A SIMULATION STUDY OF ENERGY FLOW OPTIMIZATION IN WIND ELECTRIC CONVERSION SYSTEMS

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Abstract

This paper is concerned with the interconnected operation of Wind Electric Conversion Systems (WECS) with the utility grid. It addresses problems of stability and power flow optimization from the WECS to the power lines.

The approach followed is based upon the development of computer algorithms and their verification with actual experimental results. A variable - speed constant - frequency wind electric system utilizing a synchronous generator and line commutated inverter provides the basic physical configuration for the computer simulation studies of the interconnected system. Simulation results indicate that the transient behavior of the wind electric - power grid system in satisfactory.

A maximum power tracking mechanism provides continuous matching of the wind - electric generator to the grid impedance characteristics. As a result, maximum electric power is transferred from the wind machine to the power lines. Computer simulation studies of this type of operation indicate the substantial improvement in power transfer that is achieved.

The proposed scheme tends to minimize equipment and maintenance costs while maximizing the energy transfer capabilities of the wind - electric conversion system and maintaining a high degree of reliability in overall system performance.

. INTRODUCTION

Various methods have been proposed for the interconnected operation of WECS with a utility grid where the latter is used as the energy storage medium [1,2]. Most of these methods usually present serious disadvantages due to such operational requirements as the employment of complicated and expensive control mechanisms in order to maintain a constant or nearly constant propeller rotational speed (case of directly interfacing a synchronous or asynchronous wind generator to the utility mains) [3], the need for reactive power loading (case of an induction - type wind generator) or the utility of special machine features involving multiple windings or commutators thus increasing substantially equipment costs [4].

This paper is concerned with a simple WECS architecture consisting of a horizontal axis wind machine, a synchronous three - phase generator, a rectifier arrangement and a line - commutated inverter - maximum power tracking system with the dual role of converting the wind generator dc power to ac form in synchronism with the grid characteristics as well as optimizing the power transferred from the wind conversion system to the utility lines (Figure 1). The propeller is free to rotate at any safe speed with the generator producing a variable - amplitude, variable - frequency output voltage waveform.

The design philosophy focuses upon maintaining as simple as possible the aerodynamic - mechanical machine features while clustering the necessary interfacing - control instrumentation " off line " (away from the rotating components) thus providing easy accessibility for maintenance and repair [5]. Special attention is given to the development of appropriate methods for maximizing the power transferred from the WECS to an autonomous power system.

2. THE MODELLING APPROACH

The design of the interfacing - maximum power tracking mechanism is aided by computer simulation studies involving the behavior of the interconnected WECS - grid system under various transient and steady - state conditions.

Figure 2 shows the dependence of the power coefficient C_p, representing efficiency of conversion from wind power to mechanical power, on the wind speed ratio λ (ratio of blade tip speed to wind speed) for various values of the blade pitch angle. The shape of these curves together with the operating characteristics of the generator - rectifier system contribute towards the appearance of a characteristic output behavior for the propeller - generator - rectifier system similar to the one shown in Figure 3. Sources with such characteristic behavior present an operating point at which maximum power is transferred from the source to a given load. This operating point is specified by the letter M in Figure 3. It is desirable therefore that the overall interconnected system operation be kept as closely as possible to M. From a design point of view, this is achieved by regulating continuously the inverter operation. Dynamic control is necessitated by the fact that both the wind speed characteristics and the utility load impedance, at the point of interconnection, vary randomly and continuously.

In the following paragraphs mathematical descriptions for each one of the basic subsystems are developed to be used in the simulation studies. Numerical values for some of the input parameters of the mathematical models are derived from the experimental configuration.

a) <u>The aerodynamic subsystem</u>.The tip speed ratio λ is defined by the relation

$$\lambda = \frac{\omega_p R_p}{V} \tag{1}$$

where ω_p is the propeller angular velocity, R_p the radius of the propeller and V the wind speed.

