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POWER CONDITIONING IN SOLAR PHOTOVOLTAIC ARRAY APPLICATIONS

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Summary

The design and implementation of appropriate power conditioning apparatus for the interconnected operation of PV arrays with the utility grid are presented. Problems of maximum power transfer from the PV array to the utility grid, reliability of the interconnected system operation and component protection are addressed. Because of the intermittent nature of the available solar energy, the need for conversion of dc electrical power to ac and the fluctuating loads of the utility system, optimization methodologies and associated equipment are developed for converting the maximum available solar power to electrical form and transfering it to the grid. A dual methodology is adopted containing a theoretical - system simulation - study of the performance of the interconnected system and a parallel experimental facility for the implementation of the system design. Results indicate higher energy transfer efficiencies in combination with an increased quality and reliability of performance of the PV array - utility grid system.

1. INTRODUCTION

In recent years there has been growing interest in utilizing PV arrays to provide some of the electrical demand of small autonomous power utility systems where the cost of electricity production using conventional fuels is becoming prohibitive. Such systems may be interfaced with the existing power grid for " fuel displacement " purposes as well as for earning some " capacity credit ".

Grid interface problems associated with the parallel operation of PV arrays with the utility grid have been studied recently (1,2). The technoeconomic requirements for the optimum and reliable operation of PV arrays interconnected with the power grid include (a) a high degree of efficiency for the PV array system for the whole region of its power output operation; (b) a grid capability of absorbing the maximum power produced by the array: (c) the electrical power must be introduced into the grid without distortion, and (d) the operation of the PV array system should be reliable with adequate protection and minimum possible maintenance requirements.

The interconnected operation requires the development of appropriate interfacing equipment for purposes not only of quality of operation but also of transfering maximum power from the PV generator to the load or grid (3). For these reasons, an interface - matching methodology and associated implementation devices are proposed utilizing inexpensive components and addressing a wide range of operational requirements depending upon the specific application under consideration. Basic design goals included maximum economy in system components as well as the possibility of operation under variable input - output conditions.

2. SYSTEM DESCRIPTION

A PV array may be considered as a dc source of power with strongly nonlinear voltage - current characteristics. Such typical characteristic curves are shown in Figure 1(a).

