the transfer function of the i^{th} generating unit together with its speed regulator.

For the case under study, a step load disturbance is considered, corresponding to a connect (or disconnect)action of the WECS. Thus, equation (2) may be written as:

$$\Delta f = -\frac{G_p\, DP_L}{\left(1 + \sum\limits_n \frac{1}{R_{ri}} \cdot G_p\, G_{GTi}\right)s} \qquad (4)$$

where:

$$\Delta P_L = \frac{DP_L}{s} \qquad (5)$$

it follows from (4) that

$$\Delta f_{stat} = \frac{-k_p}{1 + k_p \sum\limits_n \frac{1}{R_{ri}}}\, DP_L \qquad (6)$$

For a solution of (4), a state variable formulation and 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 time rate of the frequency variation. It is assumed thet the instantaneous introduction (or removal) of the total WECS cluster capacity constitutes the "worst case" condition 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.

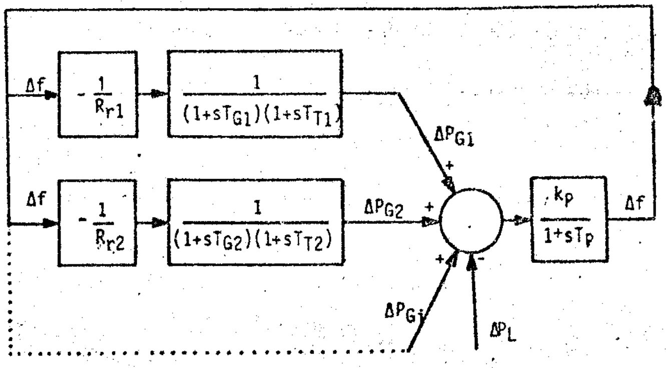


Figure 3. Transfer function representation of power control mechanism.

(c) Harmonic Distortion Program.

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

THE PENETRATION STRATEGY

(a) Static Penetration Strategy

The first step in this procedure is to determine the absolute maximum penetrating power from the WECS cluster to the grid, P_{wmax}, so that the operating constraints are not violated. Load flow simulation studies and total harmonic distortion computations, under various loading conditions, lead to the estimation of the absolute maximum penetrating power. When the WECS penetrating power remains within this maximum level, then none of the voltage swing and harmonic distortion constraints are violated.

The second step involves the selection of the most appropriate bus for connecting the WECS cluster. The 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.

Thus, implementation of the static penetration strategy involves both siting considerations for the WECS, and an estimate of the total installed wind generator capacity. The number of the cluster units may be determined, of course, when the rated power of each unit is known. The siting and unit selection process must also consider such other factors as wind availability, proximity, economics,etc.

(b) Dynamic 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 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, then:

$$P_{pmax} = P_L + P_{Gmin} \tag{7}$$

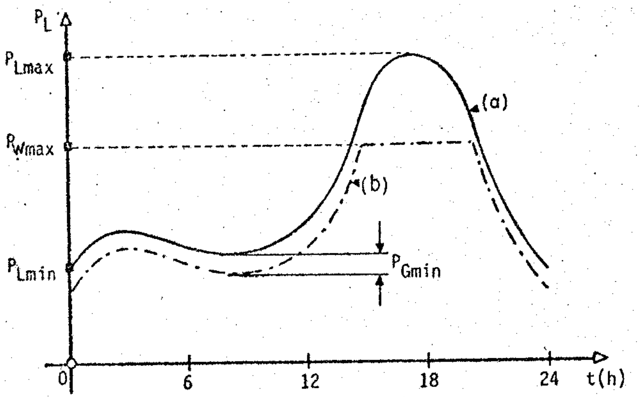
and the penetrating power, at each instant of time (P_p) must remain below P_{pmax}, that is:

$$P_p \leq P_{pmax} \tag{8}$$

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

$$P_{pmax} \leq P_{wmax} \tag{9}$$

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 4.



(a) Load demand profile
(b) Maximum permissible penetrating power from WECS.

Figure 4. The dynamic penetration strategy.

