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Positioning Of Photovoltaic Array For Maximum Power

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Abstract-*This paper describes the design, development, and evaluation of a microcomputer-based solar tracking and control Tracking and Error Monitor System for a photovoltaic (PV) concentrator array. The Tracking and Error Monitor System combines the function of sun tracking with the function of load adjustment for peak array efficiency. The complete PV array is used as the sun sensor. Test results show a deviation in maximum power of less than 1% during the day after accounting for other variations.*

I. INTRODUCTION

Solar concentrating collectors are being used in increasing numbers for various thermal and photovoltaic (PV) applications. Often, these collectors require two-axis tracking of the sun to maintain the concentrated light focused on the receiver. The idea described here examines a method of sun-tracking that uses the complete PV collector array as a sun sensor.1 this tracking and control System differs greatly from the sun-tracking methods commonly used. One method of precision tracking requires lengthy calculations of the sun's elevation and azimuth angles.2 Error information is obtained by comparing calculated values with high resolution measurements of the angular position of the array structure. Subsequent drive motor control minimizes tracking error (the difference between the calculated position and the measured position of the array).

A more common method of sun-tracking employs a shadow-band device with sensors in four quadrants. Four sensors are used in up-down (elevation) and east-west (azimuth) pairs. Sun tracking error is minimal when the pairs are equally illuminated by the sun. Differential output voltages of the elevation or azimuth sensor pairs are used as feedback to the motor drive circuitry.

II. COMPARISON OF THE TRACKING AND ERROR MONITOR SYSTEM WITH CONVENTIONAL SUN TRACKERS

Conventional sun trackers have a closed-loop control Tracking and Error Monitor System function similar to that shown in the block diagram in Figure 1. These devices use operational amplifiers to operate the ON/OFF and directional functions of the structure drive motors. The motors serve to rotate the collector structure in two axes. The tracker's sun sensor is mounted on the structure. The four outputs of this device are used to determine how well the sensor is oriented toward the sun. If the outputs are all equal, the collector structure is nearly perpendicular to the sun and tracking error is minimal. A slight off-axis angle will cause an unequal output of one or both pairs of sensors. This imbalance is amplified to actuate relays (and drive motors) in an Tracking and Error Monitor System to equalize the sensor outputs. The errors are thus again reduced to a minimum.

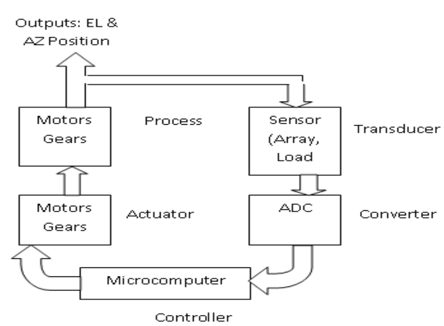

Figure 1 Closed Loop Control System

The sun tracking and Error Monitor System described in this paper uses the PV array itself as the sun sensor.

However, the output is not multiple signals that tell the controller in which direction to drive the motors, but is rather measurements of the maximum power from the array. No error information is available as in the conventional sun tracker sensor. The error information from the process of sun tracking is generated by comparing the maximum power from the array before and after a perturbation or movement is made. An increase in output is a favorable indication, and another movement in the same direction is at Tracking and Error Monitor System. A decrease in power is interpreted as an "error," causing a reversal in movement direction. This move-and-compare operation is repeated until a suitable position is found to let the array rest and allow the sun to "walk-off" a certain amount. This pause allows the power out of the array to change a small, measureable amount. After a short period of time, the update process begins again, executing the maximizing algorithm until a new peak power position is found. The controller receives maximum power information from the voltage and current measurements made by an analog-to-digital converter (ADC). However, since the array is not self-adjusting for maximum output power, the microcomputer has this responsibility, too. To find the peak power from the array, it must adjust a controllable load using a digital-to-analog converter (DAC). By adjusting the load in incremental steps about the peak power point, a maximum is found. The microcomputer then controls the drive motors and moves to a new position using its ability to turn the actuating relays on and off. Because PV concentrators have a narrow field of view (power output drops off rapidly with small off-axis angles), the peak power positioning process is not self-starting at the beginning of a day. A sun sensor can provide the information required to move the array within this field of view. Use of a sun sensor for initial positioning allows final tracking to be accomplished by peak power positioning.

