Design of a Power Conditioning Unit for Nonlinear Source-Load Systems

KOSTAS C. KALAITZAKIS AND GEORGE J. VACHTSEVANOS, MEMBER, IEEE

***Abstract*—This paper describes the development, design, and operation of an electronic device which performs dynamic matching between electric energy sources and their respective loads. This matching is achieved by monitoring the output power of the energy source and modulating a control signal which, in turn, regulates appropriately the operation of a source-load interface device. This device is characterized by a simple structure and an ability to continuously match the characteristics of the source to those of the load, for maximum power transfer, even when these characteristics are randomly time-varying. The device may be used with existing energy systems, without significant changes, and operates effectively even when the utility grid substitutes for the load. Its operation is described in terms of a configuration involving renewable energy sources, such as wind electric conversion systems and photovoltaic arrays, as the primary energy generators. The latter are attracting the growing interest of many investigators recently.**

Both theoretical and experimental procedures have been used to verify the device's effectiveness. Test results indicate that the source-interface device-load system operates efficiently, transferring maximum power continuously from the source to the load. Dynamic stability conditions are maintained, while parametric sensitivity analyses indicate the influence of design parameters on system performance. Finally, the simple and inexpensive construction of the device in conjunction with its reliable operation, contributes to the techno-economic acceptance of small, distributed renewable energy sources.

I. INTRODUCTION

MATCHING of a practical electric source to its load for maximum power transfer is, in general, a difficult problem. Indeed, electric generators, using wind or solar radiation as the primary energy source, are not only described by nonlinear output characteristics, but also these characteristics are strongly influenced by stochastically varying external factors, such as wind speed [1] or the available level of solar radiation [2], [3]. Moreover, actual loads, in certain applications, are nonlinear and time-varying.

The development and implementation of a suitable device, therefore, capable of maximizing power flow, from the source to the load, is necessary if optimum utilization of the renewable resource is to be made. The operation of this device has to be independent of any undesirable external influences.

Representative examples of nonlinear sources are wind energy conversion systems (WECS) and photovoltaic arrays (PV arrays). The characteristics of these sources are affected by such factors as wind speed, solar radiation, temperature, etc. These factors are varying unpredictably at each instant of time.

One of the most interesting cases of alternative energy source exploitation for electric power production involves its connection to the existing utility grid. The grid characteristics, when viewed from the connection point, are usually highly nonlinear and time-varying. Although there has been an increased interest in such applications in recent years, their widespread utilization has been limited, mainly due to high capital investment requirements. Consequently, any matching procedure is intended to improve energy transfer, reduce energy waste, and increase the cost-effectiveness of the source, thus making such systems attractive and acceptable to the public.

Some investigators have approached the matching problem strictly theoretically and do not propose an implementation procedure [2], [4]. Attempts have been made in the direction of modulating appropriately the source characteristics, i.e., blade pitch angle control [5], or rearranging the internal series-parallel configuration of the cells in a PV array. These techniques are characterized by the high cost of implementation and degraded operational reliability. Other researchers propose methods of modulating the WECS generator characteristics [6], [7], thus requiring expensive devices specifically manufactured for this purpose, and complex excitation systems. Design work, based on the control of the interface device between the source and the load, has also been reported [8]-[10]; the devices involved are usually characterized by high complexity or reduced efficiency, due to maximization of the source output power instead of the power injected into the grid.

The device described in this paper tracks the amount of power supplied by the source to the load, at each instant of time, and controls the system operation in such a way as to maximize the power delivered to the load. For this reason, it is called a maximum power tracker (MPT). The MPT design is independent of specific source characteristics and the device may be used in a variety of situations, where power matching is called for. Its operation is examined here only in relation to the case of a typical WECS or a PV array being interconnected to the utility grid via a line-commutated inverter, as illustrated in Fig. 1. This particular consideration is helpful in conceptualizing the design features and the operating characteristics of the device, without any loss of generality.

II. MAXIMUM POWER TRANSFER CONCEPTS

The operation of the MPT relies upon the modulation of a control signal V_c, according to variations of the actual power output and regulation of the inverter operation (Fig. 1),

Manuscript received March 15, 1984.
The authors are with the Department of Electrical Engineering, School of Engineering, Democritus University of Thrace, Xanthi, Greece.

