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THE ENERGY BALANCE ASSOCIATED WITH THE USE OF A MAXIMUM POWER TRACER IN A 100-KW-PEAK POWER SYSTEM* + ++

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SUMMARY ABSTRACT

Design of a stand-alone photovoltaic (PV) system which includes batteries for energy storage requires not only sizing the array power output and battery storage capacity to meet the load, but also fixing the number of battery cells placed in series relative to the number of PV cells in series in order to keep the battery voltage in the neighborhood of the array maximum-power-point voltage during operation. When a maximum-power-point tracker (MPPT) is interposed between the array and the battery, the design task is simplified.

The decision to use an MPPT depends primarily on the operating efficiency of the device. The recent development at MIT Lincoln Laboratory of low-cost maximum-power-point trackers capable of efficiencies greater than 98% at the 3-kW level broadens the range of applications where an MPPT can be used to advantage. In this paper, hourly simulation results for the 100-kW-peak PV stand-alone system under construction at Natural Bridges National Monument in Utah are compared for the cases with and without maximum power tracking to quantify the advantage of MPPT implementation.

INTRODUCTION

In a photovoltaic (PV) system, it is desirable to extract the maximum amount of energy out of the array; a situation that would exist if the array were to be operated at the maximum power point at every instant. In a stand-alone system where the array is connected in parallel with a battery storage subsystem, the number of battery cells which are connected in series defines the nominal dc bus voltage. Although the nominal dc bus voltage may lie in the neighborhood of the array maximum-power-point voltage for some nominal combinations of insolation level and cell temperature, there will generally be a mismatch between the actual operating dc bus voltage and the maximum-power-point voltage of the array at any particular instant in time. This mismatch, which will result in an effective decrease in the efficiency of the array, depends on the state-of-charge of the battery, the battery charge or discharge current, and on the temperature and insolation level of the PV array. If a variable lossless matching network is interposed between the array and the battery, then a maximum-power-point tracking strategy can be used to constrain the array to always operate at the maximum power point.

The decision to include or not to include a maximum-power-point tracker (MPPT) will depend on the additional useful energy which could be collected by using the MPPT and on MPPT cost.

In this paper, we will describe an MPPT device which will be used to measure the energy advantage of maximum-power-point tracking for the Natural Bridges National Monument (NBNM) stand-alone PV system in southern Utah. The expected energy gain is predicted in advance of the actual MPPT measurements by computer simulation.

THE NBNM PV SYSTEM

Figure 1 shows a simplified schematic diagram of the stand-alone PV power system at the Natural Bridges National Monument site. The nominal 100-kW-peak PV array is made up of modules procured from three different manufacturers. Power from the array flows to the dc bus through shedding switches and maximum-power-point trackers (if used). A battery storage subsystem, with a nominal storage capacity of 750 kWh, sets the bus voltage

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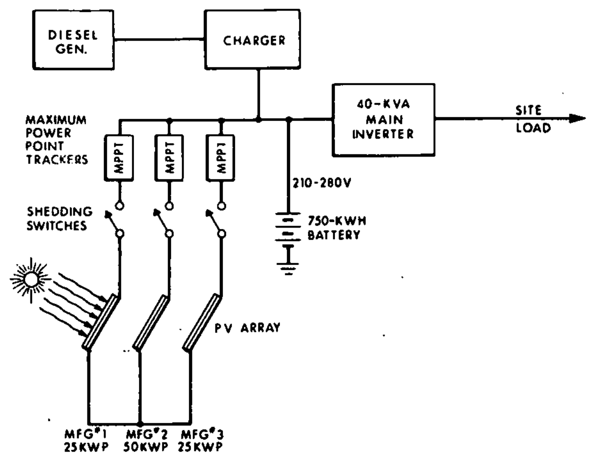
within the range of 210 to 280 Vdc. The 40-kVA site power inverter and a battery charger are also tied to the dc bus. An automatic system controller is used to switch on the diesel generator, adding additional power to the system via the battery charger, in order to protect the batteries from excessive depth of discharge. The controller is also used to shed array (progressively open shedding switches) when PV output threatens to overcharge the batteries.



NATURAL BRIDGES SYSTEM

Figure 1.

The NBNM installation also includes an automatic data acquisition system which is used to record those electrical and environmental variables which characterize system performance. Measured performance of the NBNM system will be compared with predicted performance both to monitor system behavior and to validate and refine the Lincoln Laboratory computer models of the PV system and its components. The high-efficiency electronic maximum-power-point trackers will be installed as links between small sections (three sections at 2.5 kW each) of the NBNM array and the battery load. Analysis of the array voltage and current data acquired at six-minute intervals will allow for a nearly continuous comparison between the energy output of those subarrays which are fitted with maximum-power-point trackers and the output of similar subarrays which are not so equipped.