A penetration curve is also shown in the same figure. Up to a load value of P_L, the total WECS 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 5 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. Furthermore, the μP contains information about the dynamic penetration strategy to be followed. Appropriate communication and control lines connect the μP system to both the conventional power station and the WECS cluster. Information received by the microprocessor from the power station refers to the number of generating units operating at each instant of time and their corresponding power output. The μP system, on the other hand, decides upon and sends appropriate control signals to the station controller as to which units shall remain in operation and the power level distribution among the various units. The WECS cluster feeds data to the μP referring to the power level each unit is producing, whether this amount of power is supplied to the grid via the grid interface equipment or to some auxiliary storage facility such as an array of batteries, mechanical pumping equipment, flywheel, heat or hydrogen production. If such a storage device is available, it may be used as an active buffer to smooth out the variability of the WECS output. For example, direct buffering may be achieved using battery or flywheel storage whereas pumped hydro storage will act as an indirect buffer. The μP controller monitors the state of the WECS and auxiliary storage switches along with appropriate power levels and decides upon the direction (from WECS to power grid or auxiliary storage or from auxiliary storage to power grid) of the power flow. Programming of the μP is based upon this penetration curve.

The dynamic behavior of the WECS cluster-power grid interconnected system is controlled by the μP unit according to the following procedure:

a. The μP monitors simultaneously the load power P_L and the power produced by the wind generators P_p.

b. With reference to the penetration characteristic, the maximum permissible penetrating power P_{pmax} is determined.

c. On the basis of this information, the digital controller decides upon which ones of the cluster units must be connected to the grid.

d. Given which ones of the cluster units are already in operation, the control action dictates the proper switching sequence for the WECS so that the overall system performance is maintained within acceptable bounds.

e. If an auxiliary storage is available, the μP decides, given the current status of the system, as to whether power will be provided to or from the storage facility.

AN EXAMPLE

The penetration methodology was applied to a small autonomous power system of the radial type whose single-line diagram is shown in Figure 1. The installed conventional capacity is 750 KVA. The power station consists of four diesel-driven generator units with known operating characteristics; The transmission network consists of relatively short 15 kV lines. Load characteristics for the system are specified.

First, the static penetration methodology is applied to this example. The absolute maximum WECS power, P_{wmax}, that may penetrate the power system without violating any of the network constraints is estimated to be approximately 110 kW. If, typically, wind machines with a rated capacity of 20 kW each are

