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THE SKYTRAKKER™ PARABOLIC TROUGH CONTROL SYSTEM

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ABSTRACT

The SkyTrakker™ is a highly accurate and highly efficient parabolic trough control system. The system includes the microprocessor control board, separate motor controller, and sensors (temperature, position, hydraulic pressure). The SkyTrakker™ has several distinct advantages and design features that provide better manufacturability, shorten installation time, and reduce O&M cost. Some of the advantages and features are:

1. Maximum control and performance with reduced parasitic power consumption.
2. Lower motor input power consumption during deploy, tracking and stow (the SkyTrakker™ uses 52% of the power consumed at NSO).
3. Simple 110v AC single-phase motor requirements with digital motor interface to reduce parasitic power consumption at motor start-up and during tracking.
4. Local or remote monitoring and control
5. Separate motor control providing a high level of motor power isolation from the electronics.
6. Microprocessor based control board offering fast response, monitoring of HTF temperature, SCA position, hydraulic pressures, and control of the motor.
7. Enhanced field diagnostics to isolate position sensor and motor control problems and provide run-time status of operation
8. Accurate tracking using virtual tracking algorithms, eliminating the use and maintenance of sun sensors.

The SkyTrakker™ control system is modular and designed for quick assembly and installation at the SCA pylon. The major sub-system parts (control board and motor controller) are pre-assembled and are mounted on a pre-wired mounting panel. The NEMA 4 electrical enclosure can be mounted to the pylon with or without the internal pre-wired panel, providing installation flexibility when building the field. All control system components (control board, motor controller and sensors) can be easily replaced in the field. And motor life is greatly extended due to reduced overall power and reduced parasitic power consumption.

INTRODUCTION

SkyFuel is a commercial solar energy technology provider specializing in parabolic trough and linear Fresnel technologies for Concentrating Solar Power (CSP) plants.

Research and development at SkyFuel is the continuation of work that has been underway for several years to advance CSP systems and components. Advancements have allowed SkyFuel to cut the costs of the control system while increasing its accuracy and performance.

LOCATION

Field related research, development and test activities have been performed at SkyFuel's Arvada, Colorado test field which includes a Solar Collector Assembly (SCA) and the electronics and drive controls needed to move the SCA. This location

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allows testing in low and high temperature conditions (-10°F to 110°F) with wind speeds from 0 to 80 mph.

PREVIOUS ART

Microprocessor-based solar control systems have been used in CSP plants for over 20 years since the SEGS I and II facilities began operation in 1985 and 1986. Control systems included one embedded controller at each SCA drive pylon (called the 'local' controller or LOC) and a network connection arrangement that connected the hundreds or thousands of controllers to a central computer, located at the power plant control room (called the 'supervisory' controller). In early systems, the local controller did not have the processing power to compute the sun position so the supervisory controller computed the sun position data and transmitted it to the local controllers in the field. Operational data obtained from the local controllers was limited to a) mode of operation (tracking, follow, idle), b) SCA position data, c) heat transfer fluid (HTF) temperature data and d) basic motor status. Advances in microprocessor and communications technology have allowed the local controllers to compute the sun position, track the sun, and provide operational and maintenance data to the supervisory controller.

DESIGN

SkyFuel has developed an advanced technology control and drive system for CSP parabolic trough collectors. This design was optimized for the SkyFuel SkyTrough™ collector, but is applicable to other parabolic troughs as well.

The major design goals were:

a) Provide accurate tracking to 0.06° (1 mrad)
b) Modular installation and reduced operational and maintenance (O&M) costs
c) Improved data collection for O&M data

The SkyTrakker™ control includes two main groups of components:

- the microprocessor-based control board, with variable frequency drive (VFD) motor controller and temperature and position sensors (collectively called the SkyTrakker™ Embedded Control System SECS)
- the control room hardware and software.

