THE DESIGN AND PERFORMANCE
OF AN 11 KW SOLAR ARRAY SIMULATOR*

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ABSTRACT

A Solar Array Simulator combines a high efficiency switching regulator, a high performance series regulator, and a low power analog adjustable I-V generator to duplicate the static and dynamic characteristics of photovoltaic cells operated in series-parallel combinations. Both voltage and current feedback are used to control the switching and series regulators. Stability of the series regulator over a wide range of load time constants is achieved by a compensation technique of Roberge⁽³⁾. Current-voltage and transient response characteristics of the Simulator are presented. The device was also operated into a 10 kW inverter designed for photovoltaic applications.

INTRODUCTION

The solar array simulator described in this paper was developed as a tool to test and evaluate power conditioning units for photovoltaic power systems. As such, it was designed to simulate as closely as possible the current-voltage characteristics of a photovoltaic array. It is in essence an adjustable, regulated DC power supply designed to "look like" a photovoltaic array to any load to which it is connected.

Figure 1 is a block diagram of a utility-interactive photovoltaic power system. The power conditioning unit (PCU) contains a power inverter to convert the DC power generated by the array of silicon photovoltaic cells into AC power suitable for use by the load. It also functions as a power dispatching device combining array and utility power to meet the load demand, and, if the array is producing more power than the load requires, delivering the excess power to the utility. Photovoltaic power system

Figure 1. Block diagram of utility-interactive photovoltaic power system

PCUs are designed for high efficiency ($\approx 90\%$), high quality AC power (total harmonic distortion of less than 5%), and low cost (a goal of \$.20 per rated watt).

A photovoltaic array behaves much like a voltage limited, constant current power supply. Figure 2 shows a family of current-voltage (I-V) characteristics for an array under different illumination levels and constant cell temperature. The power delivered is zero at both short circuit and open circuit conditions and reaches a maximum on the "knee" of the curve. In order to extract the maximum available array power it is, of course, necessary to operate the system at the array maximum power point. Although the I-V characteristics vary considerably with cell illumination, the voltage at the maximum power points remains relatively constant. However, the characteristics are also very sensitive to cell temperature. The open circuit voltage decreases with increasing cell temperature at a rate approximately equal to $2\text{mV}/^\circ\text{C}$ times the number of series cells making up the array. The maximum power voltage decreases at roughly the same rate. In a typical terrestrial application the maximum power voltage may vary by as much as plus or minus 20%. A device built to simulate a photovoltaic array must therefore be able to vary its short circuit current over a considerable range, e.g. to simulate the effects of a cloud passage over the array. Also, the open-circuit voltage must be variable

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Figure 2. Family of current-voltage characteristics for a photovoltaic array at constant cell temperature under different illumination levels.

to simulate the effects of cell temperature changes, although these occur over a much longer time scale than illumination changes due to cloud passage.

Figure 3 is an accepted equivalent circuit of a photovoltaic array consisting of a photon-generated constant current source, an ideal diode, a shunt resistance R_p , and a series resistance R_s . (1,2) The resistances R_p and R_s account for losses due to the inability to construct an ideal diode and additional losses due to cell interconnects. Typical values for R_p and R_s for a single cell are 1000 ohms and .020 ohm, respectively. The corresponding values for an array depend upon the number of cells and how they are connected. Shunt resistance has the effect of producing a deviation of the characteristic from zero slope at short circuit

Figure 3. Photovoltaic array equivalent circuit

current, while series resistance produces a deviation from vertical slope at the open circuit voltage.

In the following section the design of the Simulator is presented. System stability is discussed in the next section followed by a section on the results of performance tests of the Simulator.

SYSTEM DESIGN

The Solar Array Simulator is designed to duplicate the characteristic curves of a solar array in a reproducible manner so that precise tests can be repeated. This is accomplished by controlling the power to the load through a series regulator and a switching regulator using both voltage and current feedback. An analog adjustable I-V generator simulates the solar array characteristics at a low level and serves as the control signal for the regulators.

Figure 4 is a schematic of the analog adjustable I-V generator.

