11

DYNAMIC UTILITY INTEGRATION OF NEW ENERGY TECHNOLOGIES

G. J. Vachtsevanos* - K. C. Kalaitzakis**

* School of Electrical Engineering, Georgia Institute of Technology, Atlanta, Georgia 30332

** Technical University of Crete, Chania, Greece

ABSTRACT

This paper is introducing a new methodology for the dynamic integration of New Energy Technologies into the electric utility distribution network operations. Dispersed sources are viewed as active devices contributing towards the regulation of real and reactive power flows while improving the stability of the power system. Conceptual means are developed for an effective DSG-utility grid interface. Computer models of appropriate interconnection and control equipment are used in simulation studies to test the effectiveness of control strategies and optimize design parameters. Simulation results indicate that load frequency control and voltage regulation may be effectively accomplished with dispersed generators within a fraction of the time required for conventional regulating units. Appropriate modulation and conditioning of the DSG-output power can assist in damping out undesirable power oscillations. Implementation of the proposed policies may result in reduced load following requirements for conventional power generating units, increase the value and acceptability of New Energy Technologies and improve power quality and stability of the interconnected system.

INTRODUCTION

In recent years there has been growing interest in utilizing Dispersed Storage and Generation (DSG) devices to provide some of the electricity demand on a large scale [1-4]. The interconnection and operation of these devices at the electric distribution level raises numerous planning and operational concerns [5-9]. Electric utilities usually specify DSG 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 NETs 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 [1,10-11].

This paper is introducing a new philosophy for the effective integration of NET devices into the utility grid. Conceptual means are developed for the dynamic integration of DSG devices such as solar, wind, fuel cells, batteries, cogenerators, etc., into the power utility system. Appropriate interface equipment and control strategies result in reduced load-following requirements for conventional power generating units while improving power quality and stability of the interconnected system.

THE INTERFACE PROBLEM

Electric utilities are experiencing a slow but clearly evident transition in the philosophy of electric power generation and utilization: away from the centralized generation/distributed load concept and towards a more flexible and diverse power system including storage and generation devices at the distribution network level.

This obvious shift in distribution system planning and operational philosophy is accompanied with numerous problems that must be addressed so that maximum utilization of the available dispersed power will be achieved. The customary radial distribution network topology is replaced with a complex system of multiple paths resulting in bidirectional power flows. Utility personnel usually specify DSG interface requirements and protection schemes capable of responding to abnormal system conditions by disconnecting the dispersed source from their system. 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.

A methodology is presented in this paper for the operation and control of DSG devices so that they contribute towards the regulation of real and reactive power flows while providing a stabilizing effect to system disturbances. Figure 1 shows a block diagram of the proposed system configuration. The primary energy source (wind, solar, biomass, hydrogen, etc.) is converted to electrical form. Various types of conversion devices may be considered. The exact configuration of the DSG, dc interconnection and storage subsystems depends upon the type of available source. The energy storage facility is basically designed to handle minimum transient power requirements

0094-2898/85/0000/0002$01.00 © 1985 IEEE

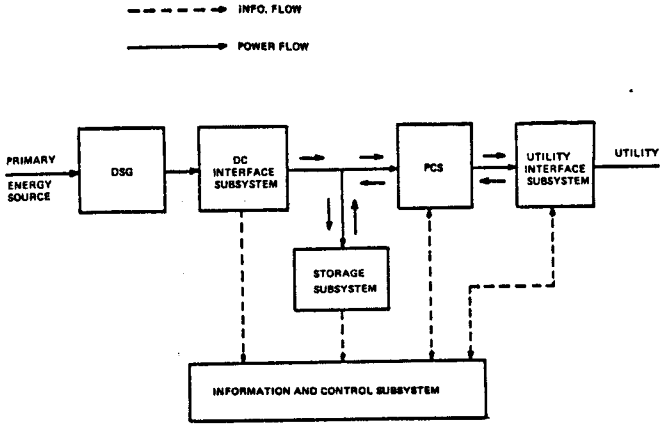


Figure 1. Block Diagram of the DSG-Utility Interface.

called for by the specified control strategies. 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 DSG. The high cost of battery and other storage devices necessitates a careful consideration of the storage design problem with the inclusion of both economic and technical criteria in the optimization procedure.

The Power Conditioning Subsystem is central to the proposed control and stabilization philosophy. It consists of a dc to ac inverter with a capability of delivering both real and reactive power to the grid. Reverse flow of power (from the utility lines to the storage device) is also possible and may be desirable under appropriate supply/load management policies. A possible inverter 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[10,12].