The control room system hardware and software is called the Solar Field Computer (SFC). The SFC monitors the entire solar field and presents the field data on a graphic screen for the control room operator. The operator can send commands to all the SECS units in the field, or can send to one or more selected units.

The SECS components are mounted in a NEMA enclosure that is attached to the center drive pylon of the SCA as shown in Figure 1. The internal components are pre-wired and mounted and are shipped ready to be mounted on the center pylon (see Figure 2).

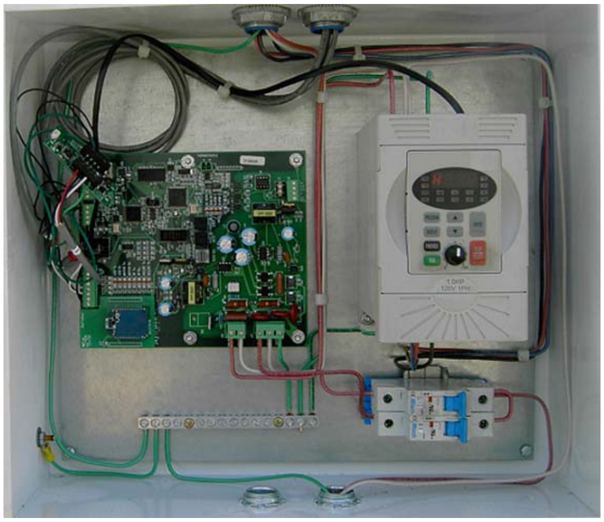

Figure 1 – NEMA Enclosure with Control Electronics

Local and remote monitoring and control were built into the design of the SECS. The motor control front panel or the USB port on the SECS board provides local control (from the unit at the pylon). Remote control is provided using either the wired RS-485 communications interface or the wireless RF interface. Configuration and setup parameters can be set using either the local or remote interface. The configuration parameters are stored in non-volatile flash memory.

The SECS control board monitors HTF temperature, hydraulic pressures and controls and monitors the SCA position.

The SECS control electronics (control board and VFD motor controller) support multiple input voltages and frequencies for use in U.S. and European solar fields.

1. 110v AC single-phase, 50 or 60 Hz.
2. 208-220v AC single-phase, 50 or 60 Hz.
3. 208-220v AC 3-phase, 50 or 60 Hz.

Regardless of the input voltage, the voltage to the drive motor is always 208-220v AC 3-phase 50-60 Hz.

One design goal was to eliminate the problems encountered in previous systems when the AC motor was directly powered from the control board. High inrush currents, a jammed motor, or other motor problems would damage the connected control board. Some designs used plug-in motor control components to provide a field replaceable solution. The SECS control board does not directly power the motor but uses a separate VFD motor controller to power, control and monitor the motor. A serial data connection between the SECS control board and the VFD unit allows the SECS board to monitor the motor status and to send commands to operate the motor. This separation provides isolation between the high currents for the motor and the low voltage electronic circuitry on the control board. The VFD motor controller also provides an excellent front panel display and keypad for manual control of the motor during system setup and periodic maintenance. The 3-phase

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motor interface allows precise speed control of the motor for SCA positioning and tracking operations.


Figure 2 - Center Pylon with Drive Components

A second design goal was to increase the data available for operational and maintenance (O&M) use. The SECS provides traditional data (SCA position, HTF temperature, mode status) and enhances operation and decreases maintenance by providing motor and system performance data. The additional data provided is:

- motor voltage, current, frequency, load percentage, motor faults
- controls and inclinometer temperatures
- closed loop feedback on movement and positioning.

Multiple communication systems were designed for the SECS, with the industry standard RS-485 wired interface and a wireless RF interface. Either interface can be used to communicate with the control room computer. A prototype of the SFC was designed and was used to test the RS-485 interface.