Figure 4. Analog adjustable I-V generator schematic

Ten silicon diodes in two dual in-line IC packages provide the diode function. These are placed in a mini-oven at 60°C to maintain a constant diode I-V relationship. Transistor Q1 simulates the photon-generated constant current

generator of the equivalent circuit. R_p and R_s are adjustable parallel and series resistors scaled down to the power level of the function generator. The load is simulated by shunting a current proportional to the load current through transistor Q2. The voltage V_l is thus proportional to the voltage of a photovoltaic array at the operating load current and serves as the reference voltage to a voltage error amplifier in the series regulator.

Figure 5 is a block diagram of the Array Simulator. The unit operates

Figure 5. Solar Array Simulator block diagram

from 3 phase, 120/208V AC power. Full-wave rectified DC at 320V is applied to a switching regulator configured to maintain a constant 10V drop across the pass transistors in the series regulator. The switching regulator is a conventional DC-DC down-converter. A second feedback loop in the switching regulator limits the input current during turn on and severe load transients, thus simulating the current limiting property of an actual array. The switching regulator maintains high system efficiency at all operating points by limiting the power losses in the series regulator to 10V times the operating current.

The second regulator is a Class A Amplifier series regulator which utilizes the low-power analog I-V generator signal to reproduce the array I-V characteristic curves. Reference voltage V_l (see Figure 4) is compared to the output voltage V in a high gain feedback loop, and the output voltage is maintained at the desired value. A signal proportional to output current I is fed back to

the reference voltage generator as described above to form the I-V curve of a solar array.

A test switch and a remotely programmable calibration signal permit the generation of a family of curves without varying the load resistance, a tedious and time consuming task. The current feedback signal is replaced by the calibration signal in this mode of operation.

STABILITY

In addition to generating the I-V curves of a solar array, the simulator must also reproduce the array dynamic characteristics while operating into a variety of loads with different resistances and time constants. A typical large time constant load is a 10kW, 60Hz inverter with 20000uf input capacitance and a dynamic negative resistance, a necessary part of the signature of switching type DC to DC converters and DC to AC inverters that draw essentially constant power over a broad voltage range from the DC source. The static positive resistance part of the input time constant ranges from 4 ohms to 360 ohms. A typical small time constant load is a 20kHz DC to DC converter with input capacitance and resistance variations essentially the same as the inverter described above.

To compensate the series regulator with a single time constant load with widely varying parameters, the technique of Roberge⁽³⁾ is adapted. An operational amplifier with a closed loop transfer function that approximates

$$(1) \quad a(s) = \frac{G}{\sqrt{s}}$$

over the appropriate frequency range is selected. A phase margin of 45° is assured for any load time constant and gain factor, and stability is guaranteed. The series regulator open loop transfer function is

$$(2) \quad F(s) = \frac{GK}{\sqrt{s} (1 + T_1 s)}$$

where K is the load related gain factor and T_1 is the load time constant.

The function $\sqrt{s}$ cannot be obtained with a lumped, finite network, but it has been approximated with surprisingly

good accuracy over five decades of frequency with an RC ladder network. Figure 6 is the schematic diagram that shows the ladder network in the negative feedback path of operational amplifier A1, a National Semiconductor JFET LF355 integrated circuit. The output is

Figure 6. Series regulator error amplifier configured for $G/\sqrt{s}$ response

further amplified and used as the base drive for the pass transistors in the series regulator. The parameter "a" in Figure 6 was selected⁽³⁾ as $\sqrt{10}$. Voltage V1 is the output of the analog adjustable I-V generator, and voltage V2 is proportional to the output voltage of the Solar Array Simulator.

Figure 7 is a Bode plot of the series regulator gain vs. frequency for two load conditions: R_L equals 100 ohms and C equals 20000uf; and R_L equals 1 ohm and C equals 2000uf. Both cases closely follow the theoretically perfect straight line approximation of $G/\sqrt{s}$. Figure 8 is the Bode phase plot of the series regulator for the same conditions. The phase margin for the longer time constant follows the theoretical line at the point of crossover. The shorter time constant load has a better phase margin than the theoretical 45°.