For our purposes, the inverter may be represented as an ac source connected to the utility grid through an impedance buffer. 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 buses, 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. Under four quadrant P-Q operation, the inverter is absorbing real and reactive power from the grid making them available for storage.

The system configuration is complemented, as shown in Figure 1, with suitable information retrieval/processing and control instrumentation.

SYSTEM REGULATION AND STABILITY

Basic control and stabilization concepts are demonstrated via simulation studies using computer models that represent the DSG-utility grid interface dynamics. A generic voltage-fed, self-commutated inverter is assumed at the output stage of the PCS. It is further assumed that the inverter is designed to handle efficiently all required power swings. A sufficient supply of dc power is available either directly from the dispersed generator or from storage.

Consider the simple situation of Figure 2. A load Y_D is supplied from an inverter and a conventional generator. A block diagram representation of the rotating generator dynamics is shown in Figure 3(a), while Figures 3(b) and (c) depict the real and reactive power control dynamics of the inverter, respectively. Similar representations are valid for situations where a number of dispersed and conventional generators are connected to a utility grid. Configurations 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. The amount of generated power that each NET 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

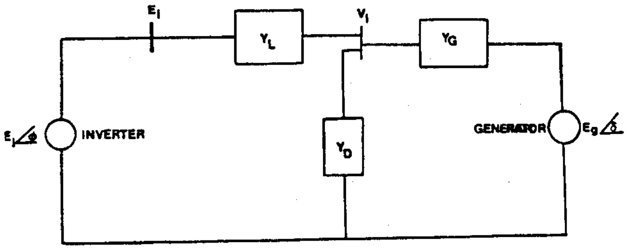


Figure 2. A Generator-Inverter-Grid System for Control and Stability Analysis.

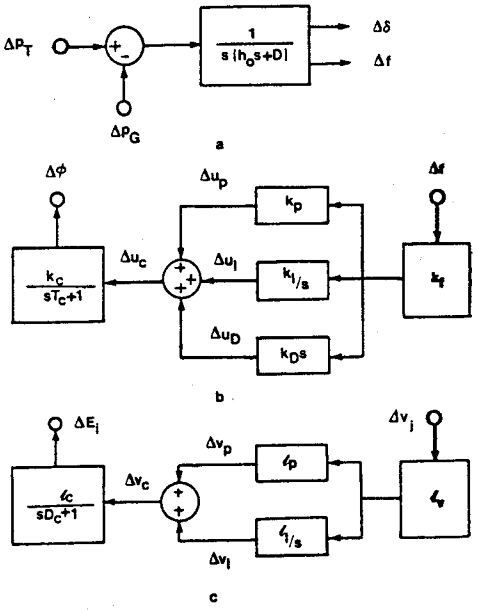


Figure 3. Block Diagram Representation of the Generator Swing, Pf and QV Feedback Control Dynamics.

characteristic is fixed numerically by the overall feedback loop gain.

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

The inverter and its associated real power control mechanism are represented by a single time constant T_c. The latter models the response time of the inverter and angle controller power electronics; typical values for T_c are in the 0.1 sec. range. A similar situation is assumed for the time constant D_c of the inverter dynamics that model the regulation mechanism for the magnitude of the output voltage waveform and, correspondingly, the reactive power supplied to the grid. Values for the coefficients k_f, k_p, and k_c were chosen so that their product ($k_f k_p k_c = -0.048$) results in a permanent frequency deviation of 0.3 Hz for a step increase in load demand of 80 kW (the same regulation is provided by the conventional diesel-powered generator under a similar load disturbance; actual parameter values are representative of an autonomous power grid located on a small island). The inverter is, of course, capable of accomplishing better regulation as will be shown in the simulation results. The same reasoning is pursued in the case of the voltage magnitude regulation where the product $\ell_v \ell_p \ell_c$ is set equal to -42.5.

The conventional generator is rated at 100 kW with an inertia constant of $h_o = 8$ kWs/Hz and a damping factor due to the machine damper windings equal to $D = P_D/f^\circ \simeq 2$ kW/Hz, where P_D is the nominal load and f° the nominal system frequency. It is assumed that the conventional generator is divorced from any control capability and, therefore, a swing equation with parameter values as specified above models the machine dynamics.

