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POWER MANAGEMENT OF GRID-CONNECTED WIND GENERATOR CLUSTERS

K.C. Kalaitzakis
School of Engineering
Democritus University of Thrace
Xanthi, Greece

G.J. Vachtsevanos
School of Electrical Engineering
Georgia Institute of Tehnology
Atlanta, Georgia 30332

Summary

This paper introduces a new methodology for the real and reactive power control, stability and coordination of a power system penetrated by a cluster of wind energy conversion devices. The proposed methodology is based upon the utilization of an appropriate voltage - fed, self- commutated dc to ac inverter with a capability of transferring variable amounts of real and reactive power from the inverter to the utility bus. An optimized storage facility provides necessary buffering and reserve power capabilities for the successful operation of the control mechanism. The paper develops appropriate models for the interconnected operation of wind generator clusters with an autonomous power system. The quality of system performance is specified in terms of operational constraints and the resultant penetration strategy is implemented via a microprocessor - based control scheme. Simulation studies indicate that load - following requirements for conventional power units are reduced while power quality and stability of the interconnected system are improved.The dynamic penetration strategy, on the other hand, 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 (WECS) to provide some of the electricity demand on a large scale (1-4). Such systems are usually interfaced with an existing power grid for "fuel displacement" purposes as well as for earning some "capacity credit". Particular interest has centered on utilizing WECS clusters or wind farms on small islands or isolated communities with a local autonomous power system. Whereas economic feasibility may be guaranteed in such cases, the small inertia of the autonomous power grid, in conjunction with the dispersed generator characteristics, present serious operational problems that must be addressed so that maximum utilization of the available wind power will be achieved while maintaining the overall power system integrity.

"Power management" for WECS - grid interconnected systems is concerned with the broad questions of coordination, control and stability, reliability of operation and optimum scheduling of generating units. From this broad perspective, this paper focuses upon power management strategies that determine (a) the optimum coordination of WECS with conventional power generating units so that load demand is continuously satisfied in a way that preserves the integrity of the power system, and (b) the control of operation of WECS so that load - following requirements for conventional power units may be reduced while improving power quality and stability of the interconnected system.

Electric utilities are encountering difficulties in agreeing on adequate protection and safety requirements for small dispersed power generators (WECS, PVs, etc). Taking a conservative view, they usually specify interface requirements and protection schemes that are capable of responding to all "abnormal" system conditions by disconnecting the dispersed source from their system. This utility philosophy - requiring extensive protection hardware and viewing the dispersed source as a nuisance- results in increased costs associated with the interconnection hardware and an inefficient utilization of available generated power. Moreover, the value of WECS and New Energy Technologies (NET) is further decreased, with a corresponding increase in power production from conventional sources, since this operating philosophy allows for stochastic output power variations from dispersed generators causing excessive ramping of the utilities' regulation units and increasing load - following, spinning reserve and unloadable generation requirements. Recently, it has been suggested that if NETs are to contribute significantly to the electric energy supply, then methods must be developed for operating these new sources in harmony with the conventional power system.

On the other hand, 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. Various technical, economic, institutional and wind siting aspects of the penetration problem have been addressed recently (5-9).

This work is introducing a new philosophy for the effective integration of WECS and other NETs into the utility grid. As far as control and stability aspects of the interconnected operation are concerned, the dispersed generator is viewed as an active device contributing towards the regulation of real and reactive power flows while improving overall system stability; penetration - related issues are resolved via a dynamic strategy, implemented with a microprocessor - based controller, which maintains, in real time, system integrity.

2. System Configuration

Figure 1 shows a block diagram of the proposed system configuration illustrating the control implementation philosophy. The primary energy source (wind energy in this case) is converted to electrical form. Various types of wind generators may be considered with an obvious preference for devices which provide direct current at their output or variable - speed, variable - frequency units followed by a standard rectification step. Such functional tasks as maximum power tracking, voltage level regulation, protection, etc. may also be accomodated through the dc interface subsystem. Dc power may be fed either directly to the Power Conditioning Subsystem (PCS) or indirectly via a suitable storage device. The energy storage facility is basically designed to handle transient power requirements called for by the specified control strategy. Moreover, it functions as a buffer smoothing out stochastic power variations due to the nature of the primary source and providing energy to the utility grid whenever it is not available from the WECS. The high cost of battery storage necessitates a careful consideration of the storage design problem with inclusion of both economic and technical criteria in the optimization procedure.