III. SUPPLEMENTARY OPERATIONS

The Tracking and Error Monitor System has other functions that make it a multipurpose sun tracker. Besides responding to user-input commands, it detects and accounts for other environmental factors. Tracking and Error Monitor System reacts to a night condition by sending the array into a stow position (determined by the user). The array remains in the stow position throughout the remainder of the night. When the sun comes up again, the sun sensor output must be used to move the array into a position to begin peak power tracking.

IV. SUMMARY OF PEAK POWER POSITIONING OPERATION

When the control program is first started on the Tracking and Error Monitor System, or the sun has just risen, the microcomputer moves the array into a position "window" (refer to Figure 3). The array position yielding peak power output will be found within this window. This initial line-up on the sun is accomplished by a process of measuring the four outputs of the sun sensor and making decisions about changing the position of the array.

After the four sensor outputs (up, down, east, and west) are measured, the related pairs, east/west and up/down, are compared. If the difference in the outputs for either axis is greater than the value that corresponds to the + 0.370 window, a position change must be made. This difference limit value is derived from the sun sensor output characterization plots. An output voltage difference for a pair of sensors of 2.5 V is equivalent to 0.370. In terms of the 8-bit ADC output (its range is 0-255), 2.5 V equals 128 counts. The direction of the necessary array movement is specified by the highest output of the pair. A motor control relay is turned on when the direction has been determined. As the drive motors move the array at a slow rate, the sensor outputs are scanned again. If the array has moved far enough so that the differences are less than 128, the motors are turned off. When this occurs, the array is aligned within the window, a flag is set in the program and a branch is taken to the peak power positioning algorithm. When the microcomputer begins executing this portion of the program, the array-to-load connection relay is energized. A position dithering process is begun to determine the peak output power location within the window. First, however, a peak power measurement is made at the present location as a reference point by a complete I-V curve scan. The azimuth axis is adjusted in 0.20 steps in the west direction. After each step, the computer determines a new peak power value by calling a subroutine designed to do this in a quick, concise manner. If the new value is greater than the reference value, the new value becomes the reference point. If a decrease in output occurs, a decision is made either to step the array in the opposite direction to try to regain some of the lost output or to leave it in the present position and allow the sun to "catch up." If the loss in output is greater than 0.7% of the previous peak, this is considered to be an overshoot and the array is moved in the east direction one step.

The elevation axis position is dithered next, and a similar procedure is followed. A position step size of 0.10 was selected in this axis because the test collector drive gear-train backlash is less than that in the azimuth axis. An initial direction for the position stepping is determined by measuring the azimuth position pot. An ADC output count of 128 indicates that the azimuth axis is oriented nearly south. The up direction is selected to "catch up" to a rising sun if the position pot value is less than or equal to 128. The array is first moved downward if the value exceeds 128 indicating afternoon and a sinking sun. When a small decrease in power is detected because of an overshoot of the peak power position, the array is held at that location. If the decrease is greater than 1.0%, a step is made in the opposite direction. One percent is used for experimental purposes and may not represent the optimal value.

This concludes a typical cycle of the peak power positioning algorithm. The cycle completes in 5-15 seconds and can be considered short when compared with sun angle changes. The array is held in this final position for several moments, allowing the sun to "move" and the peak power position to change.

The incremental movement process is repeated each cycle with the exception of the complete I-V curve scan. The complete scan is used only to find the initial peak power reference point. The process of peak power positioning continues until it becomes night.