The SECS control system uses a closed loop to position the SCA and to determine the SCA position using the inclinometer. Tuning parameters are latitude, longitude, time, date and SCA orientation for the sun calculation formula and tracking dead-band, tracking motor frequency, motor startup curve/time and motor stop curve/time. The SCA orientation parameter is 0° for a north-south orientation and 90° for an east-west orientation. The tracking dead-band is the angular position window east and west of the sun position (see Figure 3). The tracking motor frequency, the motor startup curve/time and the motor stop curve/time (Figure 4 and Figure 5) are all tunable configuration parameters during development and are fixed parameters during production and installation of the system. Default design values are shown in Table 4.

In normal operation, the SECS control board sends position commands to the VFD which in turn powers the 3-phase motor/pump assembly in the desired direction until the target position is reached, as indicated by a precision inclinometer. In tracking mode the motor runs at 10 hertz (the default tunable tracking frequency). The sun position is calculated by the on-board SECS software algorithm and is compared to the SCA position (from the precision inclinometer sensor). The SECS software will determine when the SCA needs to be re-positioned to obtain an optimum focus on the sun. Initial deployment moves the SCA to the west side dead-band position, then enters tracking mode and waits for the sun to move west of the SCA position (to the east side dead-band position). The SCA will move westward through the sun position to the west side dead-band position again. See Figure 3.

Follow mode is similar to tracking mode but the SCA is positioned 10 degrees east of the sun position during tracking.

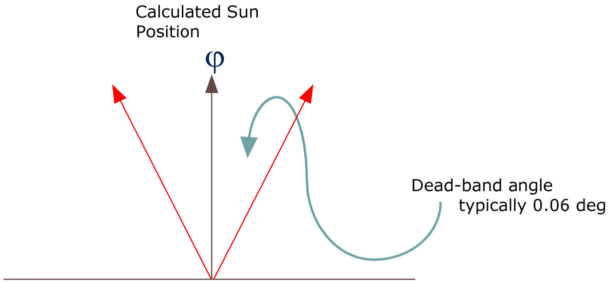

Figure 3 - Tracking Dead-Band Window

The calculated sun position algorithm is based on the PSA solar vector algorithm [3] which is stated to have an accuracy of 0.5 arc-minutes (0.017°). A discussion of total system errors as related to tracking errors are found in [1] and tracking and alignment errors are discussed in [2] and [4]. A summary of the total system error σ_{sys} and how that error relates to tracking errors are shown in Table 1.

The total error of the system (SCA and controls) is dependent on tracking error, slope error, receiver location error, specularity and sun shape intensity. Three tracking error values were selected (0.3, 1.0 and 3.0 mrads) that represent the range of tracking accuracies. Using these values and the equations from Table 1, the resulting system error is 7.54, 7.60 and 8.11 mrads.

Figure 6 in [1] shows the relationship between annual output (in BTU/ft^2-yr) and tracking error for an SCA with a system error of 10 mrads. Using the calculated system error from Table 1, the percentage differences and penalties on annual output for various tracking errors were determined (see Table 2).

The tracking accuracy can be modified by changing the tracking dead-band value (see Figure 3). Tracking accuracy is also affected by changing the motor frequency although this parameter has less effect than the dead-band. Power consumption of the drive system will vary depending on the motor duty cycle. The motor duty cycle is determined by the angular change in position needed (the dead-band) and the speed of the motor moving the SCA towards the target position as determined by the motor voltage, current and frequency. The software dynamically changes the motor frequency and the

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motor controller determines the voltage and current needed to drive the motor. Power consumption based on motor frequency is shown in Figure 11.

The VFD motor controller provides flexibility in starting and stopping the motor. The starting and stopping frequencies can follow an s-curve or a linear ramp (see Figure 4 and Figure 5) with timing options in 0.1 second increments.