The power grid consists of two buses, a transmission line, and a load. The inverter impedance up to the inverter bus is neglected. The admittance Y_L is taken to be equal to 40-j80 mho, typical of the line admittance of a small autonomous grid. The generator transient susceptance is set at -j60 mho while the load admittance is equal to 2 - j1.5 mho, corresponding to a power consumption of 95 kW when the generator bus voltage is 217 volts. In simulation studies of the system transient behavior, this admittance is varied and a new equilibrium state is reached. The power supplied by the generator, under steady-state conditions, is $P_G = 48$ kW. The inverter supplies 47 kW when the load admittance has the value specified above. The inverter, through the two feedback loops, monitors the voltage and frequency at the generator bus. The inverter bus voltage, for the base-line load, is 220 volts and the angle ϕ is set at 0.006 radians; finally, the generator power angle δ is equal to 0.017 radians.

The generator swing equation may be written as

$$\Delta P_T - \Delta P_G = h_o \Delta\ddot{\delta} + D\Delta\dot{\delta} \tag{1}$$

With $x_1 = \Delta\delta$ and $x_2 = 2\Pi\Delta f$, a state - variable formulation of the swing dynamics is expressed as

$$\begin{aligned} \dot{x}_1 &= x_2 \\ \dot{x}_2 &= h_o(\Delta P_T - \Delta P_G + Dx_2) \end{aligned} \tag{2}$$

The inverter angle feedback dynamics (Figure 3(b)) can be written in the following form

$$\begin{aligned}
x_3 &= \frac{k_f}{2\Pi} x_2 && -15 \le x_3 \le 15 \\
x_4 &= k_p x_3 && -5 \le x_4 \le 5 \\
\dot{x}_5 &= k_I x_3 && -5 \le x_5 \le 5 \\
\dot{x}_3 &= \frac{1}{k_D} x_6 && -5 \le x_6 \le 5 \\
\dot{x}_7 &= \frac{1}{T_c} [k_c(x_4+x_5+x_6)-x_7] && -1.57 \le x_7 \le 1.57
\end{aligned} \tag{3}$$

where

$$\begin{aligned}
f &= \frac{x_2}{2\Pi} \\
x_3 &= \Delta u \\
x_4 &= \Delta u_p \\
x_5 &= \Delta u_I \\
x_6 &= \Delta u_D \\
x_7 &= \Delta\Phi
\end{aligned} \tag{4}$$

The inverter magnitude feedback dynamics (Figure 3(c)) are derived in a similar way. It is assumed that the angle and magnitude control loops are independent from each other. With

$$\begin{aligned}
x_8 &= \Delta V_i \\
x_9 &= \Delta v \\
x_{10} &= \Delta v_p \\
x_{11} &= \Delta v_I \\
x_{12} &= \Delta v_D \\
x_{13} &= \Delta E_i
\end{aligned} \tag{5}$$

the state equations describing the inverter magnitude dynamics are written in the form

$$\begin{aligned}
\dot{x}_9 &= \ell_v x_8 && -15 \le x_9 \le 15 \\
\dot{x}_{10} &= \ell_p x_9 && -5 \le x_{10} \le 5 \\
\dot{x}_{11} &= \ell_I x_9 && -5 \le x_{11} \le 5 \\
\dot{x}_9 &= \frac{1}{\ell_D} x_{12} && -5 \le x_{12} \le 5 \\
\dot{x}_{13} &= \frac{1}{D_c} [\ell_c(x_{10}+x_{11}+x_{12})-x_{13}] && -100 \le x_{13} \le 100
\end{aligned} \tag{6}$$

The input turbine power, P_T, is taken to be constant; therefore, $\Delta P_T = 0$. With $\Delta P_G = x_{14}$, the swing equations may be rewritten as

$$\dot{x}_1 = x_2$$

$$\dot{x}_2 = h_o(Dx_2 - x_{14}) \tag{7}$$

Under the assumption that the system frequency f remains fairly constant, the interconnected network is considered to be in the sinusoidal steady-state. Load-flow analysis may, therefore, be used to calculate changes in the grid bus voltage and the power supplied by the generator due to changes in the control variables ΔE_i and $\Delta\Phi$.

SIMULATION RESULTS

Figure 4 shows a block diagram of the overall simulation program. Steady-state operating conditions are established using the Load Flow algorithm. During the prefault period, the load is shared equally by the inverter and the generator. The transmission line is assumed to be lossy and a sudden change in load demand initiates the post-fault condition. The change in load demand establishes a new initial condition for the load flow equations. The Load Flow algorithm is used to calculate the changes in the grid bus voltage and the electrical power supplied by the conventional generator. The generator swing dynamics are accessed next producing an output change of frequency Δf. Changes in grid voltage ΔV_i and frequency Δf are input to the amplitude and inverter angle controller algorithms, respectively. The outputs from these two programs are deviations in the inverter voltage E_i and phase angle $\Delta\Phi$. These last two quantities are the inputs to the Load Flow algorithm for the next program iteration.