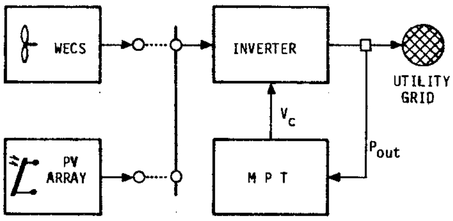

Fig. 1. Overall system configuration depicting the interaction between the MPT and major system components.

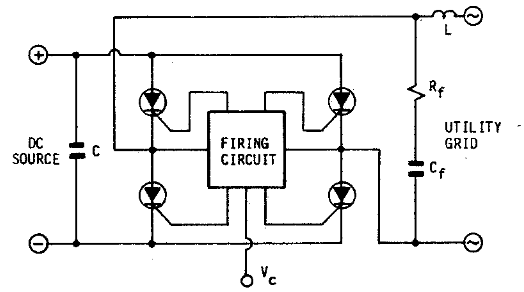

Fig. 2. Functional block diagram of the line-commutated inverter.

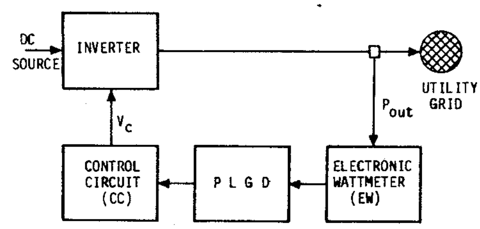

Fig. 3. Block diagram of the MPT internal configuration.

so that load characteristics are continuously matched to those of the source system. Monitoring, therefore, of the output power P_{out} is required. Next, the control signal V_c is constructed appropriately to provide the regulating action upon the inverter. The configuration depicted in Fig. 1 illustrates this particular feature. The firing circuit of the inverter (thyristor bridge) is designed so that adjustment of the conduction angle of each pair of thyristors is possible by means of the control signal V_c. This signal is applied externally to the firing circuit. The inverter, in this type of application, performs a dual task: a) inversion of the dc output voltage of the source, and b) modulation of the output characteristics of the source by means of V_c. A simplified block diagram of such a single-phase inverter appears in Fig. 2. It has been shown elsewhere [11] that appropriate adjustment of the conduction angle of the inverter circuit, while accounting for the characteristic (v-i) output curve of a WECS or a PV array, results in a noteworthy improvement of the overall system output power. Under certain conditions, this leads to the maximization of the power transferred from the source to the load.

Continuous operation of the MPT guarantees improvement in output power even when external factors, influencing the WECS/PV array characteristics (such as wind speed, solar radiation, temperature, etc.), vary stochastically [11]. Maximization of the output power P_{out} is possible by proper choice of the capacitance C (Fig. 2) and the operating frequency f of the inverter. The inductor L is inserted in order to shape the output current waveform, thus suppressing the harmonic content created by the switching operation of the inverter. However, continuous adjustment of the L and C values, according to certain operating conditions, is often practically difficult to implement. In addition, the inverter operating frequency f is fixed at the level of the power system frequency with grid-connected applications. It can be shown that the sensitivity of output power to changes in the values of C and L is considerably reduced if these values exceed some predetermined level. With the parameters C, L and the frequency f remaining fixed, the only design parameter, available for control of the inverter characteristics, is the duty cycle or correspondingly the firing angle of the thyristor bridge. Manipulation of the firing circuit results in a suboptimal operation, assuring a satisfactory level of output power P_{out} close to the optimum value.

III. MPT OPERATION DESCRIPTION

The internal organization of the MPT is depicted, in diagrammatic form, in Fig. 3. The electronic wattmeter (EW) monitors the power P_{out} and produces a proportional signal, at its output terminals. This signal is applied to the power level gradient detector (PLGD) input. The PLGD is a sequential circuit with a logic type output ("0" or "1" levels). The output signal of the PLGD is fed to a control circuit change of output power ΔP_{out} during the current time step and the output logic state during the preceding time step. The output signal of the PLGD is fed to a control circuit (CC) which produces the desirable control signal V_c according to a procedure described later in this paper.