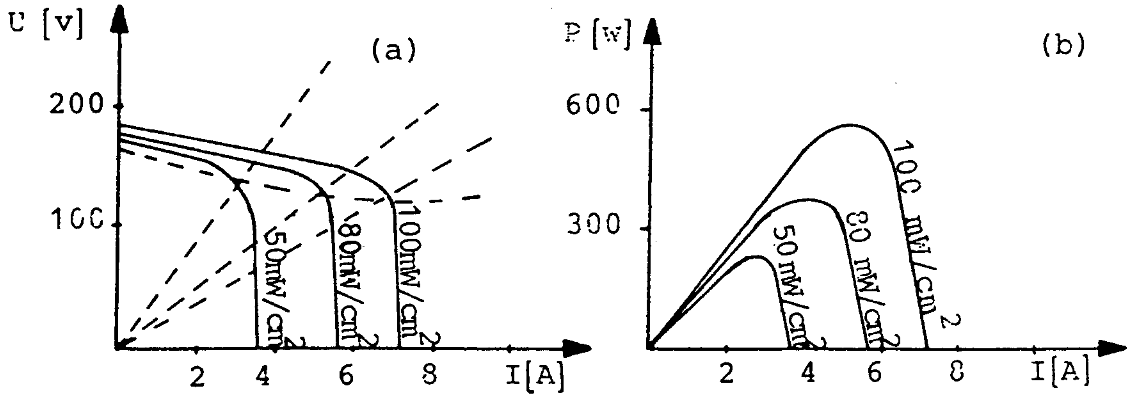

FIGURE 1

It is observed that the array voltage drops almost linearly as the current increases up to a certain value. From that point on, an abrupt change in the characteristics occurs. It is also noteworthy that the general shape of the v-i characteristics remains essentially unchanged for various values of incident solar radiation, H. Figure 1(b) shows that the array power output, P, as a function of the current, attains a maximum value near the knee of the characteristic curve. For varying solar intensity, the maximum output power is delivered to a load whose value places the operating point in the region of the knee of the characteristic curve. Since this point is constantly changing as a function of the solar intensity, a matching circuit must be interposed between the PV array and the grid which will guarantee maximum power to be transfered from the generator to the power lines, at each instant of time. Moreover, the constant (dc) form of the voltage waveform at the array output terminals imposes an additional requirement upon the interconnecting mechanism: The power output must be synchronized to the ac constant frequency characteristics of the utility mains. This goal is achieved with a new type synchronous inverter (4); it 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 transfered from the PV 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). Figure 2 shows a conceptual block diagram of the proposed scheme.

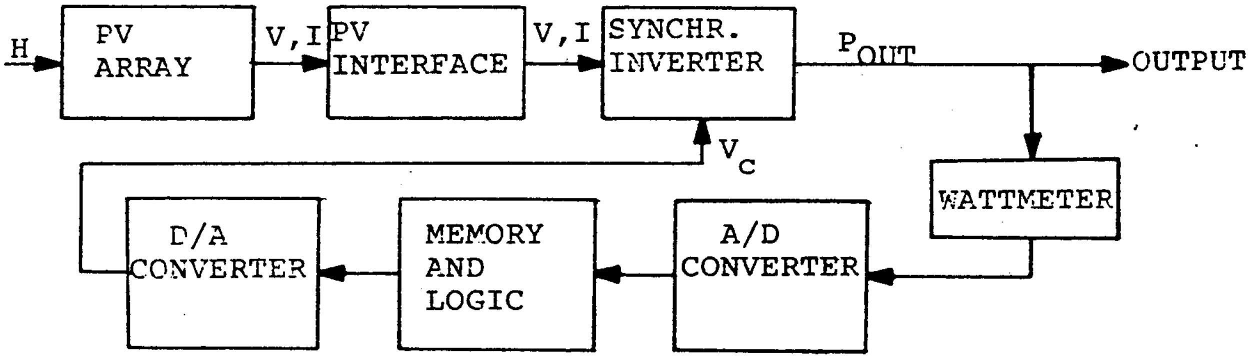

FIGURE 2

For any solar intensity H, the array output feeds into the inverter via a PV interface circuit which assists in improving signal quality while maintaining an approximate "static" matching between the generator and load impedance characteristics. The values of the L,C components are design parameters of the optimization procedure.

The feedback circuit includes the following subsystems:

1. An electronic wattmeter that continuously measures the power level at the utility grid terminals and provides a signal output proportional to actual power.

2. An A/D converter which converts the analog signal into digital form.

3. The "Memory and Logic" circuit is effectively a digital power level gradient detector which samples the wattmeter signal output and holds it for comparison with the next sample. The detector includes a comparator that works in combination with a logic circuit to determine if a given sample represents a power level that is greater or smaller than the previous sample. The logic circuit changes state whenever a new sample is smaller than the preceeding one, but remains in the same state if the new sample is larger than the preceeding, thus representing an increase in power level.

4. A D/A converter provides a constantly changing analog output whose direction of change is increasing for one state of the logic circuit and decreasing for the other. This control signal is used to fire the inverter thyristors, thus controlling the power level transfered to the grid.

The design approach used has both a theoretical and an experimental component. The theoretical study consists mainly of computer simulations of the steady - state behavior of the interconnected system while the experimental method involves testing of a particular PV conversion system interfaced to the power grid. Experimental results are compared, on a step by step basis, to those obtained from the simulation studies. This dual nature of the approach allows for an optimum design of system components and verification of theoretical results.

