PV POWER SYSTEM COMPONENT CHARACTERIZATION AND SYSTEM SIMULATION

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ABSTRACT

A dynamic system simulation approach to photovoltaic power system (PVPS) sizing is presented. A compact statistical solar irradiance model provides the energy input to the system. Performance characterization studies on PV modules and storage batteries were undertaken to ensure their reliable operation and to provide accurate model for simulation. Hourly simulation over a year provides information on battery cycles and performance; loss of load frequency (LOLF) and loss of load hours (LOLH); which are relevant parameters to describe system reliability. Using a two-dimensional inverse interpolation, a family of iso-LOLH curves are generated from the simulation results. Optimum cost is achieved when the marginal rate of substitution equals the array-storage price ratio. These results coupled with economic or financial analyses predict that a hybrid system may be more economical than either a PV- or conventional generator-only system.

INTRODUCTION

Every decision made during the design of a PVPS affects the cost. If the PVPS is oversized, the initial cost is increased unnecessarily. If less efficient system components are specified, maintenance and replacement costs are increased. Life-cycle cost estimates can easily double with inappropriate choices made during system design. An inexact estimate of irradiation as well as consumption pattern and a faulty knowledge of the performance of system components affects system availability and cast doubts on results from any sophisticated approach to system sizing.

It is therefore profitable to have a reliable estimate of the local meteorological conditions and be able to characterize and predict the performance of system components subjected to the installed conditions. Accurate component testing and characterization ensures reliable operation and provides models to system simulation. Simulation results are as good as its input and models used.

It is not acceptable just to have a good simulation but the accuracy of the model is twice as important.

1. Irradiation Model

Based on detailed studies of irradiance data for Thailand¹ a compact computer simulation code to generate daily total irradiation and hourly irradiance is developed. The model is expected to be applicable over the entire Southeast Asia between latitudes of 25°N and 25°S. Provision is made for the separation of the solar irradiance into their direct and diffuse components and for the generation of random sequences of irradiance values with appropriate statistics (Figure 1).

The model constitutes the reduction of information on irradiation in Thailand to a compact form that reproduces the mean values and the random fluctuations of hourly irradiance throughout the year.

Fig. 1 Statistical Simulation of Solar Irradiation on a Tilted Surface 14° Due South in AIT

Fig. 2 Functional Block Diagram of the AIT PV Test-Bed System

2. PV Module Characterization

A computerized system for the characterization and performance testing of PV modules under natural sunlight and ambient conditions was designed and installed in AIT.² The system comprises two phases: first, the performance testing of PV modules through computer-controlled electronic hardware (monitoring phase); second, softwares were coded for data processing, file management and data analyses (analysis phase) (Figure 2).

The monitoring phase consists of the PV module test-bed and software-controlled instrumentations which automate daily monitoring of module performance (Figure 3). The PV module test-bed is a two-axis tracking structure with power input terminals and temperature sensors to accommodate 16 modules. Standard instruments to measure tilted-global irradiance, diffuse irradiance, wind velocity and shaded ambient temperature are installed and calibrated regularly. Multiplexer and relays switch four modules for simultaneous monitoring. An N-channel 75 watt dc MOSFET device serves as the electronic variable load to each module being monitored. A ramp voltage signal drives the MOSFET to generate the I-V characteristic curve of the module.

Softwares are coded to control monitoring, measurement and data storage sequences. Provisions are made for time-interval and fixed-irradiance monitoring. Logics within the code check to ensure constant irradiance during the generation of an I-V curve.

Outdoor performance testing of PV modules requires a compilation of vast amount of data in order that module characterization can be reliable and statistically acceptable. The analysis phase consists mainly of a code named PVMOD. PVMOD version 2 handles routine tasks such as data processing, file handling and maintenance, graphical and statistical data presentation and also provides numerical and analytical characterization of PV modules in terms of its internal physical parameters such as the shunt and series resistance, the reverse saturation current, the photo-generated current and the module ideality factor (Figure 4).