The PLGD and control circuits are organized on a digital basis. Thus, storage of the successive power values, in the PLGD circuit, does not suffer from the drawbacks of analog storage techniques (sample and hold). In addition, changes of the control circuit output voltage (V_c) are performed in fixed time steps. Thus, any degradation of system performance quality, due to transient phenomena appearing during V_c changes, is avoided. Synchronization of all MPT functions is achieved by means of an appropriate timing circuit.

The operation of the MPT is described with reference to Fig. 4. In this figure, the relation between the system output power P_{out} and the control voltage V_c (and therefore the conduction angle of the inverter) is illustrated. It is assumed that, at a given instant of time, the system operating point is specified by the coordinates (V_{c1}, P_{out1}). Also, during the next time step, the value of V_c is increased from V_{c1} to V_{c2}, so that the new operating point of the system becomes (V_{c2}, P_{out2}). However, for the new output power level P_{out2} it is true that $P_{out2} < P_{out1}$ and the MPT circuit logic introduces a change in direction of the control signal V_c. Since V_c had increased to the value V_{c2} during the first time step, it is decreased back to the original value V_{c1}. The power corresponding to V_{c1} is $P_{out1} > P_{out2}$ and the MPT directs a new change of V_c in the same direction as V_{c2}, that is to V_{c3}. The resulting new power value is $P_{out3} > P_{out1}$. Therefore, V_c continues decreasing, while the output power P_{out} increases, according to the above logic. At some instant of time, P_{out} passes through the point (V_{ca}, P_{outa}) and

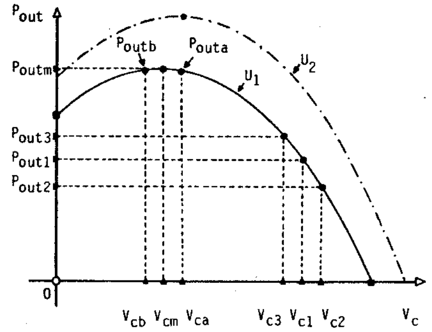

Fig. 4. Output power P_{out} of a WECS-inverter-grid system versus the inverter control voltage.

continues on, through the maximum power (V_{cm}, P_{outm}), to (V_{cb}, V_{outb}). However, at this point, it is true that $P_{outb} < P_{outm}$, therefore, V_c is given another change in direction and its value goes back to V_{cm} from V_{cb}. Because of an increase in power, the direction of V_c is reversed and the control signal reaches the value V_{ca}, where $P_{outa} < P_{outm}$, forcing a new change in the direction of V_c. In this way, the operational cycle described above is repeated continuously. That is, whenever the output power is in the vicinity of P_{outm}, it oscillates between the points (P_{outa}, P_{outb}). Provided that the changes of the control signal V_c are kept small, the values of P_{outa} and P_{outb} differ only slightly from P_{outm}. The system is then considered to operate at the maximum power point. If any of the external parameters influencing the source characteristics (wind speed, solar radiation, etc.) is changed, the power curve is transposed to the one shown in dotted lines on Fig. 4. The matching procedure is then repeated, until a new maximum output power value is obtained.

The theoretical study for the operation of the system illustrated in Fig. 3 is pursued via modeling the dynamic behavior of each major subsystem block and simulating, on a computer, the interconnected system performance. Thus, appropriate computer models for the source (WECS or PV array), the line commutated inverter, and the utility grid must be developed. Detailed description of the developmental steps for these models may be found in references [1], [12]. They are used here, in combination with the MPT computer model, to illustrate the effectiveness of the MPT device via performance simulation runs. Attention is focused below upon those important aspects of the MPT model which relate its characteristic behavior to that of the remaining system components.