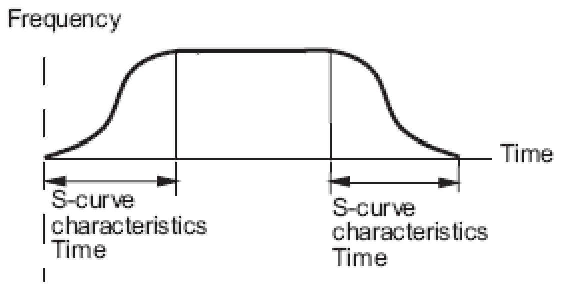

Figure 4 – VFD S-Curve Start and Stop Characteristics

$$\sigma_{sys}^2 = \sigma_t^2 + (2\sigma_e)^2 + \sigma_r^2 + \sigma_{sp}^2 + \sigma_{su}^2$$

$$\sigma_t^2 << (2\sigma_e)^2 + \sigma_r^2 + \sigma_{sp}^2 + \sigma_{su}^2$$

$$0.3\sigma_t^2 < \sigma_t^{2'} < 3\sigma_t^2 , \ \sigma_{sys}^2 \approx \sigma_{sys}^{2'}$$

Where:

σ = standard deviation of Gaussian error
σ_t = tracking error, σ_t' = new tracking error
σ_e = slope error
σ_r = receiver location error
σ_{sp} = specularity
σ_{su} = sun shape intensity (assumed gaussian)
σ_{sys} = error of system, σ_{sys}' = new system error

The following assumptions were made:

σ_e = 3.0 mrad
σ_{sp} = 2.0 mrad
σ_{su} = 4.1 mrad
σ_r = 1.0 mrad

$$\sigma_{sys}^2 = \sigma_t^2 + (2 * 3)^2 + 1^2 + 2^2 + (4.1)^2$$
$$\sigma_{sys}^2 = \sigma_t^2 + 56.81$$

Resulting in:

Tracking Error σ_t	System Error σ_{sys}
0.3	7.54
1.0	7.60
3.0	8.11

Table 1 - System Error and Tracking Error

Tracking Error (in mrads)	Annual Output (in BTU/ft^2-yr) (From Figure 6 in [1])
0	100%
1.0	99.75% (- 0.25%)
2.0	99.50% (- 0.50%)
4.0	98.4% (- 1.6%)
8.0	94.5% (- 5.5%)

Table 2 - Annual Output and Tracking Accuracy

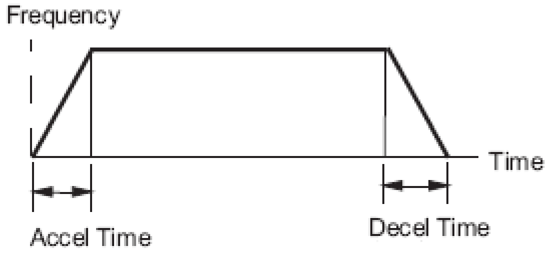

Figure 5 – VFD Linear Ramp Start and Stop Characteristics

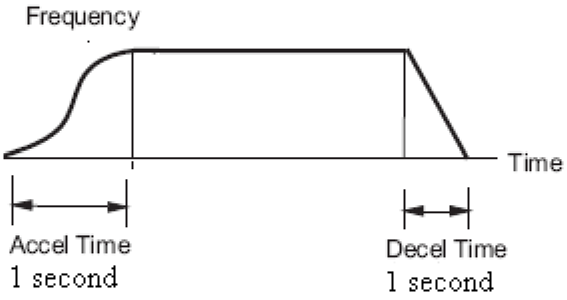

Figure 6 - Programmed Start and Stop Characteristics

Other tracking control devices designed and observed by the primary author have virtual tracking accuracies shown in Table 3. Virtual tracking is tracking using the calculated sun position instead of using a sun position sensor.