The Power Conditioning Subsystem is central to the proposed control philosophy. It consists of a dc to ac inverter with a capability of delivering both real and reactive power to the grid. An appropriate design for control purposes is based upon the principle of self - commutation. Voltage-fed, self-commutated inverters have been developed using techniques of square wave generation with harmonic neutralization, various PWM methods and high frequency linking of the input to output power flow (10). For our purposes, the inverter may be represented as an ac source connected to the utility grid through an impedance buffer (Figure 2) System frequency variations, Δf, are continuously monitored at the grid bus and a control signal proportional to Δf is used to vary the phase difference Φ between the inverter and grid busses, thus transferring more or less real power to the utility. Control of the amplitude of the inverter voltage E in relation to the line voltage V regulates reactive power flow. The inverter may even be designed not only to provide variable real and reactive power to the utility but also to absorb such quantities from the grid, making them available for storage (four quadrant P-Q operation) (11). The system configuration is complemented, as shown in Figure 1, with suitable information retrieval/processing and control instrumentation.

3. Real and Reactive Power Control.

System power regulation and stability improvement, via the proposed configuration of Figure 1, are made possible due to the relatively faster response of the electronic inverter/control circuitry components compared to time constants of conventional power regulator units. Thus, adjustment and modulation of the power flow from the inverter to the utility may be accomplished before any control mechanisms of the conventional power units are activated. Basically, the procedure involves base/gate control, in the transistor/thyristor bridge, of the angular separation between the inverter output fundamental and the utility bus voltage resulting in control of the real power generated by the inverter. Adjustment of the input-output var flow may be achieved by base/gate control of the pulse-width angle (the ac voltage wave magnitude).

For purposes of analysis, it is assumed that one or more WECS, and maybe such other dispersed generators as PVs, of the type specified previously are operating in a coherent power system consisting of diesel-powered generating units, power transmission and distribution facilities and typical loads. Situations of this category are already in existence in several small islands or isolated communities with WECS clusters and PV arrays operating in parallel with the local power system (11).

Figures 3(a) and (b) are transfer function representations of the real and reactive power control mechanisms of a single PCS operating in parallel with a conventional diesel-powered system. Similar representations are valid for all other dispersed generators connected to the grid. The amount of generated power that each unit contributes to a particular load demand is a function of its rated capacity and is determined by a static frequency - load characteristic of the unit. The slope of this characteristic is fixed numerically by the overall feedback loop gain.

The system of Figure 3 is configured on the basis of the following assumptions:

1. The linear models of (a) and (b) are valid for small load disturbances corresponding to linear changes in system frequency.
2. All system machine inertias (generating and load units included) are assumed to be represented by a single time constant, T_G.
3. The inverter is represented by a first-order transfer function assuming that angular displacements $\Delta\Phi$ are kept small. Indeed, the inverter output power is proportional to $\sin\Phi$; for small changes of the angular displacement Φ, $\sin\Phi \simeq \Phi$ and changes in output power are, therefore, proportional to $\Delta\Phi$. Similarly, since $\Delta\Phi$ is small and reactive output power is proportional to $\cos\Phi$, var flow from the inverter to the utility is not affected by changes in Φ.
4. The inverter time constant, T_{INV}, is due to all time delays that the real power is subjected to as it is transferred from the inverter output to the utility bus.
5. The feedback loop consists of a frequency to voltage converter, a PID controller and an angle controller. The frequency to voltage converter is represented by a constant conversion coefficient, assuming that its reaction time to changes in system frequency is negligible. Time delays associated with the PID controller are also assumed to be relatively small. The angle controller converts the output voltage of the PID controller to a proportional angular displacement suitable for modulating the real power output of the inverter. The angle controller is similarly described with a single time constant which collectively represents

time delays due to the controller circuitry as well as any filtering present in the feedback loop.

6. In the voltage control loop, the power grid is again represented with a first-order transfer function under the assumption that small changes in ΔQ produce proportional changes in the amplitude of the utility voltage $\Delta|V|$. The transfer function time constant, in this case, is, of course, relatively small. An exact ΔQ vs. $\Delta|V|$ relationship would involve solution of the system load flow equations. Accounting for overall problem accuracies, such a step is not presently warranted.