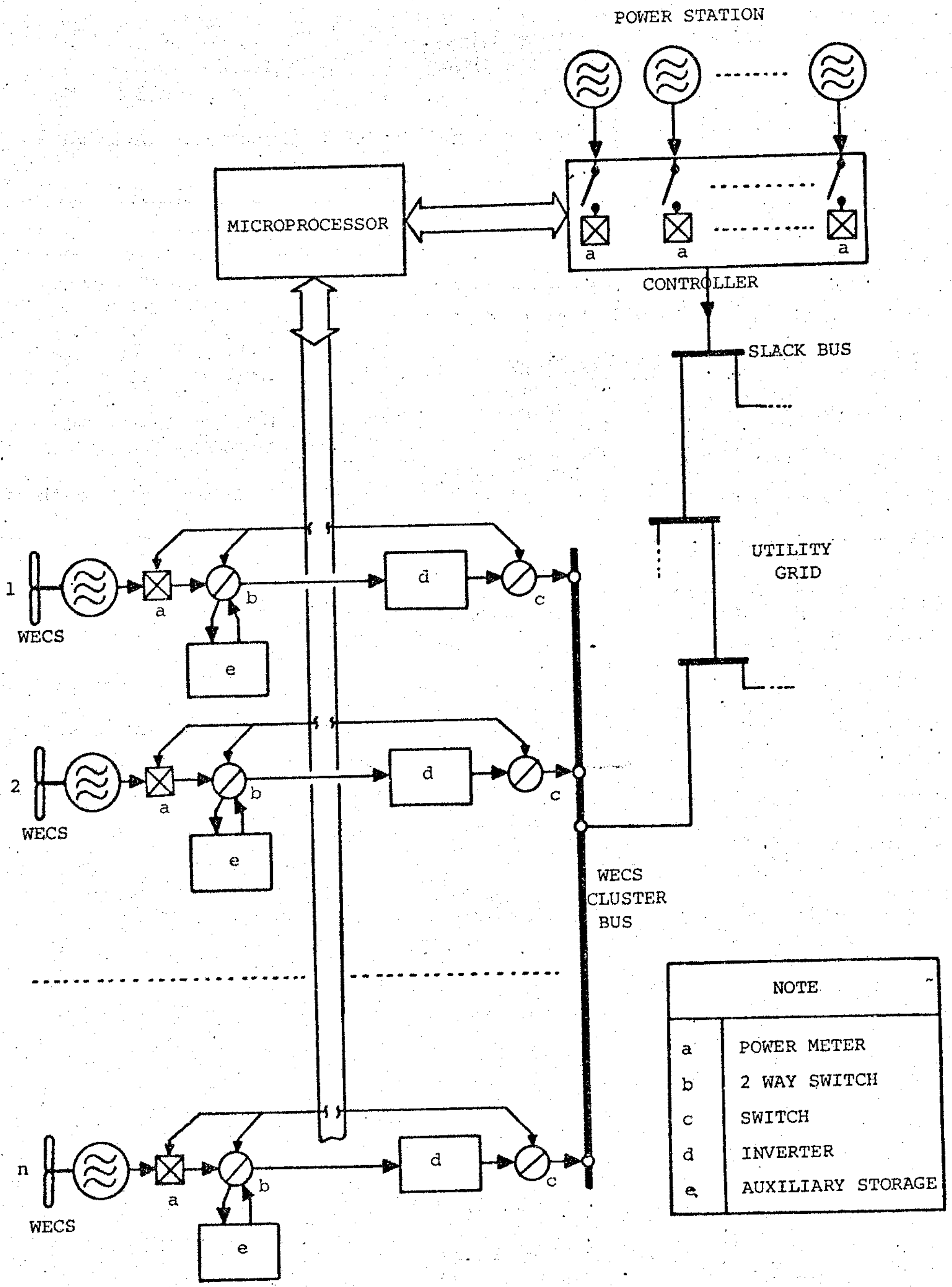


Figure 5. Block diagram of the WECS - power grid interconnected system.

available, then six such idential units may comprise the cluster.

Load flow studies were used to locate the grid bus with the maximum voltage swing under extreme loading conditions. These simulation studies lead to the identification of a particular grid bus where, if the WECS cluster is connected, will result in an optimum line voltage distribution while minimizing network losses. The WECS cluster will be connected at this grid point if all other siting constraints are of no special importance. For the example considered, the interfacing bus selected shows a reduction in voltage swing sensitivity and line losses of 1.33% and 1431 W, respectively. This completes the static penetration part of the study.

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 10kW 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.

It is noted that load changes for each unit referred to in this table are within typical generator winding temperature limitations or constraints imposed by possible carbonizing of the diesel engines.

A statement is in order with regard to the load following capabilities of the WECS - diesel unit combination. A change in the WECS cluster output power by ± 20% of total rated capacity due to wind gusts or high turbulence conditions corresponds to a change of 110 kW X 20% = ± 22kW of power delivered to the grid. For such rapid changes in WECS output, the load following rate of the diesel units is satisfactory and does not present any problems. It is evident, from Table 1, that even when only one unit of the conventional power plant is in operation the maximum permissible step change in loading is ± 35 kW. An output power change of ± 22 kW from the WECS cluster is, therefore, within this permissible load change of ± 35kW. Thus, model results show that even under worst conditions (i.e. wind gusts) and corresponding abrupt changes in output power, the system frequency is contained within specified bounds.

Development of the dynamic penetration strategy is based upon the entries of Table 1. The strategy is finally implemented by appropriately programming the μP unit of Figure 3.

CONCLUSIONS

The work reported in this paper is concerned with the development of a penetration strategy for WECS clusters interconnected with an autonomous power system. The strategy is implemented using a μP-based controller programmed with the assistance of appropriate modeling algorithms simulating the steady-state and dynamic behavior of the interconnected system.

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 generator clusters with a power utility system.

TABLE OF SYMBOLS

ΔP_L : change in the power system loading.

Δf : change of the power system frequency.

ΔP_G : change of conventional generated power.

Δf_{stat}: permanent frequency error.

ΔP_{Gi} : change of i-th generator output power.

R_{ri} : speed regulation parameter.

T_{Gi} : time constant of i-th generator speed governing mechanism.

T_{Ti} : time constant of i-th diesel generator set.

G_p : transfer function of grid-load combination.

k_p : grid-load constant.

T_p : grid-load time constant.

G_{GTi} : transfer function of i-th generating unit.

P_L : load of the power system.

P_p : penetrating power from the WECS.

P_{pmax} : maximum permissible penetrating power at each instant.

P_{wmax} : absolute maximum penetrating power (WECS rated power).

P_{Gmin} : minimum permissible conventional power.

P_{Lmin} : minimum grid load.

P_{Lmax} : maximum grid load.

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