Tracking System	Virtual Tracking Accuracy
SkyTrakker™	0.06°
AdLoC (NSO)	0.07° to 0.10°
SEGS II (Daggett)	1.4°

Table 3 – Virtual Tracking Accuracy Comparisons

Design Parameter	Default Value
Tracking Dead-band	0.06 degrees (1mrad)
Tracking motor frequency	10 Hz.
Motor Startup Curve/Time	S-Curve, 1 second (Figure 6)
Motor Stop Curve/Time	Linear ramp, 1 second (Figure 6)

Table 4 - Default Design Parameter Values

To estimate worst-case daily power requirements of a single SCA control and drive system, the designers assumed a daily start-up of the solar field from the stow position (-30°) to

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a tracking position (10°), then 11 hours of tracking, followed by an end-of-day stow from 180° back to -30°. The full load amp rating of the motor was used for these calculations.

Motor Tracking Values	SkyTrakker™	NSO AdLoC
Voltage (V)	40	110
Current (Amps) (Instantaneous)	< 0.1	4.0
Current (Amps) (Running)	2.4	5.4
Frequency (Hz)	10	60
Duty Cycle (%)	8	5
Single SCA Daily Power Consumption (kWh/day)		
During Start-up	0.034	0.022
During Tracking	0.146	0.568
During End-of-day	0.178	0.115
Totals	0.358 (51-52% of NSO)	0.705

Table 5 - SCA Daily Power Consumption (Worst Case)

For comparison purposes, the observed voltage, current and tracking data from NSO were used (where the primary author designed the tracking controls hardware and software).

The two systems provide similar tracking performance but differ in the drive system approach. The SkyTrakker™ control and drive system uses a variable speed motor and dynamic frequency control to slowly position the SCA during tracking. The NSO system uses two conventional single phase capacitive start motors, a high speed motor and a slow speed motor. The slow speed motor is used during tracking. Tracking is accomplished by sending a pulse to the motor at short intervals several times each minute.

The comparison data is shown in Table 5.

INSTALLATION

One SCA was installed in the test field and after structural and mechanical tests were complete the electronic controls and modular hydraulic drive unit were installed on the center pylon (Figure 1 and Figure 2) of the SCA. Four SkyTrough™ units were axially connected directly to each side of the actuator unit to build the entire SCA (Figure 7).

The VFD motor controller was used in manual mode to test the drive system, hydraulics, and SCA positioning in both the east and west directions. Communications with the SECS was tested using both the RS-485 wired communications feature and the RF option.

Figure 7 - SCA Installed and Tracking the Sun

INSTRUMENTATION

Data collection and data logging instrumentation was developed during the initial design and this instrumentation was used to test the functional operation of the electronics controls and to collect the tracking and operational data.

Data was collected using both the wired RS-485 and wireless RF hardware interfaces present on the SECS control board. The following data was recorded and analyzed:

1) Real-time status of the SECS and SCA (operating mode, motor status, alarm data, SCA position)
2) Detailed motor data (real-time motor voltage, current, frequency, load percentage and power factor)
3) SECS and motor fault data

DATA

Data is collected from the SECS control unit by the SFC on a real-time basis. The SFC collects some data frequently (such as control unit status) and other data is collected less often (such as run-time motor data, fault data and diagnostic data). The control unit status data provides the most critical data needed for control and monitoring of the solar field. Motor data includes run-time parameters such as operating voltage, current, frequency, motor load percentage, and power factor. Commands are sent to the SECS by the SFC when initiated by the SFC operator.

During initial system checkout and calibration, the VFD motor controller was used in manual mode to test the drive system and SCA positioning in both the east and west directions. Once the basic movement and control functionality was tested, the SECS controls were placed in automatic mode and the software controlled the SCA.

During functional testing of the SCA drive and control electronics the system was placed in ‘tracking’ mode. The SECS computed the calculated sun position, moved the SCA using the VFD motor controller and read the SCA position using the position sensor. Tracking data was recorded and is shown in Figure 8.