In state-variable form, the dynamic system model of the coupled real and reactive power control mechanisms (Figures 3 (a) and (b)) is expressed with the following equations:

$$
\begin{aligned}
\dot{x}_1 &= x_2 \\
\dot{x}_2 &= x_3 \\
\dot{x}_3 &= x_4 \\
\dot{x}_4 &= -a_3x_4-a_2x_3-a_1x_2-a_0x_1+\Delta P_L+a\Delta V \\
\dot{x}_5 &= x_6 \\
\dot{x}_6 &= x_7 \\
\dot{x}_7 &= x_8 \\
\dot{x}_8 &= -aq_3x_8-aq_2x_7-aq_1x_6-a_{q0}x_5+\Delta Q_L
\end{aligned}
\qquad (1)
$$

where:

$$K = k_{inv}k_ck_fk_G \qquad a_3 = \frac{T_{inv}T_c+T_{inv}T_G+T_cT_G}{T} \qquad b_2 = T_{inv}T_ck_G$$

$$T = T_cT_{inv}T_G \qquad a_2 = \frac{T_{inv}+T_c+T_G-Kk_D}{T} \qquad b_1 = (T_{inv}+T_c)k_G$$

$$a = \frac{\partial P}{\partial|V|} \qquad a_1 = \frac{1-Kk_p}{T} \qquad b_0 = k_G$$

$$a_0 = -\frac{Kk_I}{T}$$

$$K_q = k_{qinv}k_{qc}k_{qv}k_{qG} \qquad a_{q3} = \frac{D_{inv}D_c+D_{inv}D_G+D_cD_G}{D} \qquad b_{q2} = D_{inv}D_ck_{qG}$$

$$D = D_GD_{inv}D_G \qquad a_{q2} = \frac{D_{inv}+D_c+D_G-K_qk_{qD}}{D} \qquad b_{q1} = (D_{inv}+D_c)k_{qG}$$

$$a_{q1} = \frac{1-K_qk_{qP}}{D} \qquad b_{q0} = k_{qG}$$

$$a_{q0} = -\frac{K_qk_{qI}}{D}$$

For a step change in real and reactive load power, ΔP_L and ΔQ_L, the corresponding changes in system frequency and line voltage are written as:

$$
\begin{aligned}
\Delta F &= -\frac{1}{T}(b_2x_4+b_1x_3+b_0x_2) \\
\Delta V &= -\frac{1}{D}(b_{q2}x_8+b_{q1}x_7+b_{q0}x_6)
\end{aligned}
\qquad (2)
$$

Numerical values for design parameters and system constants are specified on the basis of available data from existing facilities, systems and components. The power grid is representative of a small autonomous system providing electrical power to consumers of an isolated community. The methodology is applicable to any control area which supports both conventional and dispersed sources. Table I lists the parameter values used in the simulation.

Table I

Parameter	P-f Control		Q-V Control	
inverter gain	$k_{inv} = 1$	kW/rad	$k_{qinv} = 1$	kVAr/V
controller gain	$k_c = 24$	rad/Volt	$k_{qc} = 4$	V/V
proportional gain	$k_P = 1$	V/V	$k_{qP} = 1$	V/V
integral gain	$k_I = 0$	V/V	$k_{qI} = 0$	V/V
differential gain	$k_D = 0.001$	V/V	$k_{qD} = 0.001$	V/V
gain of f to V converter	$k_F = -10$	V/Hz	$k_{qv} = -10$	V/V
grid gain	$k_G = 0.1$	Hz/kW	$k_{qG} = 0.4$	V/kVA
inverter time constant	$T_{inv}=0.01$	sec	$D_{inv} =0.01$	sec
grid time constant	$T_G = 4$	sec	$D_G = 0.1$	sec
controller time constant	$T_c = 0.001$	sec	$D_c =0.001$	sec

With a step load disturbance of $\Delta P_L = 80$ kW and $\Delta Q_L = 60$ kVAR, three different cases were examined and results are presented in Figures 4 (a), (b) and (c), respectively. The response of Figure 4(a) is arrived at with zero integral control ($K_I = K_{qI} = 0$). As it is anticipated, a permanent frequency and voltage deviation from their nominal values results, following the load disturbance. It is observed that the percent Δf and ΔV errors are within the maximum permissible tolerances (± 0.5 Hz and ± 5% voltage deviation). The time response in this situation is determined primarily by the power system time constant rather than the inverter and controller time constants.

Both integral and differential control are employed for the results of the second case, shown in Figure 4(b), with $k_{qD} = 0.1$. The voltage waveform is progressing in time more smoothly and the effect of the integral control is to drive steady - state errors to zero.

