6

SIMULATION STUDY OF WIND GENERATOR CLUSTER PENETRATION INTO THE UTILITY GRID

K. KALAITZAKIS and G. VACHTSEVANOS

School of Engineering
Democritus University of Thrace
Xanthi, Greece.

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.

1. 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 [1,2]. 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 or battery storage) 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 accute 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 level distribution along the grid, 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 and wind siting aspects relating to the penetration problem have been addressed recently [3-5].

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. Such situations often arise in small islands or isolated communities which are not directly connected to the main lines.

2. 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 maybe of the radial type. A wind generator cluster consisting of small units of the synchronous type with their output rectified and then inverted to AC in synchronism with the utility lines is considered to penetrate the power system. In the modeling effort the wind - electric conversion systems are connected as "negative loads" directly to the power lines. 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.

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.

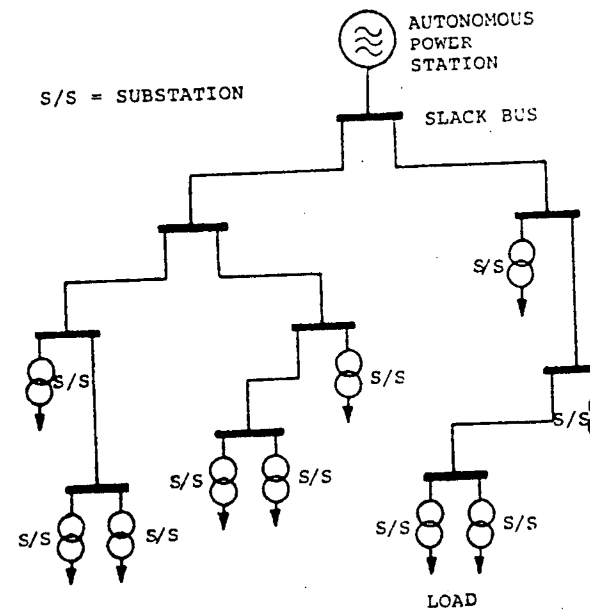


Figure 1. Typical topology of an autonomous power system.

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.

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

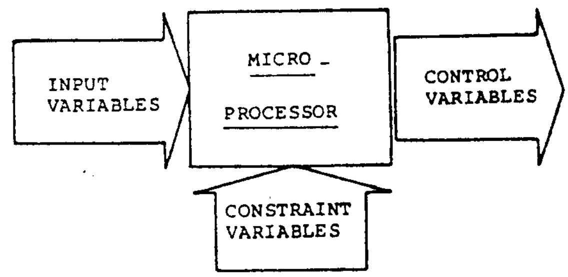


Figure 2. Schematic of the µP input - output configuration.

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 modeling algorithms simulating the interconnected operation of the WECS - utility grid system and used for the determination of the degree of penetration, under various loading conditions, are described in the next paragraph.

3. THE SIMULATION APPROACH

(a). The load flow program.
A modified classical "load flow" routine is employed in order to simulate the steady-state behavior of the power system. With input data the characteristics of the transmission and distribution networks and the loading conditions at each bus, the program calculates the admittances of the power lines, the real and reactive components of power along the same lines as well as the voltage level at each bus. As a result also the network impedance at any point along the grid may be computed. The load flow program determines the maximum bus voltage variation 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. A computational algorithm simulates the autonomous power station reactions to load variations and provides, as an output, the maximum frequency variation for a given load disturbance, the permanent frequency variation following primary or analog frequency control as well as the time - rate of the frequency variation. It is assumed that 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, system performance.

(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.

4. THE PENETRATION STRATEGY

Figure 3 shows in block - diagrammatic form the main features of the dynamic penetration implementation scheme. The diagram highlights the philosophy of the penetration strategy ommitting 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 convertional power station and the WECS cluster. Information received by the microprocessor from the conventional 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 them. 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, heat or hydrogen production. The µP controller monitors the state of the WECS switches and decides upon the direction (power grid or auxiliary storage) of the power flow.