THE MAXIMUM-POWER-POINT TRACKER

The maximum-power-point tracker, an electronic switching regulator, behaves as a dc-to-dc transformer with an adjustable input-to-output voltage ratio. The input-to-output voltage ratio (which can be greater than or less than one) is determined by a microprocessor-based optimizing controller. The controller continuously maintains PV array operation at the maximum power point by measuring array power and adjusting the input-to-output voltage ratio using a "hill climbing" algorithm.

The switching regulator and control system incorporated in the MPPT utilize state-of-the-art components to achieve exceptionally high efficiency and small size. The power handling and control technologies are borrowed from the growing microcomputer industry; in particular, the recent explosive growth of the market for high-efficiency computer power supplies ("off-line switchers") has led to the availability of the inexpensive, high-performance power-handling components (transistors, capacitors, etc.,) which are required in this application.

The simplified schematic of Figure 2 shows the topology of the MPPT power-handling state. The MPPT has four modes of operation which correspond to specific ranges of desired input-to-output voltage ratio; these modes are identified as follows:

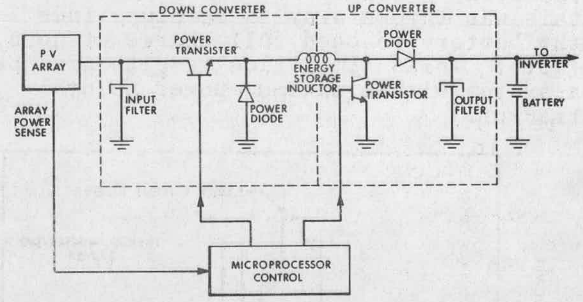
1. Down-conversion mode - The input-to-output voltage ratio is greater than one. The transistor switch in the down-converter section (Figure 2) is opened and closed at a 20-kHz rate with a duty cycle inversely proportional to the microprocessor-specified input-to-output voltage ratio. The transistor switch in the up-converter is left open. Efficiency ≅ 98%.

2. Up-conversion mode - The input-to-output voltage ratio is less than one. The transistor switch in the up-converter is opened and closed at a 20-kHz rate with a duty cycle proportional to the microprocessor-specified input-to-output voltage ratio. The transistor switch in the down-converter is left closed. Efficiency ≅ 98%.

3. Short mode - The input-to-output voltage ratio is nearly equal to one. The transistor switch in the down-converter is closed. The transistor switch in the up-converter is open. Efficiency ≅ 99%.

4. Search mode - The input-to-output voltage ratio is nearly equal to one. Both transistors are switched at the 20-kHz rate. Input-to-output voltage ratios above and below one are possible. This mode is periodically entered from the

"Short" mode for a short time in order to determine if it is appropriate to enter either the up-conversion or down-conversion modes. Efficiency ≅ 97%.



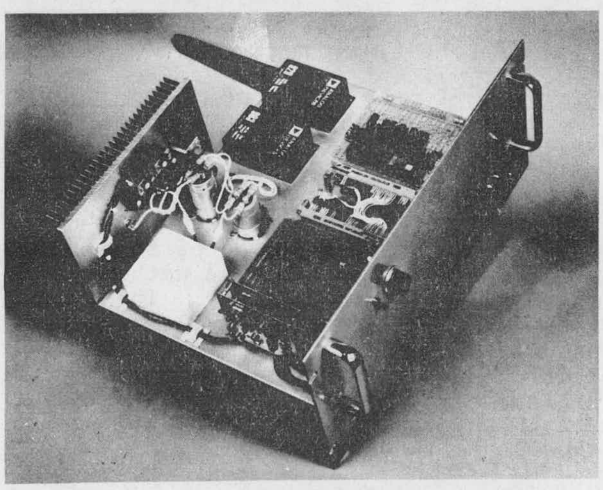
SIMPLIFIED 3KW MAXIMUM-POWER-POINT TRACKER SCHEMATIC

Figure 2.

The very high efficiencies for the various modes of MPPT operation are the result of advanced design techniques, including:

- low-power regenerative-transistor switch drive[1];
- lossless transistor protection circuits (snubbers)[2];
- switching transistors of exceptional speed[3];
- compact power-stage construction.

A photograph of a prototype MPPT capable of handling 3 kW at 250 to 300 Vdc input is shown as Figure 3.



PROTOTYPE MAXIMUM-POWER-POINT TRACKER
Figure 3.