In the final case, large values for the integral controller gains are used while a substantial differential gain is maintained for the voltage control loop, i.e.
$k_I = 10$, $k_{qI} = 10$ and $k_{qD} = 0.1$.
The system response is clearly underdamped exhibiting small oscillations and reaching zero steady-state condition in a relatively short time.

The dynamic stability of a power system in the presence of dispersed generators is determined by formulating the swing dynamics of the rotating machines, the load flow equations for real and reactive power transfer during transient conditions in combination with the inverter control dynamics of the previous paragraph. The dispersed generators are used to improve system stability by appropriately modulating the inverter output power. Disturbances on the utility system usually result in power oscillations along the lines. These oscillations can be damped out by injecting real power from the inverter into the grid. The approach is implemented by monitoring the amplitude and frequency of the oscillating power and generating control signals which shape accordingly the inverter output power. Simulation results verify the effectiveness of the proposed scheme.

4. Dynamic Penetration Strategy

Wind electric conversion systems operating in parallel with a small autonomous power system usually tend to disturb such quality performance characteristics as voltage, frequency and harmonic content. The normal operation of the power grid - load system presupposes that a number of constraint parameters are maintained within predetermined bounds. Such parameters are taken to be the voltage and frequency variations and the harmonic distortion introduced by the WECS interface into the utility lines. Dynamic penetration deals with operational matters of the combined WECS cluster - utility grid system so that none of these constraints is violated. The strategy is implemented with a microprocessor controller which receives and processes information from both the WECS 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 units may be connected to the grid and under conditions the autonomous power station will operate. Penetration characteristics are studied with the assistance of load flow, frequency control and harmonic distortion simulation techniques

5. Conclusions

Simulation studies of the proposed methodology indicate that both control and damping actions are effectively achieved. Time constants of the electronic inverter/controller are comparatevely much smaller than those for conventional diesel or thermal power plants, thus adjustment and modulation of the power flow is affected before any control mechanisms of the conventional units are activated. On the other hand, a dynamic penetration strategy results in increased reliability of system operation while optimum coordination between the WECS and the conventional diesel units is maintained.

"Power management" of the WECS - grid interconnected system is indeed a complex technical and economic issue. This paper initiates a particular methodology for the effective integration of dispersed generators with the utility system. Many more questions must be addressed and resolved before a widespread acceptance of new energy technologies becomes reality.

6. References

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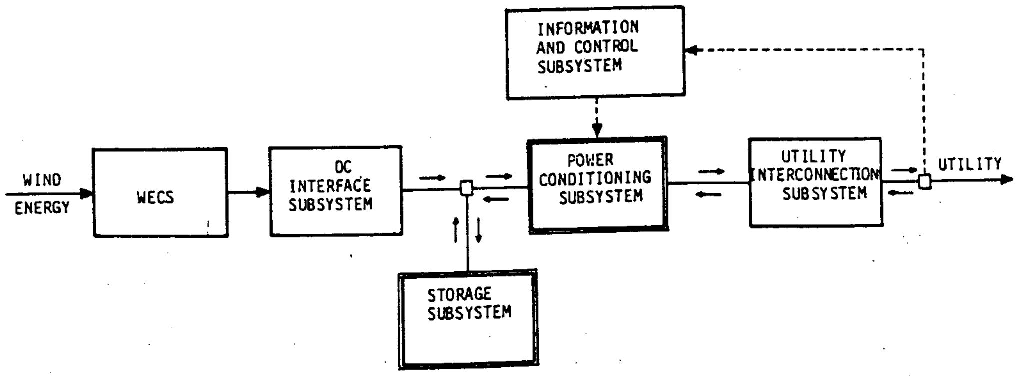

Figure 1. Block diagram of WECS - PCS - grid interconnected system.

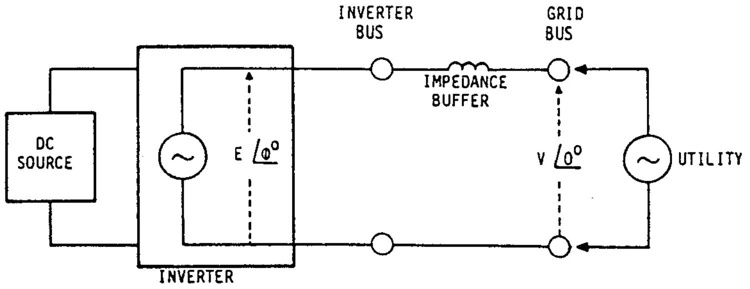

Figure 2. Equivalent representation of inverter - grid system.