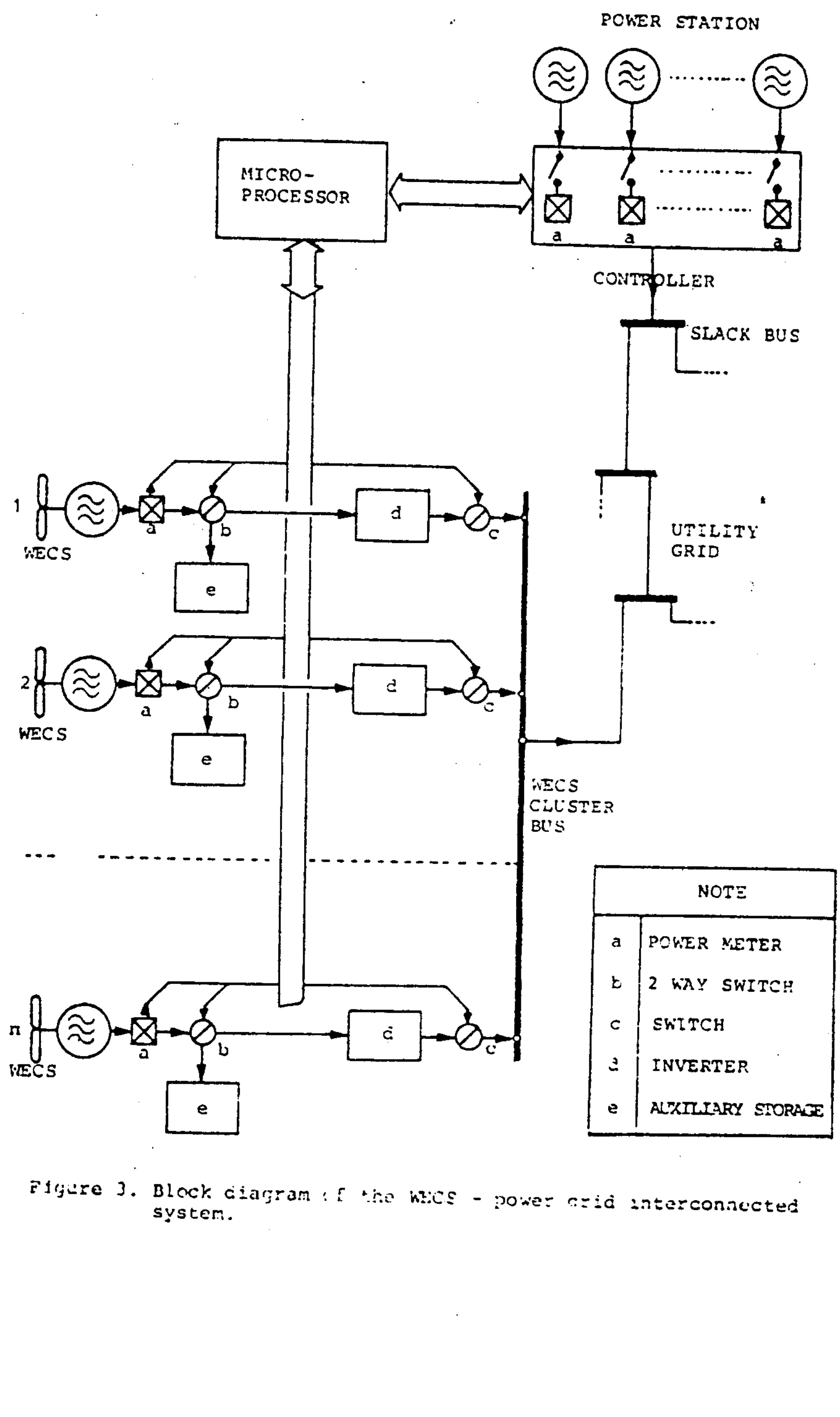


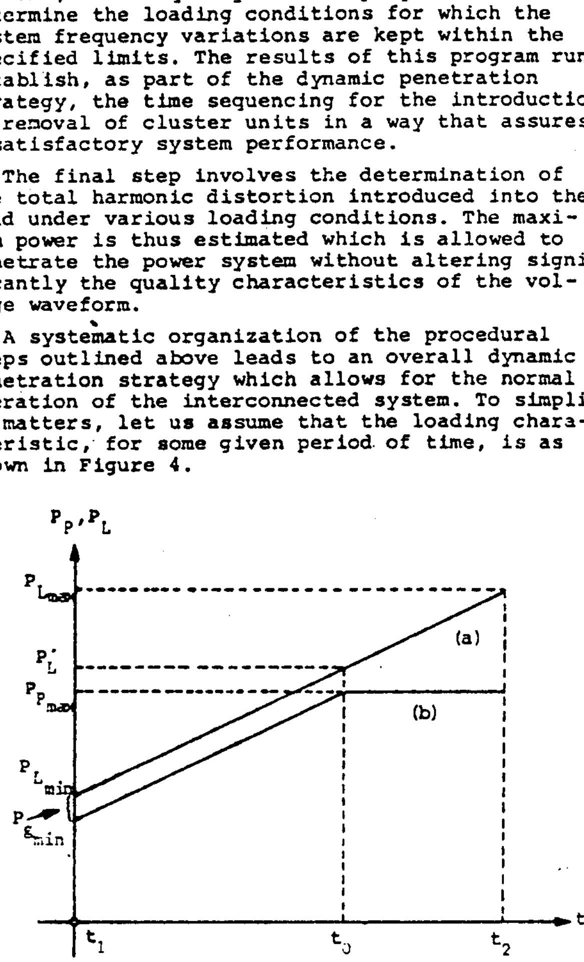
Figure 3. Block diagram of the WECS - power grid interconnected system.