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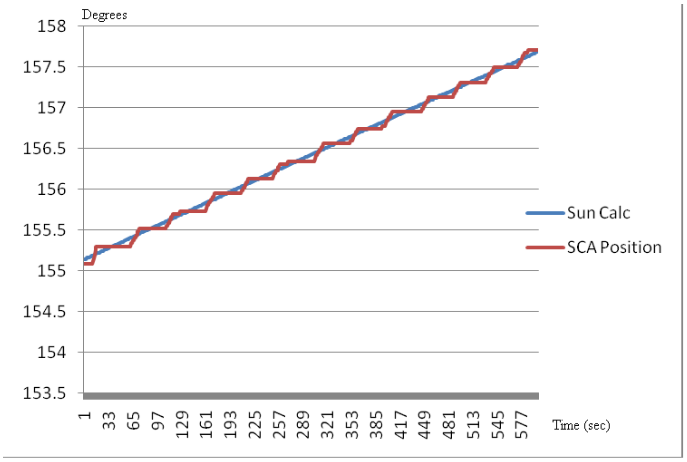

Figure 8 - SCA Tracking Data, Sun Position and SCA Position

The SECS software drives the motor at different frequencies depending on whether the SCA is being positioned to a specific angle or is actively tracking. During tracking, the motor speed is dynamically changed to provide the movement required to accurately track the sun.

The sun position is determined by the calculation algorithm and the SECS approximates the sun position through a series of short motor movements based on the dead-band value (to create the step-wise movement shown in Figure 8).

Testing of tracking accuracy occurred when wind speeds were below 25 mph. At wind speeds of 25 mph or greater the SCA was moved to the "stow" position and the SCA position was monitored for a correctly retained position. Tracking data was collected when ambient temperatures were in the 10°F to 85°F range (see Figure 12 and Figure 13 for 2009 wind and temperature data). Additional testing will be performed during the summer and fall of 2009 to obtain higher temperature data and results.