The switching regulator, which operates at 1500Hz, has a closed loop response that is flat to 150Hz. This response is sufficiently fast to compliment the series regulator for all expected load time constants. Optimum performance was achieved by adding a stabilizing feed-

Figure 7. Bode plot. Series regulator gain vs frequency

Figure 8. Bode phase plot for series regulator

back network that utilized a sense coil across the inductor in the switching regulator to provide a signal proportional to the rate of change of current in the inductor. This signal is added to the signal from the voltage across the series pass transistors in the series regulator. The 1500Hz operating frequency was selected as a trade-off compromise between efficiency, speed of response, and audible noise.

PERFORMANCE

The ability of the Simulator to generate a family of curves typical of photovoltaic arrays is demonstrated in Figure 9, which shows the extremes of adjustment for three insolation levels. These curves were generated by applying sawtooth current signals to the base of the "load" transistor Q2 in Figure 4 while applying a three step wave "insolation" signal to the base of transistor Q1.

Figure 9a shows three I-V curves for nominal settings of R_s and R_p in Figure 4, with short circuit currents ranging from 10A to almost 30A and a nominal open circuit voltage of 160V. By setting the adjustable series resistance R_s in Figure 4 to a minimum, the family of curves shown in Figure 9b were generated. These illustrate the sharpest possible knee that can be generated with the Simulator. The family of curves shown in Figure 9c correspond to the maximum value of series resistance R_s resulting in the maximum deviation from vertical slope at the open circuit voltage.

Similar curves have been obtained under static conditions using high power resistors and a variety of capacitance loads. The curves can be reproduced within 1%, provided the temperature controlled diodes are allowed at least five minutes to achieve thermal equilibrium.

The response to a step change is shown in Figure 10, which was reproduced from a Brush recorder trace. By a step change in gate current to transistor Q1 (Figure 4), corresponding to an abrupt change in solar cell illumination, a step change in output voltage from 200V to 240V resulted. The step was applied at near maximum load current and minimum load capacitance. The excellent transient response stability results from the inherent stability of the $G/\sqrt{s}$ transfer function of the series regulator.

20 V/cm
Fig. 9a

20 V/cm
Fig. 9b

20 V/cm
Fig. 9c

Figure 9. Solar Array Simulator I-V characteristics for nominal (9a), minimum (9b), and maximum (9c) series resistance settings

Figure 10. Brush recorder trace illustrating response of Solar Array Simulator to step change corresponding to abrupt change in cell illumination.

Finally, a series of tests of the 11kW Solar Array Simulator were conducted with a single phase, 240V AC inverter designed for photovoltaic applications⁽⁴⁾. The inverter has three modes of operation:

- (1) Stand-Alone, in which power is applied to a dedicated load, with no utility back-up.
- (2) Phaselock, in which mode (1) is augmented by operating the inverter frequency synchronized to the utility frequency; and
- (3) Utility Interface, in which the inverter returns the power generated by a photovoltaic array to the utility distribution system.

In mode (3), the inverter also has the optional capability of extracting the maximum power from the solar array by finding and remaining at the maximum power point on the array current-voltage characteristic.

Tests were performed at insolation levels typical of early morning, high noon, and late evening in all three modes with satisfactory results. In the stand alone and phaselock modes, the output voltage of the Simulator collapses to zero in the same manner as an actual array when the load demand exceeds the Simulator power settings. Within the design ranges of 160-240 Volts and 5-45 Amps the maximum power tracker of the inverter was able to find and hold the maximum power point to within three volts in the utility interface mode. This three volt "dither", resulting

primarily from disturbances on the utility voltage, produced deviations from maximum power of less than one percent.

The current limiting properties of the Simulator were tested by switching the unit on with either a short circuit or a 40,000uf capacitance load. In both cases the unit did not draw excessive current.

CONCLUSION

The design and testing of an 11kW solar array simulator has been discussed. The ability of the unit to duplicate the static I-V characteristics of a photovoltaic array has been demonstrated. The unit was also tested with a load typical of that for which it was designed, viz. a 10kW inverter designed specifically for photovoltaic applications, and it performed satisfactorily.

A 75kW array simulator is presently being designed by paralleling 11kW modules. The purpose of this unit is to test a 62.5kW, three phase inverter also designed for photovoltaic applications. The simulator will cover the voltage range 50-400 Volts and the current range 0-250 Amps.

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