SIMULATION STUDIES

The objective of these simulation studies was to determine for the 100-kW-peak NBNM system how much improvement, if any, in system performance could be obtained with the inclusion of an MPPT. To accomplish this task, hourly simulations of a year's system performance with and without an MPPT were conducted. The computer model took as inputs a prescribed, time-varying load, time-varying insolation and temperature (the latter two obtained from a SOLMET tape), and simulated the current-voltage characteristics of the PV array, the batteries, and the inverter. It calculated at each hour the bus voltage, the array maximum-power-point voltage, and all power flows: e.g., from the array, into or out of the battery, into and out of the inverter, from an auxiliary supply, and surplus. A full description of the hourly simulation used in support of the design of this remote, stand-alone system is given in another paper presented at this Conference[4].

The current-voltage characteristics of one manufacturer's subarray are shown in Figure 4. (This particular manufacturer's modules make up approximately half the total array on a power basis.)

The I-V curve was modeled using

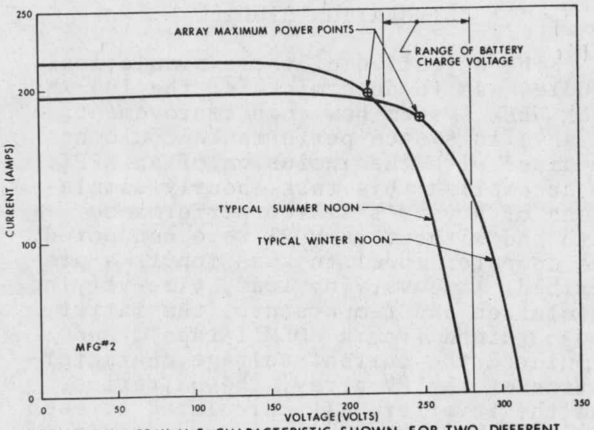
$$I = I_{sc}\left[1 - e^{k(V/V_{oc}-1)}\right]$$

where the short-circuit current, I_{sc}, and the open-circuit voltage, V_{oc}, were defined at a reference-cell temperature, T, and insolation level, L. The relationship between current and voltage at another temperature, T', and light-intensity level, L', were obtained from the transformation

$$I' = I + I_{sc}\left[\frac{L'}{L} - 1\right] + \alpha(T' - T)$$

$$V' = V - \beta \cdot (T' - T)$$

where α and β are temperature-correction coefficients.



TYPICAL PV ARRAY V-I CHARACTERISTIC SHOWN FOR TWO DIFFERENT TIMES OF THE YEAR REVEALING MISMATCH BETWEEN ARRAY AND BATTERY

Figure 4.

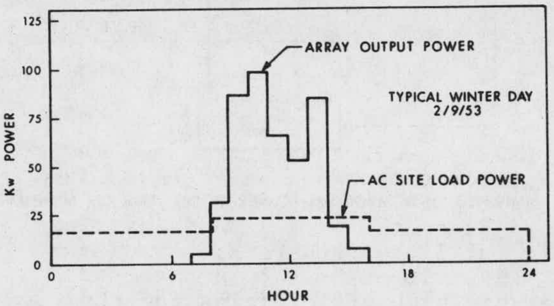
The I-V curve for a typical winter day near solar noon, shows a cell temperature of 40°C, a maximum-power-point voltage of 248 volts and a maximum power output of approximately 45 kW. At solar noon on a typical summer day, this manufacturer's subarray exhibits a cell temperature of 75°C, a maximum-power-point voltage of 217 volts and a maximum-power output of approximately 42 kW. (In the array model used, the difference in cell temperature and ambient air temperature is assumed to vary linearly with insolation.)

The range of the bus voltage when the battery is in a charging mode is also shown in the figure. The high limit at 280 volts corresponds to a battery cell voltage of 2.5 volts per cell. The battery would reach this state only at around 90-100% state of charge. If the bus voltage exceeds this high limit, array shedding is programmed to occur.

From Figure 4, we can discern the potential mismatch between array maximum-power-point voltage and dc bus voltage. The greatest mismatch will occur in the summer (high cell temperature) when the array is charging the battery.

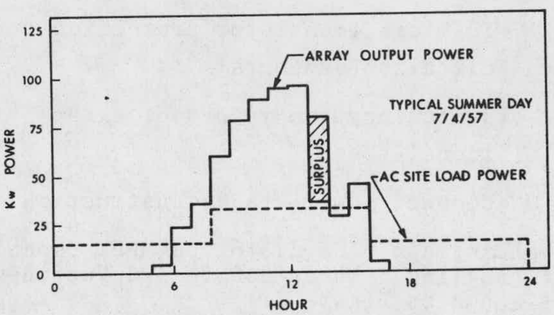
For purposes of simulation, the load on the system was estimated to be 150 MWh/year with daily totals ranging from 330 kWh in October to 450 kWh in January. Simulation showed that the 100-kW-peak array nominally produces 200 MWH/year with monthly totals ranging from 14 MWh in December to 19 MHw in August. (The array was tilted to an angle equal to the latitude of the site.)