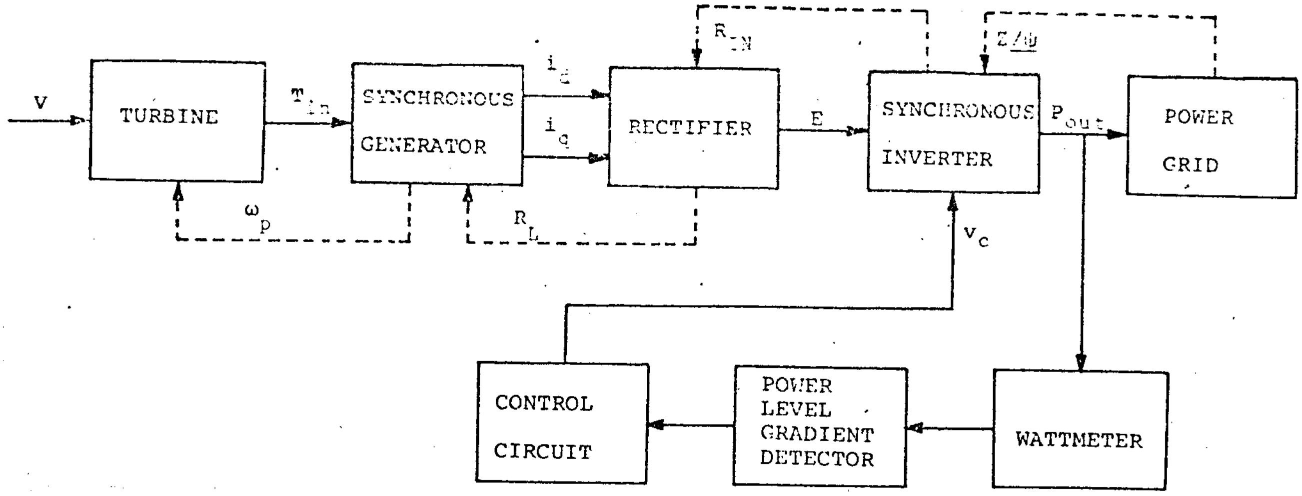

Figure 1. Block diagram of the wind electric conversion system.

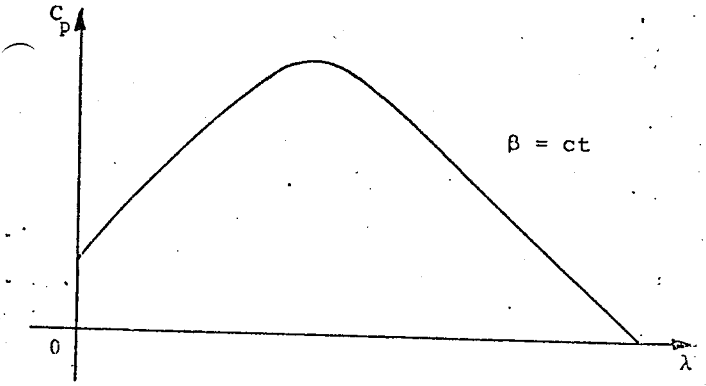

Figure 2. Relationship between the power coefficient C_p and the wind speed ratio λ.

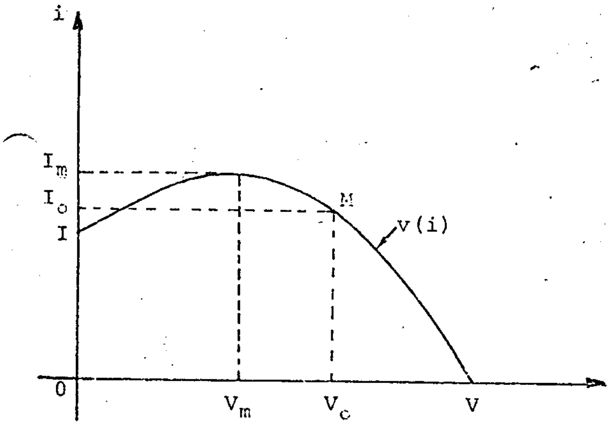

Figure 3. Characteristic curve for the wind generator.

The shaft torgue of the propeller is given by

$$T_{IN} = \frac{1}{2} k\rho\pi R_p^3 V^2 C_T \qquad (2)$$

where k is a constant, ρ the density of atmospheric air and C_T the torgue coefficient. The C_T vs. λ characteristic curve of the experimental wind turbine is approximated by the relation

$$C_T = -0.23.10^{-5}\lambda + 0.19.10^{-3}\lambda^3 - 0.01\lambda^2 + 0.16\lambda + 0.25 \quad (3)$$

Equations (1), (2) and (3) define the mathematical model of the wind turbine subsystem. Wind speed V is the input variable and shaft torgue T_{IN} the model's output variable with ω_p an intermediate input variable.

b) The synchronous generator. The synchronous generator is described by the matrix equation

$$\frac{d}{dt} i_B = -L_Z^{-1} R i_B + L_Z \omega_p i_B - L_Z^{-1} \begin{bmatrix} R_L i_d \\ R_L i_q \\ v_f \end{bmatrix} \qquad (4)$$

where the vector i_B defines the direct, quadrature and field currents of the generator. The equation coupling the electrical to the mechanical machine quantities takes the form

$$\frac{d\omega_p}{dt} = \frac{1}{J_g} \left\{ T_{IN} - (L_d - L_q) i_d i_q - L_5 i_q i_f \right\} \qquad (5)$$

where J_g is the inertia of the propeller - generator system and L_d, L_q, L_5 are elements of the machine inductance matrices.