3. Storage Batteries

An electronic constant-current charge and discharge controller for storage battery is used to monitor the performance of SLI batteries under room temperature³ (Figure 5). Charge and discharge characteristic curves are investigated at various rates. Problems affecting self-discharge and vertical stratification of the electrolyte were simulated and measured. Charge and discharge cycle of a battery as part of a PVPS was simulated and its performance monitored to ensure proper operation when installed and to provide reliable information for system sizing and system reliability prediction.

4. Dynamic Sizing of a PVPS

The hourly energy balance between the power system and energy consumption is controlled simultaneously by the meteorological data, the array characteristics, the charge-discharge characteristics and efficiency of the storage battery and the shape of the load profile⁴ (Figure 6).

The solar irradiance model of section 2.0¹ has been coded into an interactive user-friendly software.⁵ This code is used to generate the meteorological input data. The ambient temperature is assumed to have a sinusoidal variation over the day throughout the year. Daily averages are also assumed to vary sinusoidally over a year.

The PVPS voltage floats with the battery voltage and the available output current from the array is a function of the incident irradiance and the cell temperature. The cell temperature is modelled by empirical formulae based on simplified theoretical considerations. The effect of current generation on cell temperature is also considered.

Fig. 3 AIT PV Module Test-Bed Instrumentation Schematic Diagram

Fig. 4 Menu Tree of PV Mod 2.0

Fig. 5 Single Line Diagram of Constant Current Charge-Discharge Battery Test-bed

Fig. 6 Block Diagram of Simulation Software to Compute LOLH

The array model is defined by three points from the I-V Characteristic curve⁶: the open-circuit voltage V_{oc} , the short-circuit current I_{sc} , and the maximum power point V_{mp} and I_{mp} . Then the array current I is expressed as a function of the array voltage V by,

$$I = I_{sc} \{ 1 - C_1 [\text{Exp}(V/(C_2 * V_{oc})) - 1] \}$$

$$C_1 = (1 - I_{mp}/I_{sc}) \text{Exp}[-V_{mp}/(C_2 * V_{oc})]$$

$$C_2 = (V_{mp}/V_{oc} - 1) / \text{Ln}(1 - I_{mp}/I_{sc})$$

The state of charge $S(t+dt)$ of a storage battery can be calculated from the previous state of charge $S(t)$ together with the other battery parameters according to the relation⁷,

$$S(t+dt) = S(t) (1 - D_s * dt) + K_1 (V * I_b - K_2 * I_b^2) dt$$

where D_s is the rate of self-discharge in Wh/hr; K_1 is the battery charge/discharge efficiency; K_2 is the battery charge/discharge apparent resistance in ohms; V is the system voltage and I_b the battery current.

The battery charge/discharge voltage and resistance are updated every dt according to the following relations,

$$R_2 = S(t)/S_{\max}$$

$$V_{\text{ch}} = 2 + 0.148 * R_2$$

$$V_{\text{dch}} = 1.926 + 0.124 * R_2$$

$$R_{\text{ch}} = (0.758 + 0.1309 / (1.06 - R_2)) / S_{\max}$$

$$R_{\text{dch}} = (0.19 + 0.1037 / (R_2 - 0.14)) / S_{\max}$$

where subscript 'ch' and 'dch' denotes charge and discharge respectively; $S_{\max}$ is the battery maximum state of charge.

The inverter is modelled by an efficiency value in the range of 0.85 to 0.95. A charge/discharge controller directs excess energy from the array to the storage battery; dissipating this energy when the battery is fully charged. The load is cut-off from the PVPS when the array and the storage battery cannot supply enough energy to the load. This event is recorded as an LOLH.