The photovoltaic array characteristics are modelled using a series approximation of the form:

$$V = c_1 I - c_2 I^{c_3} \tag{1}$$

For any given grid impedance, $Z \angle\underline{\varphi}$, at the point of interconnection, the mathematical model for the filter - inverter system relates the inverter average power output, P_{out}, to the dc input voltage level, V, and the control signal V_c. This relation may be represented, functionally, by

$$P_{out} = g(V, V_c, Z \angle\underline{\varphi}) \tag{2}$$

The power grid is viewed, at the point of interconnection, as a voltage source of fixed amplitude in series with an impedance Z φ. Protective devices are employed for the safe operation of the PV array - grid interconnected system. The nature of the overall system design prevents a bidirectional power flow thus elliminating the possible negative consequences of such an operation. Their mathematical representation employs simple magnitude constraints on certain variables which are easily implementable during the simulation runs. Finally, the model describing the operation of the maximum power tracker is represented by a set of switching state equations describing the state of the control variable V_c, at each instant of time, depending upon the gradient of the power at the grid terminals, P_{out}.

The computer simulation establishes initially an equilibrium state between the inverter input - output characteristics, for a step change in solar radiation intensity, assuming an arbitrary initial condition for the control variable V_c and a constant value for the grid impedance $Z \angle\underline{\varphi}$. Next, the control signal V_c is given a new value and the equilibrium procedure is repeated. The two consequtive values for the power output, P_{out}, are used as inputs to the maximum power tracker model whose goal is to set a new value for the control voltage V_c which increases the power output. The previous computational steps are repeated until the power output, P_{out}, oscillates about a maximum value at which instant the program is terminated.

3. RESULTS

Figure 3 shows a typical power output vs. solar radiation intensity characteristic with and without the maximum power tracker in operation. A typical photovoltaic array with characteristics as shown in Figure 1(a) has been used and the experimental results are in agreement with those obtained from the computer simulation runs. Design parameters were chosen to optimize system performance with the assistance of sensitivity analysis techniques using the computer model. It is observed that the power transfer efficiency improves by as much as 33% with the maximum power tracking mechanism in operation.

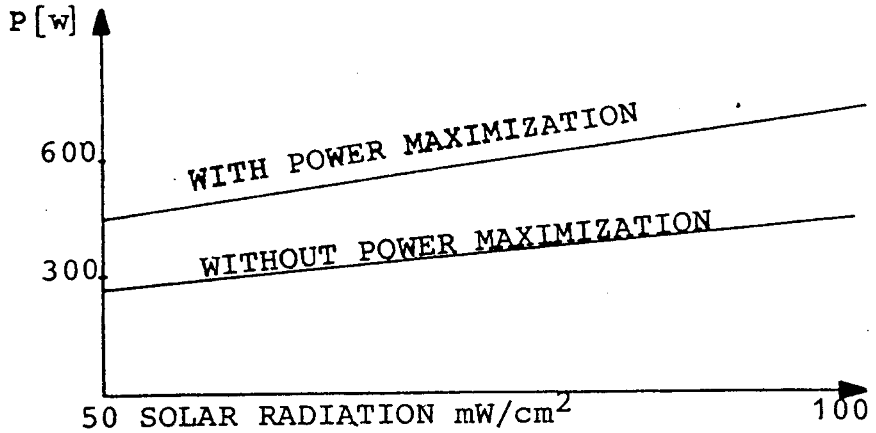

FIGURE 3

Total harmonic distortion introduced by the inverter operation is of the order of 1.5%. The safety equipment employed protect effectively both the PV array and the power grid from various fault conditions.

Both impedance matching and power tracking result in maximizing the energy transfered from the PV array to the grid. Thus, an optimum operation, from a technical and economic standpoint, is achieved for a large range of solar radiation variations.

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

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It gives me pleasure to inform you that based upon the abstract we have received, your paper:

Code: P1-022
Entitled: A simulation study of energy flow optimization in wind electric conversion systems
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has been accepted for presentation at the IASTED International Symposium, Applied Modelling and Simulation, AMS'82 , to be held at the Sheraton Hotel in Paris June 29 to July 2, 1982. Enclosed are special forms for the preparation of your manuscript. Your paper will be reviewed for possible publication in the IASTED journal 'International Journal of Modelling and Simulation'. Please supply us with a letter confirming your attendance.

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