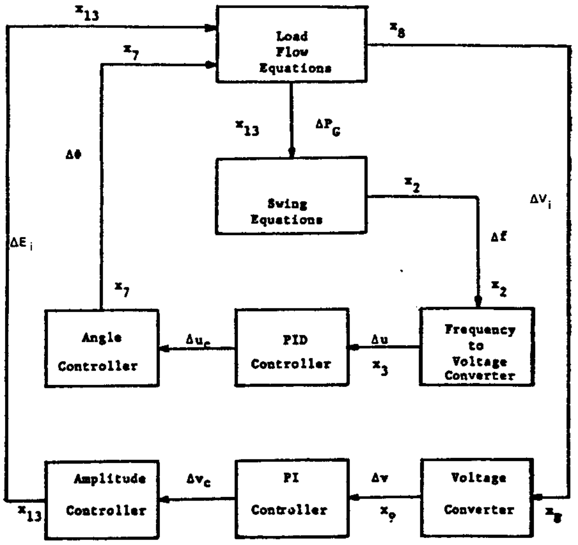
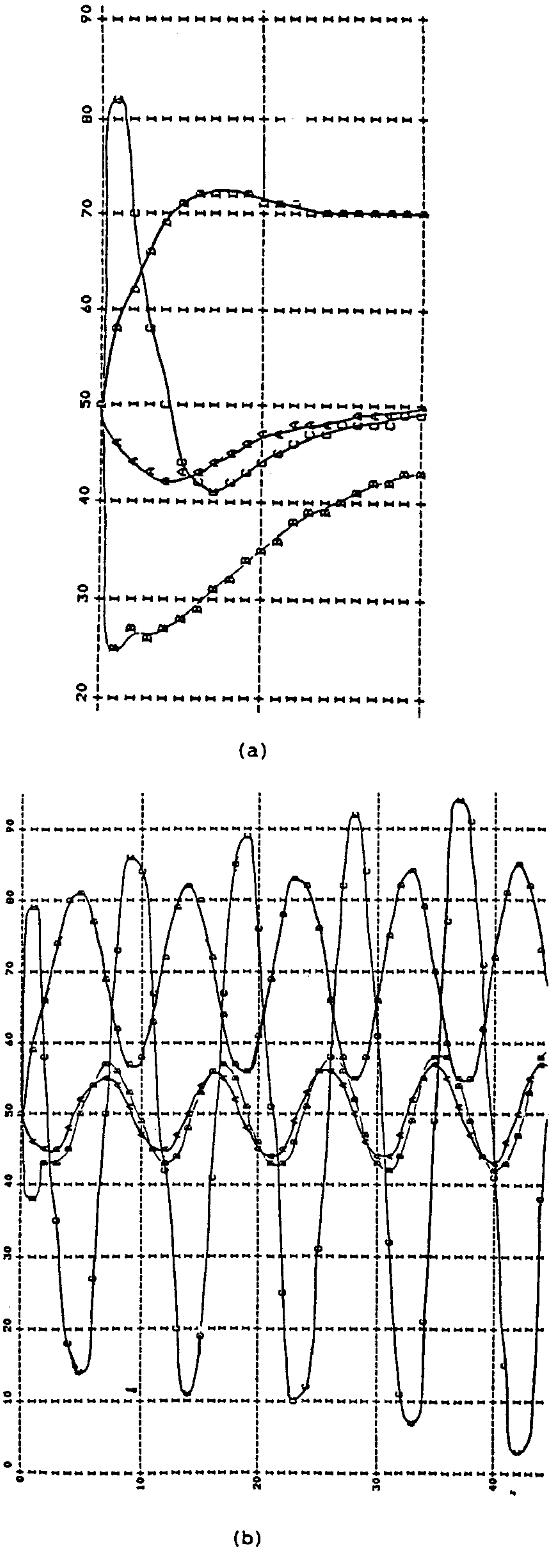


Figure 4. Block Diagram of the Combined Generator-Inverter-Grid Simulation Algorithm.

Typical simulation results are shown in Figures 5(a) and (b). Time constants and design parameters are assigned values which are typical of inverter--diesel generator--PID controller characteristics for the power capacities considered.



(a)

(b)

Figures 5(a) and (b). Frequency (A), Grid Voltage (B), Generator Power (C), and Inverter Power (D) as Functions of Time.