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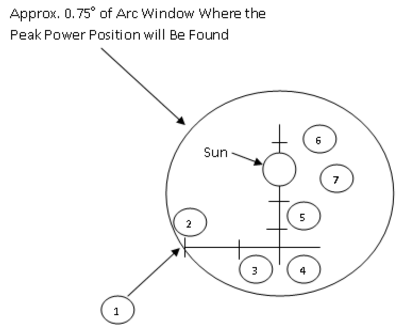
The microcomputer detects either situation by a scan of the sensor outputs immediately before the window position test. If it is night, determining the window location is nearly impossible. Night is detected if all outputs are below the night threshold value. The ADC output value of 5 counts was experimentally chosen for this threshold. (Very little light must fall on phototransistors to produce this output.)

If night conditions are detected, the microcomputer moves the array to a stow position where it remains until sunrise.



1. Starting Position-Sun Sensor used for Tracking
2. Array with Window, Peak Power Position begins.
3. Azimuth Position Steps
4. Possible Azimuth Position
5. Elevation Position steps
6. Possible Elevation Position
7. Final Position giving peak in output power

Figure 2 Peak Power Positioning steps

V. EVALUATING THE PEAK POWER POSITIONING OPERATION

Because of the complexities of peak power positioning, this mode of operation has many parameters to monitor including tracking error, update cycle time, tracker movement patterns, maximum power output and response to clouds. In use at the Sandia National Laboratories Photovoltaic Advanced Tracking and Error Monitor Systems Test Facility is a device referred to as a Tracking and Error Monitor System. It has an analog output that is a function of the off-axis error of a tracking structure relative to the sun. The output is approximately linear over a + 2.00 range with an 0.10 usable resolution. Initial data were collected with a small data acquisition Tracking and Error Monitor System that plotted tracking error versus time. A pair of Tracking and Error Monitor System was mounted on the array structure next to the sun sensor with one oriented to record azimuth errors and the other rotated for elevation. The outputs were sampled at 0.5-second intervals and plotted on the display. A hard copy of the display was produced on a thermal printer at the end of each plotting period. The result of plotting the data was a "saw-tooth" waveform with the long straight-line periods representing times when the array is stationary showing how tracking errors change as the sun "moves."

VI. MONITORING THE ACTIVITY

Two input channels of a desktop data acquisition Tracking and Error Monitor System were connected to the outputs. Other channels measured array voltage, current, and direct normal in-isolation (DNI). This data was plotted in real-time allowing the complete operation of the Tracking and Error Monitor System to be monitored. Correlations to changes in DNI could also be made to evaluate the effects of clouds. The accumulated data, stored in a disk file, were also available for further analysis at a later time. A plot of typical system operation is shown in Figure 4. The top line represents DNI, which was fairly constant at about 1000 W/m2. The next lower line is a plot of measured power. The periodic spikes in this line were generated during the update process. Due to a comparatively slow sampling rate, peaks occur that do not represent the true array output power. Voltage and current are not sampled concurrently. Rather, the sequential sampling often occurs as the load is being adjusted, producing pairs of erroneous voltage and current values and the misleading power peaks.

The next lower lines represent azimuth and elevation errors, respectively, as measured with a Tracking and Error Monitor System. These are similar to the saw-tooth plots describe earlier. An offset was adjusted in the outputs. Close examination of this plot shows the azimuth axis first being moved incrementally and then the elevation axis in the process of finding the new peak power position.