DISCUSSION

The results of the hourly simulation were used to generate Figure 7. Figure 7 represents a family of iso-LOLH curves. Four curves representing array to battery price ratio cut through the iso-LOLH curves at intersections identifying points of marginal rate of substitution at a prescribed LOLH. These are points of optimum economic combination of array and battery capacities at a specific system availability. Along the same iso-LOLH curves, towards the left of the knee of the curve, the battery experiences lower charge/discharge cycle, lower loss-of-load frequency (LOLF) with longer energy-loss duration (Figure 8). Towards the right of the knee of the curve, the battery will experience higher charge/discharge cycle, higher LOLF with shorter energy-loss duration (Figure 9). Choices of types of battery will differ along the same iso-LOLH curve according to the cycle. The differences in loss-of-load duration constitute an essential consideration in designing PV/diesel hybrid system. Diesel systems

Fig. 7 Iso-LOLH Curves at constant load of 2 kWh/day

- Optimum design points of four price ratio at different system reliability.
- Diminishing marginal rate of reliability improvement.

Fig. 8 Array and battery combination towards the left of the knee of the Iso-LOLH curve exhibit yearly charging cycle. Batteries of low self-discharge, deep DOD is required for this particular case.

suffer a significant efficiency degradation for about 30 minutes following start-up, indicating that they should not be cycled on and off frequently⁸.

Diminishing marginal rate of improving LOLH is also evident in the figure. Improving the last few percent of availability requires an oversized PV system. Particularly beyond 1 kWh/day, the cost of oversizing a PV system to improve availability can become appreciable, making it uneconomical to use PV-only system. It is interesting to investigate the extent to which a diesel system can improve system availability and cut system cost due to oversizing of PV. If properly designed, a hybrid system can overcome the major liabilities of each system.

When the conventional generator operates as a back-up subsystem in a hybrid system, it replaces the oversized, poorly utilized segments of the PV-only system. Using the simulation model, optimum combination of array and battery for various LOLH (or availability) is computed. A diesel system is then designed to cover a certain amount of the LOLH not supplied by PV. Assuming 1987 value and costs, a hybrid system was designed to service 2 kWh load per day. The installed cost for PV system is taken as US\$12/W_p with 10 years' lifetime while the battery at US\$120/kWh with 5 years' lifetime. The diesel system consists of a 4 kW, 7,000 hours operation life costing US\$400 with efficiency at 50% load factor of 20%. Diesel caloric content is 10 kWh/liter at US\$0.75/liter. Economic parameters of 10% discount rate, 4% energy escalation rate and 4% inflation rate were assumed for this example. The results of these computations are shown in Figure 10. It shows that the lowest overall system cost occurs when the hybrid system operates at 3.4% (300 hours) diesel and 96.6% (8,460 hours) PV.

When the PV system operates as a back-up, it reduces the fuel use and resultant operation and maintenance costs of the diesel generator. From a sandia study⁸, techno-economic considerations fixed the limits of minimum PV share at 30% and minimum diesel share at 10% of the diesel recurrent costs (fuel and the O & M costs). PV back-up should be able to offset the diesel recurrent costs and its own cost, reducing the overall cost to an optimum. Using the previous example, the PV back-up cuts 62.3% (US\$939) of the recurrent costs of a diesel-only system. However, additional US\$7,527 was spent to install the PV back-up in order to save US\$939 in diesel recurrent costs. According to the specified economic parameters, costs and level of load consumption, it will not be economically justifiable to introduce PV as back-up to the existing diesel system; it is economical, however, to use diesel as back-up to improve availability and cost to the existing PV system.

Fig. 9 Array and battery combination towards the right of the knee of the Iso-LOLH curve exhibit daily charging cycle. It is evident that the battery is oversized to cover several bad days during the year.

Fig. 10 PV/diesel hybrid cost variation with respect to diesel generator running time. Minimum total cost at 300 hour diesel running time.

CONCLUSION

Starting from component testing and characterization, dynamic system sizing through hourly system simulation over a year, optimum size of array and battery for a specific LOLH is computed. Using these results with economic analyses predicts the possibility and the economic advantage of a hybrid system. User's requirements and criteria for adopting a hybrid system is not the same depending on their existing power system and load consumption. The diesel share in a hybrid system may increase when they are asked to charge batteries, to offset degradation of efficiency during starting, and made to run periodically to keep them in operating condition, about four hours every two weeks (or 104 hours per year); which were not considered in the simulation. With higher level of consumption, running PV system to offset diesel recurrent costs may be economically feasible.

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