Figure 5(a) depicts the system frequency variation, the grid bus voltage variation, the variation of the generator output power level and the variation of inverter output power as functions of time. A step decrease of load impedance equal to 20% of its nominal value is introduced. It is observed that the system frequency returns to its steady-state value after a short transient excursion. The grid voltage exhibits a similar behavior--the voltage variation is less than 0.04 volts after 2 seconds of simulation time. The generator power, P_G, undergoes an oscillatory cycle and returns quickly to its original value since there are no generator controls and the mechanical power driving the generator shaft remains constant. The inverter real output power reaches a new steady-state value corresponding, as anticipated, to the change in load demand.

Figure 5(b) illustrates the behavior of the same variables under a 50% load disturbance. Considering basic modeling assumptions, only a qualitative interpretation of the results is attempted. The unstable behavior of the system is clearly indicated. Sensitivity runs show a strong dependence of system behavior upon integral controller gain values. Optimum gain settings are determined using sensitivity analysis tools and classical stability theory considerations.

Implementation of the control and stabilizing strategies involves the utilization of an appropriate frequency vs. power "drooping" characteristic for each inverter. A permanent load disturbance is shared by the operating power conditioning units according to their capacity. The proposed scheme thus "simulates" the control characteristics of a conventional unit.

CONCLUSIONS

The proposed control and stabilization methodology constitutes a significant departure from accepted utility practices in the interconnection of dispersed storage and generation devices with the utility grid. The requirement for extensive protection hardware and the view of the DSG as a parasitic source are substituted with a positive approach where the dispersed generator is contributing beneficially to the operation of the power system.

Simulation results indicate that the response time of the control elements is extremely short with the overall DSG--utility grid--generator systems exhibiting stable transient behavior.

Immediate benefits in improved voltage regulation will be realized via implementation of the proposed control strategies even at small DSG penetration levels. Future increased penetrations are bound to bring about positive results as far as frequency control and stability improvement are concerned.

Equipment costs may be kept to an acceptable level while the operation of the devices may be fully automated.

Probably, the most significant limitation, from an economic standpoint, of the scheme refers to the utilization of an energy storage facility. Careful sizing of this device to maintain an acceptable reliability threshold will ensure optimum technical and economic results.

REFERENCES

1. Oak Ridge National Laboratory, Research Needs for the Effective Integration of New Technologies into the Electric Utility, Proc. of Conf., CONF-820772, May 1983.
2. Systems Control, Inc. and James B. Patton, "Interconnecting DC Energy Systems: Responses to Technical Issues," prepared for EPRI, EPRI AP/EM-3124, June 1983.
3. G.J. Vachtsevanos, "Dispersed Generation - An Overview of Issues and Approaches," Proc. of MECO '83-EES '83 International Symposium, August 1983.
4. Public Utilities Regulatory Policies Act of 1978, Public Law 45-617, 16 U.S.C. 2601.
5. "Protection of Electric Distribution Systems with Dispersed Storage and Generation (DSG) Devices," ORNL/CON-123, Oak Ridge National Laboratory, Oak Ridge, TN, Sept. 1983.
6. D.T. Rizy, W.T. Jewell, and J.P. Stovall, "Operational and Design Considerations for Electric Distribution Systems with Dispersed Storage and Generation (DSG)," ORNL/CON-134, Oak Ridge National Laboratory, Oak Ridge, TN, Sept. 1984.
7. Monitoring and Control Requirements Definition Study for Dispersed Storage and Generation (DSG), General Electric Co. Corporate Research and Development, SRD-80-042-1, Final Report, Volumes I through V, Schenectady, NY, Oct. 1980.
8. H. Chestnut, et. al., "Monitoring and Control Requirements for Dispersed Storage and Generation," IEEE Trans. on Power Apparatus and Systems, Vol. PAS-101, No. 7, July 1982.
9. G.J. Vachtsevanos, A.P. Meliopoulos, and B.K. Paraskevopoulos, "Distributed Photovoltaic System Impact upon Utility Load/Supply Management Practices," Proc. of Fifth EC Photovoltaic Solar Energy Conference, Oct. 1983.
10. S. Krauthamer, et. al., "Photovoltaic Power Conditioning Subsystem: State of the Art and Development Opportunities," DOE/ET-20356-9 Report, Jan. 1984.
11. G.J. Vachtsevanos and K.C. Kalaitzakis, "Power Management of Grid--Connected Wind Generator Clusters," Proc. of the European Wind Energy Conference, Hamburg, Oct. 1984.
12. Westinghouse Electric Corp., "AC/DC Power Conditioning and Control Equipment for Advanced Conversion and Storage Technology," EPRI EM-271, Palo Alto, CA, Nov. 1976.