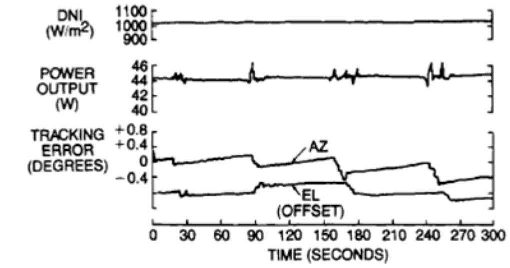


Figure 4 Tracking and Control normal operation

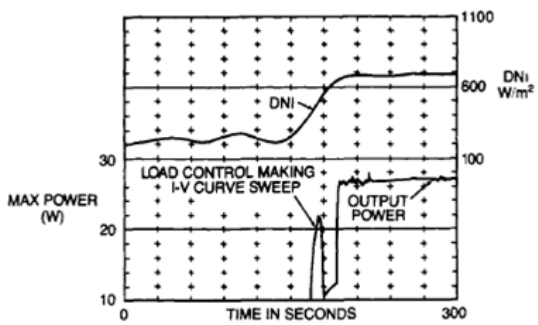


Figure 5 Tracking and Control operation when cloud passes

Again, the long, sloped lines are produced when the tracker is stationary. The steps produced in tracking error when the Tracking and Error Monitor System is searching for the new peak power position are also evident from the staircase shape in the plot. Effects of a cloud moving away are shown in Figure 5.

In the first half of the plot, a wavering is seen in the DNI (upper line). This is the "tail end" of a cloud. The power output line is off scale during the first half of the plot. When the peak power positioning begins after the cloud is gone, an I-V curve sweep is made and the maximum power rises sharply to the peak level. A subsequent update cycle is also shown near the end.

VII. SUMMARY AND COMMENTS

In this paper, I have described the design and development of a Tracking and Error Monitor System and control for PV concentrator arrays. The Tracking and Error Monitor System combines into one unit two specific functions ordinarily found in separate equipment making possible a new method of sun-tracking that is implemented on a readily available single-board computer.

The sun-tracking operation consists of changing the position of the array and adjusting the load on the array to the peak power point. A series of incremental movements is used to determine the position relative to the sun at which the array operates at maximum efficiency. Peak power positioning results as the procedure is repeated at regular intervals accounting for sun movements. Within the limits of the microcomputer program memory capacity, the Tracking and Error Monitor System proved to be an excellent device to test the concept of peak power tracking. The low-cost, 8-bit data converters (both DAC and ADC) provided adequate resolution of input signal measurements and control signal outputs. Higher resolution devices (i.e., 10- or 12-bit) may improve the Tracking and Error Monitor System operation by increasing the sensitivity to measured changes in array power or sun sensor signals. However, extra circuitry is required to allow the microcomputer to read the extra bits of information. During the testing phase, the array had to be moved "manually" from stow to a position within roughly 45o of the sun before the automatic tracking would begin functioning. The low output of the sun sensor at angles greater than 45' is interpreted as cloud cover.

Changes in the sun sensor design and closer scrutiny of the threshold value used to make decisions about cloud cover might solve this problem. Programming the Tracking and Error Monitor System to move the array to a "wake-up" position from the stow position after detecting sunup is also a possible solution.

The peak power positioning mode performed generally as expected. Some refinements could be made to enhance the speed of operation during the searching for the peak on the power curve. The method employed in the Tracking and Error Monitor System works quickly and accurately, but is not optimal. In the control program, the upper and lower bounds of the peak power point are determined by a short procedure. When defined, these bounds are 10 DAC counts apart. The computer sweeps all 10-points and stores the DAC value that corresponds to the peak power point. After about two seconds, the 10-point scan is complete, and the load is returned to the peak power point. Because of the possibility of least-significant bit errors (both DAC and ADC) causing erroneous peak power values, all 10 points are checked for the maximum.

An optimal search technique based on the Fibonacci number sequence (i.e., 1, 2, 3, 5, 8, 13, 21, 34, etc.) for finding the peak should be implemented as follow-on work. To do this, the upper and lower bound can be defined within 8 counts instead of 10, providing a basis for the final search for the peak value. The optimal search technique requires a maximum of three steps when the bounds are 8 steps apart. The technique uses progressively smaller step sizes and compares measurements before and after each step. After 3 steps (e.g., 5, 3, 2), the peak will be known + 1 step and can be considered maximized.

Generally, the experimental results of this research were as expected, showing that sun tracking by this method gives potentially high-performance results. It is a method which virtually assures peak efficiency from the array with little regard for structural deformations, dust, dirt and poor alignment problems. When coupled with an adjustable load on the array, a peak power positioning sun tracker constitutes a major component in a photovoltaic concentrator array power Tracking and Error Monitor System.

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