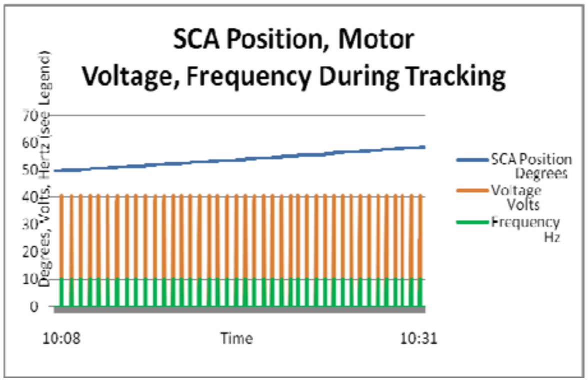

Figure 9 - SCA Tracking with Motor Voltage and Frequency Shown

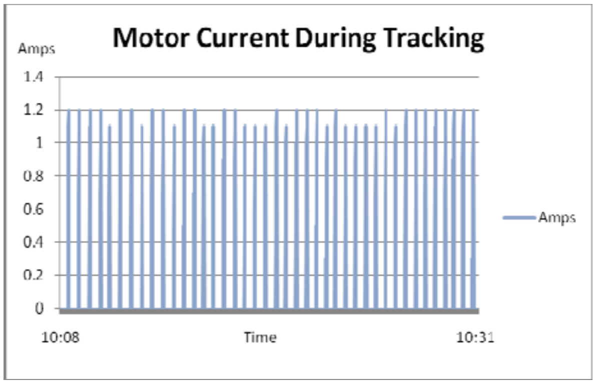

Figure 10 - SCA Tracking with Motor Amperage Shown

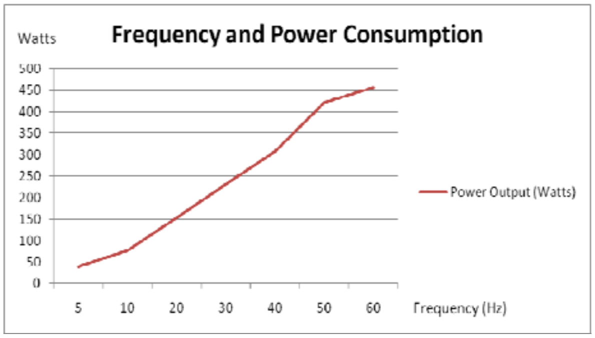

Figure 11 - Frequency and Power Consumption

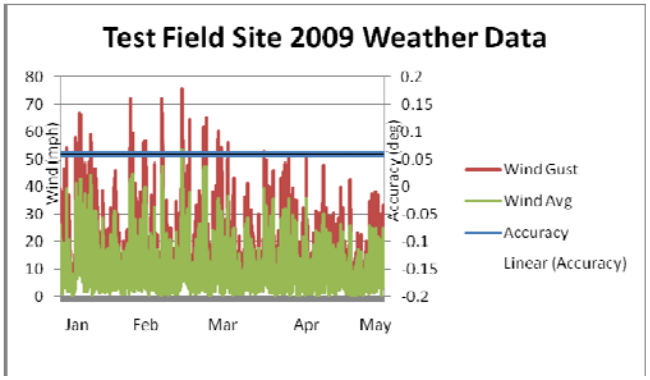

Figure 12 - Test Site Wind Speed and Accuracy

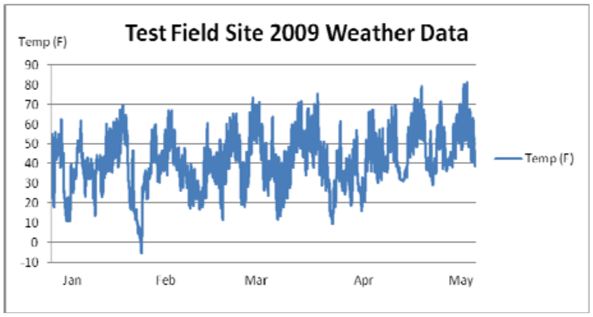

Figure 13 - Test Site Temperatures

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RF testing of a single SECS control board has been underway for several months. Testing multiple SECS controllers with the SFC and an RF connection is beginning. These tests will determine the effective transmission range between the single field base antenna and the multiple controllers and their individual RF antennas. Data testing will also be performed to determine the maximum data rate and the practical data rate that can be used in the field. This testing will also provide results on data accuracy (the percentage of commands successfully sent and received verses the data that is corrupt or missing). External interference will be introduced to test the robustness of the RF hardware and the built-in RF communication protocol (between the RF base station and the RF transceiver at the SECS unit).

DATA ANALYSIS

The SECS controls and drive system were operated over several months between August 2008 and May 2009 in both tracking and follow modes. The SCA was also moved to various positions between maintenance stow (about 60 degrees below the east horizon) and the end of sun tracking (about 180 degrees or due west) to verify positioning accuracy. See Figure 15.

Various tracking frequencies were tested while in the tracking and follow modes of operation. Frequencies below 5 Hz did not always provide sufficient SCA movement in different wind conditions. Frequencies higher than 10 Hz provided sufficient SCA movement in all wind conditions but often caused the SCA to overshoot the desired tracking or position angle. From this testing, the optimal range of tracking frequencies was 5 Hz to 10 Hz. The motor voltage, current, frequency and start and stop times also determine the average duty cycle during tracking. The relationship between frequency and duty cycle times are shown in Figure 14.