Equations (4) and (5) describe the dynamic behavior of the synchronous generator when it is terminated at a symmetrical load R_L and an input torgue T_{IN} is applied to its shaft. The model output variables are the direct and quadrature axis currents and the angular velocity of the shaft. Equations (4) and (5) are in state - variable form and may be solved for the four state variables i_d, i_q, i_f and ω_p using a Runge - Kutta routine.

The steady-state behavior of the machine is arrived at by setting the left-hand side of equations (4) and (5) equal to zero. With the field excitation current, i_f, having reached its final value, v_f/r_f, the functional form of the steady state equation is

$$\begin{aligned} f_1(i_d, i_q, \omega_p) &= 0 \\ f_2(i_d, i_q, \omega_p) &= 0 \\ f_3(T_{IN}, i_d, i_q) &= 0 \end{aligned} \qquad (6)$$

c) The rectifier circuit. A classical bridge rectifier is used to convert the variable frequency ac output of the generator to dc form. The rectifier is assumed to be loaded by the input impedance of the synchronous inverter, R_{IN}. Thus the direct and quadrature axis input currents, i_d and i_q, produce an average component of voltage, E, at the rectifier output given by the relation

$$E = 0.7388 R_{IN} \sqrt{i_d^2 + i_q^2} \qquad (7)$$

Also, the rectifier load R_{IN}, when reflected to the input side, is linearly related to the generator equivalent load, R_L, by

$$R_L = \frac{R_{IN}}{1.832} \qquad (8)$$

d) The synchronous inverter. The inverter circuit, is based upon a four thyristor bridge designed so that an external voltage signal may be used to vary the thyristor firing angle and, therefore, the amount of electrical power being transferred from the wind generator to the utility grid. Variation of the firing angle accomplishes the dynamic matching required for maximum power transfer between the input characteristics of the inverter (dc voltage) and its output characteristics (power grid). For any given grid impedance, $Z\underline{/\psi}$, at the point of interconnection, the mathematical model for the capacitor-inverter-filter system relates the inverter average power output, P_{out}, to the input voltage level, E, and the control signal V_c. The exact mathematical relation is rather cumbersome but may be represented, functionally, by

$$P_{out} = g_1(E,\ V_c,\ Z\underline{/\psi}) \qquad (9)$$

Similarly, the inverter input impedance, R_{IN}, is computed from the same input quantities. This last relation is expressed, in functional form, by

$$P_{IN} = g_2(E,\ V_c\ ,\ Z\underline{/\psi}) \qquad (10)$$

Equations (9) and (10) define the line-commutated synchronous inverter model.

e) Maximum power tracking circuit. The feedback circuit includes an electronic wattmeter that continously measures the power level at the utility grid terminals; a hydrid power level gradient detector which samples the wattmeter signal output and holds it for comparison with the next sample; a logic circuit changes state whenever a new sample is smaller than the preceeding one, but remains in the same state if a new sample is larger than the preceeding one, thus representing an increase in power level; finally, an integator circuit provides a constantly changing output whose direction of change is increasing for one state of the logic circuit and decreasing fo the other state. This control signal is used to fire the inverter thyristors, thus controlling the power level transferred to the grid.

The mathematical model describing the operation of the maximum power tracking device is simply represented by the switching state equations:

$$V_{c_{k+1}} = V_{c_k} + \lambda_k \delta V_c \qquad (11)$$

$$\lambda_{k+1} = \lambda_k \ \mathrm{sign}\left[P_{out_{k+1}} - P_{out_k}\right] \qquad (12)$$

3. SIMULATION STUDY AND RESULTS

The simulation assumes a given step change in the wind speed, while the grid impedance remains constant, and calculates in sequence the shaft output torque, the generator currents, the voltage input to the inverter circuit and the power output. The program is executed iteratively until the turbine - generator - rectifier - inverter model stabilizes. This procedure is repeated so that a value for the control voltage is reached at which the power output oscillates about a maximum setting. The simulation is performed with or without the feedback loop for both transient and steady - state conditions of the generator.

a) The dynamic behavior. Figure 4 shows the computer simulation results for the transient behavior of a generator whose output impedance is matched to a power line with an impedance of 0.6 Ω and power factor of 0.3 at the point of connection and at approximately the rated speed of the machine.

The input signal is originally a step change in wind speed from 0 to 10 m/sec. The excitation remains at the 10 m/sec level until the system behavior reaches steady-state conditions (approximately 120 sec).At that moment, the wind speed is reduced from 10 m/sec and the simulation is repeated using the previous steady-state values as the new model initial conditions. The results indicate that transient phenomena proceed smoothly without a need to initiate the operation of any protective devices. Similar runs with various wind speed input functions lead to parallel conclusions as far as the transient behavior is concerned.