The dynamic penetration methodology is based upon the assumption 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 $P_{g_{min}}$ so that at least one unit of the conventional power station is always in operation. With this assumption in mind, the bus voltage deviation, for each grid bus, from its nominal value is computed for maximum available WECS power and under various loading conditions. Load flow simulation studies are used and those cases are identified for which the voltage constraint is violated.

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 this 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.

The final step involves the determination of the total harmonic distortion introduced into the grid under various loading conditions. The maximum power is thus estimated which is allowed to penetrate the power system without altering significantly the quality characteristics of the voltage waveform.

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 POWER CURVE

(b) MAXIMUM PENETRATION CURVE

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 by $P_{g_{min}}$. For load values P_L', one of the specified constraints is violated and the penetrating cluster power is kept at the maximum value of $P_{p_{max}}$. 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 possible penetrating power P_p 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 sequencing for the WECS so that the overall system performance is maintained within acceptable bounds.

5. AN EXAMPLE

The penetration methodology was applied to a small autonomous power system of the radial type. 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.

Load flow studies were used to locate the grid bus with the maximum voltage swing under extreme loading conditions. Next, using the harmonic distortion algorithm, the maximum power penetrating into each bus is calculated so that the quality of the resulting waveform is maintained within acceptable bounds. 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 from 1.33% and 3642 W to 0.65% and 1431 W, respectively.

The maximum WECS power 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 available, then six such identical units may comprise the cluster. This completes the static penetration part of the study.

For the dynamic penetration characteristics, with $P_{g_{min}} = 10$ kW, load flow simulation studies show that the voltage variation is always maintained within the constrained values under extreme loading conditions. Harmonic distortion simulation results, on the other hand, dictate a dynamic penetration curve similar to that shown in Figure 4 with $P_{L_{min}} = 50$ kW and $P_{L_{max}} = 440$ kW. Also, $P_L' = P_{p_{max}} + P_{g_{min}} = 120$ kW.

Total harmonic distortion is thus kept below 5% for grid loading values smaller than P_L'; for loading values greater than P_L' and a penetration level of $P_{p_{max}}$ the distortion stays within the 5% limit.

Finally, using the frequency control program and with a maximum system load of 440 kW (up to three diesel units in operation), the maximum allowable load variation is computed. The results are shown in Table 1.

Each entry specifies the maximum allowable load power variation without exceeding the frequency and rate of frequency variation constraints. Development of the dynamic penetration strategy

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

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

6. 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.

7. REFERENCES

1. T.S. Jayadev, "Windmills Stage a Comeback", IEEE Spectrum, pp. 45-49, November 1976.
2. H. Davitian, "Wind Power and Electric Utilities: A Review of the Problems and Prospects", Wind Eng., Vol. 2, No. 4, pp. 234-255, 1978.
3. G.H. Bontius, A. Manders and T. Stoop, " Implications of Large Scale Introduction of Power from Large Wind Energy Conversion Systems into the Existing Electric Power Supply System in the Netherlands", Proc. of Int. Symp. on Wind Energy Systems, Amsterdam,Neth., pp. G3.27-G3.38, 1978.
4. R.A.Schlueter, G.L. Park, H. Modir, J. Dorsey and M. Lotfalian, " Assessment of the Effects of Large Wind Generator Arrays on Power System Operation ", Proc. of IEEE Power Eng. Soc. Winter Meeting, New York, paper A80 110-7,1980.
5. L. Larson , " Large Scale Introduction of Wind Power Stations in the Swedish Grid: A Simulation Study ", Wind Eng., vol.2, No. 4, pp. 221-233, 1978.