The time constant of the combined source-inverter-grid system is much longer than the time constant of the MPT device. The time response of the electronic circuits comprising the MPT is the main reason for the validity of this assertion. This fact permits a significant simplification of the MPT computer model. Let δV_c be the amount by which the control signal V_c changes, during successive time steps. Also, V_{ck} and P_{outk} are the values for the control signal and the output power at the kth step, respectively. The value of V_c, at the $k+1$ time step, is given by the expression

$$V_{ck+1} = V_{ck} + \lambda_k \delta V_c \tag{1}$$

where

$$|\lambda_k| = 1. \tag{2}$$

The new value for P_{out}, due to the change in V_c, is P_{outk+1}. The control signal V_c is now modulated, according to the relation

$$\lambda_{k+1} = \lambda_k \operatorname{sign}[P_{out\,k+1} - P_{out\,k}]. \tag{3}$$

Thus, a new value for V_c will result in accordance to relation (1) and will be given, therefore, by

$$V_{ck+2} = V_{ck+1} + \lambda_{k+1}\delta V_c. \tag{4}$$

The function sign $[x]$ is defined as follows:

$$\operatorname{sign}[x] = 1, \qquad \text{if } x \geq 0$$

$$\operatorname{sign}[x] = -1, \qquad \text{if } x < 0.$$

Relations (1) and (3) constitute the MPT computer model. This model is combined with those of the remaining subsystems in order to study the transient and steady-state performance of the interconnected system [1].

IV. MPT DESCRIPTION

A detailed block diagram of the MPT is shown in Fig. 5. The three basic units (see Fig. 3) comprising the MPT are enclosed for clarity in dotted lines. The digital structure of the PLGD and control circuits is apparent here. The description of the structure and operational characteristics of the MPT is made with reference to this figure.

A. Electronic Wattmeter (EW)

The electronic wattmeter is based upon the use of a classic analog multiplier which multiplies the instantaneous values of the output voltage and current. An averaging circuit follows the multiplier, whose output signal is proportional to the mean output power P_{out}.

B. Power Level Gradient Detector (PLGD)

The wattmeter output provides the input signal to the PLGD. The operation of this unit is synchronized with pulses produced by the timing circuit. A full cycle of the MPT operation is integrated every four pulses. During the first pulse, the A/D converter converts the PLGD input signal (P_{out}) to an 8-bit digital signal. This signal is compared with the corresponding signal stored, during the preceeding cycle, in the latch circuit. This is done via a digital comparator whose output is a logic state "1" or "0", according to whether there is a power output increase or decrease, respectively. This state inhibits or permits access of the next (second) timing pulse through the AND gate. The FLIP-FLOP operates in a toggle mode and stores the previous state. During the second timing pulse, if the output power has been decreasing, the FLIP-FLOP changes state. Otherwise, it remains in the same state. The logic output of the FLIP-FLOP constitutes the input signal for the next stage of the MPT, that is the control