Figure 5 shows a typical winter day's time history of array power and load power. For the purposes of simulation, the load profile was assumed to peak for eight hours of the day. On this particular day, the array produced approximately 400 kWh. Simulation of typical summer day's behavior is shown in Figure 6. On this particular day, the array produced 590 kWh. Some of this was thrown away as surplus since the battery reached full charge at noon. (Note: These simulation results are for a system with a maximum-power-point tracker.)



TYPICAL WINTER DAY PV ARRAY OUTPUT WITH MAXIMUM-POWER-POINT TRACKER (COMPUTER SIMULATION)

Figure 5.

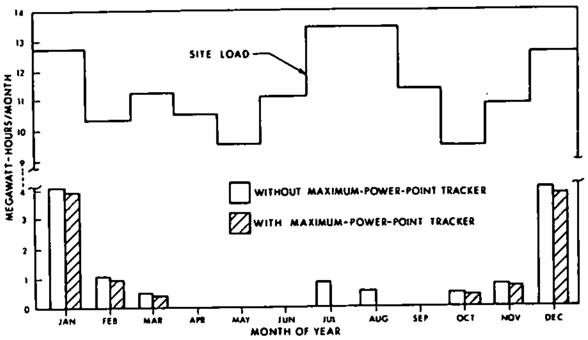


TYPICAL SUMMER DAY PV ARRAY OUTPUT WITH MAXIMUM-POWER-POINT TRACKER (COMPUTER SIMULATION)

Figure 6.

SIMULATION RESULTS

Figure 7 shows the results of a computer simulation of the performance of the system both with and without a maximum-power-point tracker. The relatively large demand for auxiliary power in December and then again in January reflects the relatively low amount of available insolation during the winter months and the high site load during those same two months.



SYSTEM AUXILIARY POWER REQUIREMENT

Figure 7.

Use of a 100%-efficient maximum-power-point tracker decreases the demand for auxiliary power by a small amount. In July, 5.8% of the site load is carried by the auxiliary source if the system does not include a maximum-power-point tracker. In August, this drops to 3.8% of the site load. The system with a maximum-power-point tracker requires no auxiliary power.

Over the entire year, the array without a maximum-power-point tracker requires auxiliary energy in the amount 8.2% of the site load; with a maximum-power-point tracker, the system requires the auxiliary source to provide energy in the amount of 7.3% of the site load--a 1% difference equivalent to 1.5 MWh/year. As shown in Table 1, the total array energy produced with a maximum-power-point tracker was found from the simulation to be 227.0 MWh/year; without a maximum-power-point tracker, it was 191.9 MWh/year. But for the system with the tracker, 36 of those 227 MWh were discarded as surplus. Discounting surplus, the system with a tracker produced 190 MHh/year of usable energy, while the system without a tracker produced 187 MWh/year. This amounts to an effective increase of only 1% in usable array output. This 1% of additional useful array output is gained only if the maximum-power-point tracker is 100% efficient. This gain will be offset almost exactly by the loss due to the inefficiency (approximately 1%) in the MPPT device itself.

In order to see if a more significant improvement in performance would be obtained with our array sized to carry less than the full load, simulation of a system with less array than is actually installed at NBNM was also performed. Cutting out approximately 30% of the array showed again that the system without a maximum-power-point tracker performs over the course of a full year to within 5% of the system with a 100%-efficiency maximum-power-point tracker. These results are also shown in Table 1.

TABLE 1
SUMMARY OF COMPUTER SIMULATION RESULTS

ALL IN MWH/YEAR							
ARRAY RATING		TOTAL ARRAY OUTPUT	SURPLUS	ARRAY -SURPLUS	AUXILLIARY ENERGY	LOAD	% AUX/LOAD
100 KWP	WITH	227.0	35.7	190.3	10.4	151.0	6.9%
	W/O	191.9	4.81	187.1	12.3	151.0	8.1%
70 KWP	WITH	154.6	1.6	153.0	44.1	151.0	29.2%
	W/O	148.7	0	148.7	47.7	151.0	31.6%

CONCLUSIONS

In summary, the expected advantage of the maximum-power-point tracker is small in this application despite the significant mismatch between the battery voltage and the array maximum-power-point voltage which occurs during the summer months. The potential energy gain of the maximum-power-point tracker is highest during seasonal periods when the average available PV supplied energy is in excess of the site load. Consequently, the use of an MPPT simply increases the amount of PV power which is shed to prevent battery overcharge.

If the simulation results obtained for the case with 30% less array are representative, it appears that the use of an MPPT may never prove economically feasible for a system with battery storage. Further studies are planned to determine the conditions which do make it advantageous to incorporate an MPPT.

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