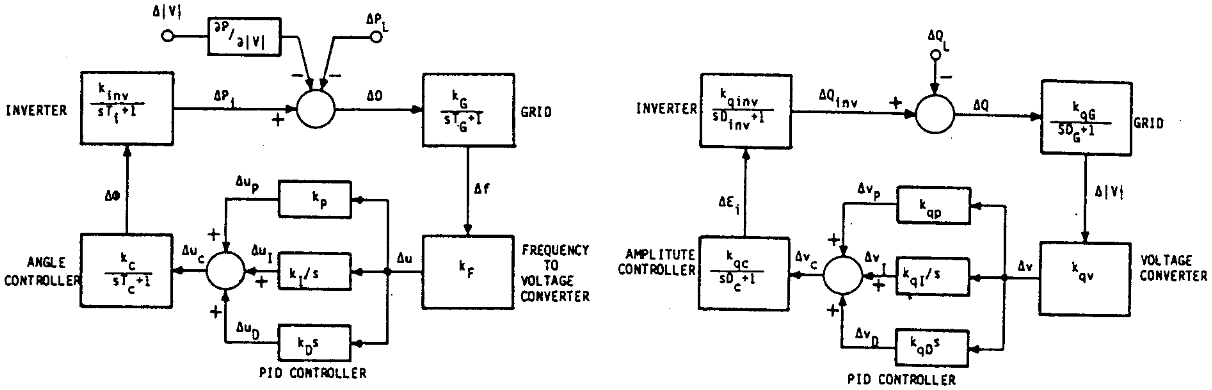

Figure 3. (a) and (b). Transfer function representation of real and reactive power control, respectively.

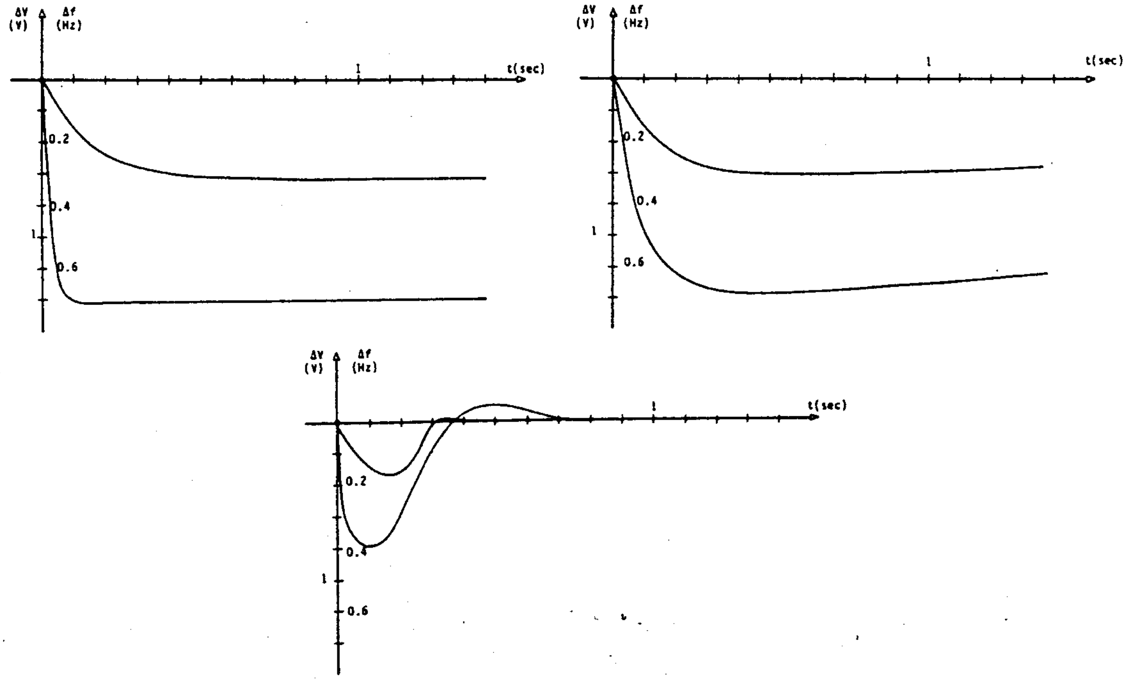

Figure 4. (a),(b) and (c). Simulation results for three cases of control action.