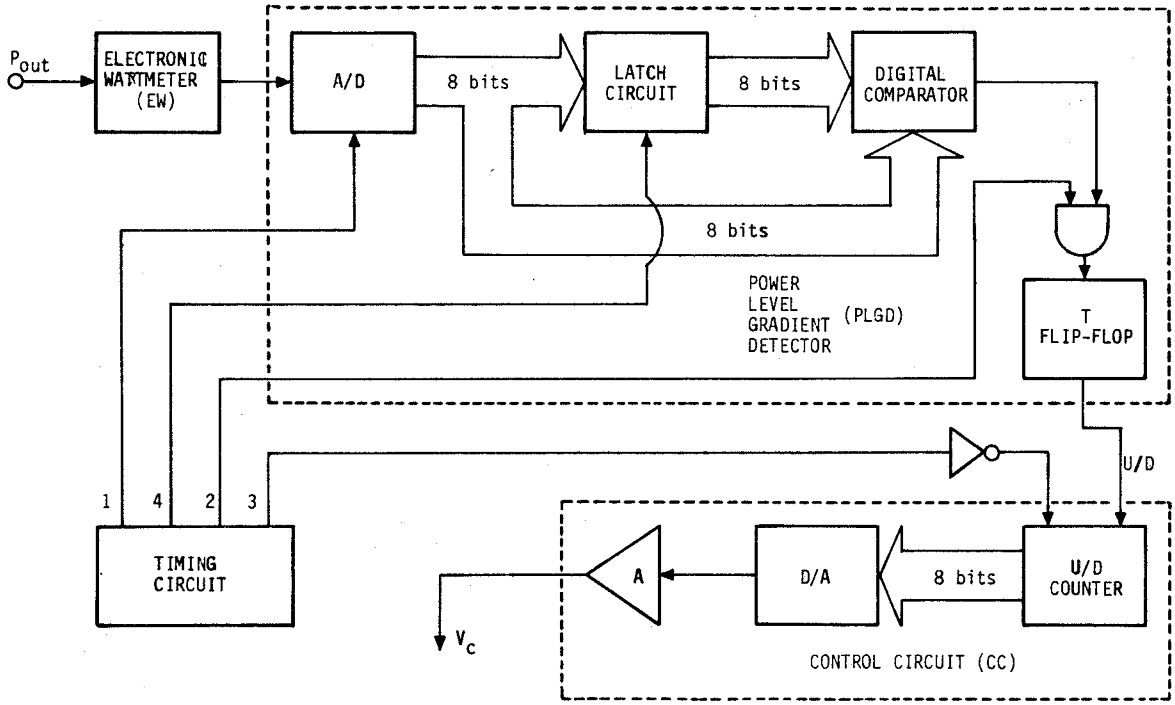

Fig. 5. Detailed block diagram of the MPT.

circuit. The third timing pulse relates to the function of this control circuit. During the fourth pulse, the existing signal at the output of the A/D converter is stored in the latch circuit and remains there until the next cycle of operation.

C. Control Circuit (CC)

The PLGD output is fed to the U/D input of an up/down (U/D) counter, which is the first of the control circuit stages. The up or down counting is controlled by the input U/D. Thus, the third timing pulse is added to or subtracted from the content of the counter, with respect to the PLGD output. The digital output of the counter (8 bits in parallel form) is converted to an analog signal, via the D/A converter. This signal is properly amplified by amplifier (A). The amplifier output is the control signal V_c.

D. Timing Circuit (TC)

This is a conventional timing circuit with four sequential outputs. The pulse duration of this circuit can be easily adjusted. Thus, the total duration of the MPT operational cycle can be set to any value, according to the requirements of the specific application. The digital storage, for the successive P_{out} values, does not suffer from drift, offset, and noise-characteristic disadvantages of analog storage. Also, the digital procedure for the construction of V_c ensures that, during each cycle of operation, the control signal remains constant. This limits additional transient problems generated during the integrated system operation. The accuracy of the MPT operation is not degraded by this technique, since the whole power region is divided into $2^8 = 256$ levels. So, successive levels differ from each other by not more than 0.4 percent of the maximum power, a satisfactory criterion for the accurate performance of the device. The detailed electronic diagram of the MPT circuit is shown in Fig. 6.

V. RESULTS OF THE MPT OPERATION

The impact of the MPT operation upon power maximization of a WECS or a PV array is studied both theoretically and experimentally. The results presented in this paper refer to the configuration of Fig. 1.

Fig. 7 depicts the output power P_{out} of a synchronous wind generator, as a function of wind speed U. The generator output is rectified and then inverted to ac form before connecting the unit to the utility power lines. Curve (a) represents the output power without the MPT in operation, while curve (b) is the output power with the MPT in operation. The improvement in output power, achieved in this application, is of the order of 80 percent.

Fig. 8 depicts the output power P_{out} of a PV array, interconnected to the utility grid, by means of an inverter, as a function of solar radiation. The output power, without the MPT in operation, appears as curve (a), while curve (b) shows the output power after the MPT is connected. The improvement achieved in this particular application is of the order of 40 percent. Paralleling these experimental results, a computer simulation of the integrated system is employed for sensitivity studies. Here, the sensitivity of the output power as a function of various design parameters is studied. The same computer model is also used for transient stability studies.