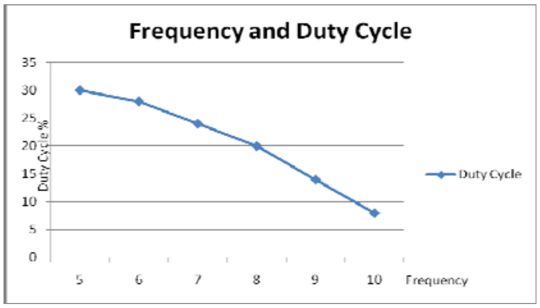

Figure 14 - Frequency and Duty Cycle

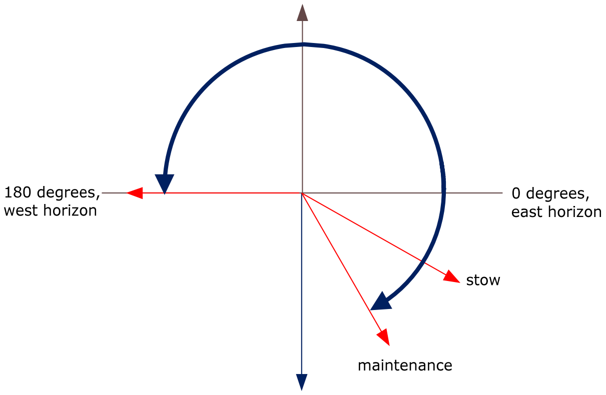

Figure 15 - SCA Range of Motion Travel

Tracking accuracy results were determined from the recorded data showing the differences between the SCA position and the calculated sun angle. Difference values were recorded and compared to product accuracy specifications. The motor on and off times were also calculated from the recorded data taken during tracking. Figure 9 and Figure 10 show the graphed results of the recorded motor voltage, current and frequency data. From this data, an average duty cycle was calculated. The kWh per day was calculated using the motor duty cycle, motor voltage, motor current and hours of use data. For this kWh calculation, it was assumed that one startup and one end-of-day operation were performed per day and that the tracking operation was performed without other positioning operations.

The tracking results were entered into the formula shown in Table 1 and a system error value was determined. Using the system error value in [1] and from Table 2, the output energy efficiency was determined to be 99.75%. This value meets the product design criteria.

The SCA was moved and positioned in various wind and temperature conditions to test the robustness of the system. The system was tested during fall and winter conditions when the temperature was between -10°F and 85°F. The SCA was moved from extreme west orientation (180°) to the stow position in various wind conditions from 0 to 40 mph. The starting SCA position was marked for reference, the inclinometer was set to a known value and then the SCA was moved east and west to the end-points (Figure 15). The SCA was moved back to its marked reference position and the inclinometer was checked for agreement with the starting position. Tracking accuracy testing was performed and tracking data was collected when temperatures were above 10°F and the wind speeds were below 25 mph. Below 10°F only movement and positioning operations were performed.

With the SCA at the stow position (-30°), the SCA position was monitored in high wind conditions to determine if the SCA retained its original position after the high wind event. The correctly retained position was determined from monitoring the position data and from moving the SCA to a known reference

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position and comparing the reference position to the inclinometer's stated position.

The tracking accuracy results verified the software motor algorithms, the use of the VFD motor controller and the accuracy and responsiveness of the entire system.

CONCLUSIONS

The SECS components were easily mounted and wired into the NEMA enclosure panel. Sensors and motor wiring were connected from the NEMA enclosure to the junction box located at the motor and pump. All components connected easily and performed as expected at initial power-up. The newly designed system with the separate SECS control board and VFD controller performed as expected. The SCA accurately tracked the sun in a variety of conditions without difficulty. The tracking accuracy in the tested temperature range (10 to 85°F) and 0 to 24 mph wind conditions met the design criteria of 0.06°. Additional temperature and wind testing will be performed during the summer and fall of 2009.

NOMENCLATURE

AdLoC	Advanced Locating Controller
CSP	Concentrating Solar Power
HTF	Heat Transfer Fluid
LOC	Locating Controller
mph	Miles per hour
mrad	Milliradian (approx 0.057°)
NEMA 4	Weatherproof Enclosure
NSO	Nevada Solar One
O&M	Operational and Maintenance
RF	Radio Frequency
RS-485	Serial communication interface suitable for long distance data transfer
SCA	Solar Collector Assembly
SECS	SkyTrakker™ Embedded Control System
SEGS	Solar Energy Generating Systems
SEGS I SEGS II	An operating solar facility system at Daggett, California.
SFC	Solar Field Computer
VFD	Variable Frequency Drive

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