It is noted that the time constant of the mechanical subsystem is of the order of several seconds. Thus, the time constants associated with the electrical subsystem (response times of the order of msec) may be neglected when compared with the mechanical sybsystem response. As a conclusion it may be stated that the system is electrically in a steady-state condition at each instant of time. The steady-state model of the synchronous generator may, therefore, be used in the study of power transfer phenomena.

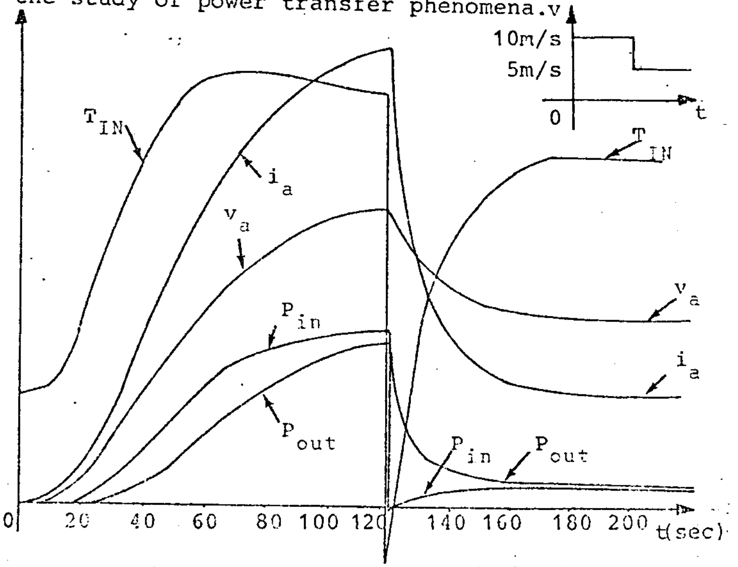

Figure 4. Transient response of the interconnected system variables. The wind input excitation is shown at the top right.

b) The steady-state behavior. In this study the wind speed is varied while the grid impedance is kept constant. Both the unmatched and mathed generator models are employed in the simulation runs when the WECS is connected to a power grid with specified characteristics. The system model is considered first with the feedback loop open and subsequently with the loop closed. Thus the combinations of simulation runs produce the four power output cutves of Figure 5. It is observed that the power transfer efficiency improves by as much as 80% for the unmatched model whereas the improvement is about 5% for the matched case with the maximum power tracking mechanism in operation.

It is also noteworthly that the curves corresponding to maximum power being transferred from the two types of machine models coincide. This implies that the maximum power transfer scheme achieves always the maximum power transfer for the interconnected system.

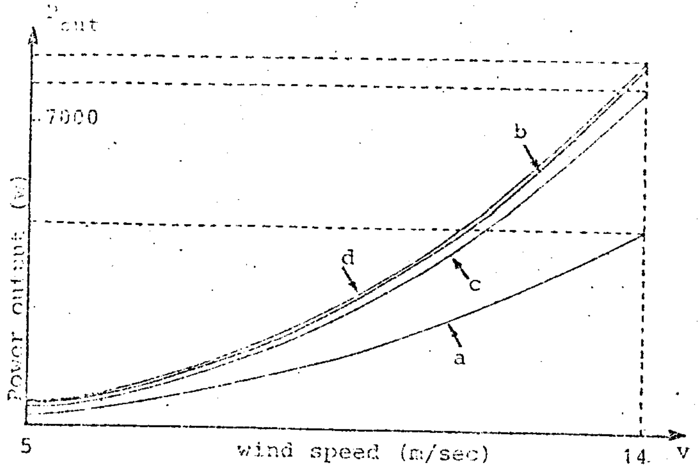

Figure 5. Power output vs. wind speed

(a) - unmatched system without feedback

(b) - unmatched system with feedback.

(c) - matched system without feedback.

(d) - matched system with feedback.

4. CONCLUSIONS

The dynamic behavior of the interconnected system reveals no undesirable transient phenomena such as mechanical oscillations or over-voltages and currents. These results are also verified by experimentation. Thus, the requirements for mechanical and electrical endurance of the particular WECS studied are not severe, with obvious consequences for system costs.

The safety equipment protects effectively both the wind generator and the power grid from various fault conditions.

Both impedance matching and power tracking result in maximization of the energy transferred from the WECS to the grid.

These results, coupled with the fact that a simple and inexpensive synchronous generator is employed, indicate that an optimum operation, from a technical and economic standpoint, is achieved for a large range of wind speed variations.

Finally, the low cost of components (inverter-tracker) and maintenance adds to the economic attractiveness of the proposed scheme.

5. REFERENCES

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