Computer results are verified experimentally by means of the corresponding laboratory configurations. The actual WECS consists of a synchronous two-blade horizontal axis wind generator with dc-output and rated power of 2.2 kW. The inverter utilized is a novel laboratory design, with rated

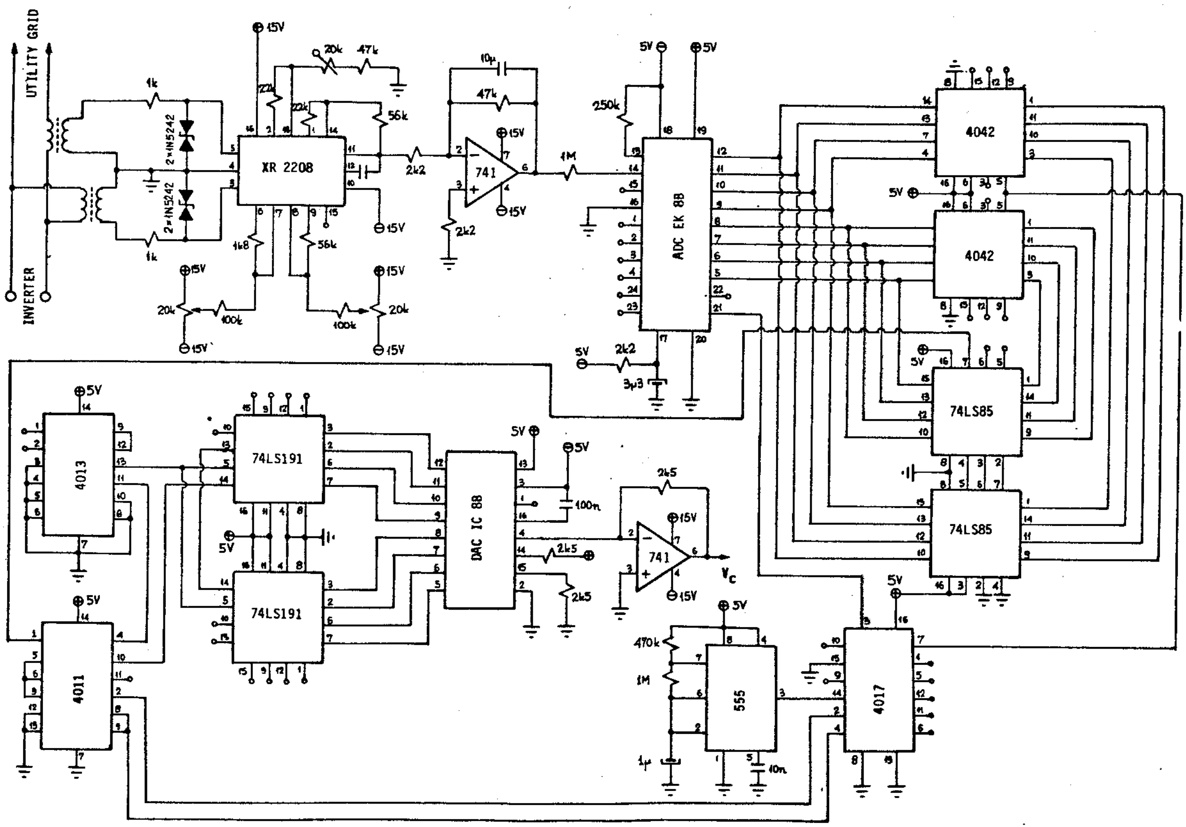

Fig. 6. Detailed electronic diagram of the MPT.

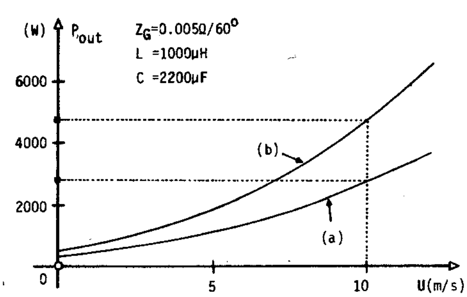

Fig. 7. Output power P_{out} of a WECS-inverter-grid system versus wind speed U. (a) Without the MPT in operation, and (b) with the MPT in operation.

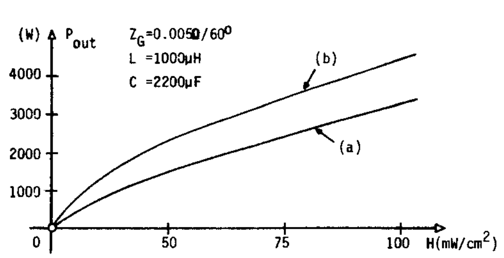

Fig. 8. Output power P_{out} of a PV array-inverter-grid system versus solar radiation H. (a) Without the MPT in operation, and (b) With the MPT in operation.

power of 2.5 kW and the means for continuous adjustment of the conduction angle via an externally applied control voltage. In place of the PV array, a laboratory constructed PV simulator [13], with rated power of 2.5 kW, is used in combination with the inverter. Both systems are connected to the low-voltage side of the local utility grid. Improvement in power output with the MPT in operation and smooth system transient behavior, during abrupt perturbations, are observed. Experimental results thus closely match model predictions, verifying the overall reliability of the interconnected system.

VI. CONCLUSIONS

The main advantages of the MPT device, described in this paper, are:

1) considerable improvement of the output power for various renewable electric energy sources, thus increasing their attractiveness as a means for supplying a substantial amount of our future energy needs;
2) it may be connected to any existing system, without requiring significant changes in its basic system units;
3) maximization of output power continuously, regardless of external parameter variations (wind speed, solar radiation, etc.);
4) simple and compact structure, with its construction requiring only conventional components;
5) reliable operation over a wide range of conditions.

The MPT presented here may be used in a variety of applications, wherever dynamic matching between source and load characteristics is called for.

REFERENCES

[1] K. C. Kalaitzakis and G. J. Vachtsevanos, "Power optimization of wind electric conversion systems integrated into the utility grid," *Wind Eng.*, vol. VI, no. 1, pp. 24-36, 1982.

[2] Z. Zinger and A. Braunstein, "Dynamic matching of solar electrical (photovoltaic) system: An estimation of the minimum requirements on the matching system," *IEEE Trans. Power App. Syst.*, vol. PAS-100, no. 3, pp. 1189–1192, Mar. 1981.

[3] G. J. Vachtsevanos, K. C. Kalaitzakis, and E. J. Grimbas, "Power conditioning in solar photovoltaic array applications," in *Proc. Fourth EC Photovoltaic Solar Energy Conf.*, (Stressa), May 1982, pp. 325–329.

[4] T. Kuono, "Maximum power obtainable in a nonlinear system," *Proc. IEEE*, vol. 66, no. 9, pp. 1085–1086, Sept. 1978.

[5] R. I. Thomas and J. S. Thorp, "Integration problems with large wind energy conversion systems," in *Proc. 18th Annual Allerton Conf. Comm. of Control and Comp.*, (Monticello), Oct. 1980, pp. 206–213.

[6] R. Ramakumar, "Wind electric conversion utilizing field modulated generator systems," *Sol. Energy*, vol. 20, pp.109–117, 1978.

[7] J. D. Van Wyk, "Electro-wind energy system with oversynchronous cascade and simple adaptive maximal power control," in *Proc. Int. Soc. Silver Jubillee Congress*, vol. 3, (Atlanta), May 1979, pp. 2291–2295.

[8] A. Cocconi *et al.*, "High frequency link 4kW photovoltaic inverter for utility interface," in *Proc. 4th Photovoltaic Sys. Definition and Appl. Projects Integration Meet.*, (Albuquerque), Apr. 1983, pp. 103–113.

[9] G. Beghin and V. T. Nguyen Phuoc, "Power conditioning unit for photovoltaic power systems," in *Proc. Third EC Photovoltaic Solar Energy Conf.*, (Cannes), Oct. 1980, pp. 1041–1045.

[10] J. Pivot *et al.*, "Optimization of the PV array-load energy transfer by means of an electronic adaptor," in *Proc. Third EC Photovoltaic Solar Energy Conf.*, (Cannes), Oct. 1980, pp. 1033–1037.

[11] G. J. Vachtsevanos and K. C. Kalaitzakis, "Maximum power transfer in nonlinear source-load systems," to appear in *Int. J. Circuit Theory*

[12] G. J. Vachtsevanos and K. C. Kalaitzakis, "A simulation study of energy flow optimization," in *Proc. IASTED Int. Symp. Applied Modelling and Simulation*, June 1982.

[13] G. J. Vachtsevanos and E. J. Grimbas, "A photovoltaic simulator," *Int. J. Solar Energy*, vol. I, no. 4, pp. 285-292, Jan. 1983.