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TPV Network Sensitivity: A Simulation Study

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Abstract. A viable thermophotovoltaic power conversion system requires an electrically connected network of diodes that is designed to be fault tolerant for a prescribed power rating and generator life. This paper describes simulation studies investigating the sensitivity of various series/parallel network configurations to diode variability. The results show the effect of diode mismatch and reverse breakdown behavior on network performance.

INTRODUCTION

Although individual thermophotovoltaic (TPV) diodes have been extensively studied (Charache et al, 1999, Wang et al 1999), the behavior of electrically connected TPV diode networks (Reiche et al, 1994, Pinkerton, 2000, Gow and Manning, 1999, Ortega et al, 2001, and Vaz et al, 1994) is not adequately understood to enable the construction of fault tolerant, large-scale arrays. The design of solar cell arrays is described in Ranschenbach, H.S. 1980 and Lasnier, F. 1990. However, differences exist between the operating environments and diode characteristics for TPV and solar arrays that warrant independent quantification of TPV network performance.

A viable TPV power conversion system requires a diode network that will be fault tolerant for a prescribed power rating and generator life. In particular, the electrical configuration of the network should be designed to maximize performance output of a given diode set and to minimize the impact of operating penalties that may be incurred due to non-uniform illumination, diode variability, and diode or interconnection failure.

To address these design considerations, a relatively large number of factors must be investigated for a variety of network sizes and configurations. Simulation (Banks, J. 1984) provides an economical means for conducting a wide variety of engineering studies without constructing and testing physical TPV devices. This technique has been employed to evaluate the effect of diode variability on TPV network performance using a software simulator that was developed to model the electrical behavior of TPV diodes and networks.

This paper presents the results of simulation studies and associated hardware test results that quantify the effect of diode variability. These results are used to guide the electrical design and sizing for fault tolerant TPV networks. In addition, the use of simulation is illustrated for developing network design criteria.

METHODOLOGY

The efficiency of simulation techniques becomes especially manifest when evaluating the many factors that influence TPV network performance. Such an approach is particularly useful when hardware is limited. Additionally, conducting sensitivity studies prior to hardware assembly has yielded valuable insights into the selection and placement of diodes. Further, the results of the studies predict the actual performance of the network. The combination of modeling and hardware testing is considered advantageous as it provides a comparison of empirical and theoretical results.

The TPV network design process, as shown in Figure 1, consists of

- choosing the network size, series/parallel connectivity, and interconnection resistances;
- selecting diodes from the inventory and placing them into network locations;
- conducting an electrical analysis to measure network performance.

Figure 1 - TPV Network Design Process

Diode placement and selection, network size, and series/parallel configuration are explicitly chosen when designing a TPV network. The values for these parameters should be selected to mitigate the effects of non-uniform illumination and diode or interconnect failure. The TPV Simulation System allows networks to be designed and evaluated under a variety of illumination and failure conditions.

The simulation system provides a fully integrated, simulate-analyze-evaluate suite of software. The major components of the simulation system are

- diode simulator to generate electrical characteristics of diodes;
- network assembly tool for specifying network characteristics and selecting and placing diodes;
- electrical circuit analysis software;
- relational database for storing diode and network parameters.

Each of these software components and their associated modeling assumptions are further described below.

Diode Simulator

In the simulation system, the current (I) and voltage (V) characteristics of individual diodes are modeled using a modified ideal diode equation (Sze, 1969):

$$I = I_s \left[e^{\frac{q(V - IR_s)}{nkT}} - 1 - e^{\frac{q(V - IR_s - V_{br})}{bkT}} \right] - I_L + \frac{V - IR_s}{R_{SH}}$$

where, I_s is the saturation or dark current, I_L is the light generated current, n is the ideality factor, k is Boltzmann's constant, T is the diode temperature, R_s is the series resistance, R_{SH} is the shunt resistance, V_{br} is the breakdown voltage and b is the breakdown parameter.

Through a graphical user interface (GUI), each of the individual ideal diode parameters may be specified either deterministically or stochastically; in addition, a variety of statistical distributions are available. The GUI also allows the user to specify the number of diodes to be simulated and additional diode properties such as active area and number of junctions. The simulated diode properties, along with appropriate identifying information, are recorded in the database.

Network Assembly Tool

Electrical network performance is one component of a direct energy conversion system. For the purposes of the studies described here, network performance measured by network efficiency, $\eta_{network}$, is considered. Network efficiency is defined as,

$$\eta_{network} = \frac{\text{Maximum Power of Network}}{\sum \text{Maximum Power of Individual Diodes}}$$

where maximum power is the maximum electrical power point on a current-voltage curve. Network efficiency describes the (DC - nontransient) power losses incurred through a collection of interconnected diodes. The power losses can be split into two groups, those independent or those dependent on the diode characteristics. Power losses independent of the diodes are due to non-uniform illumination, interconnect I^2R losses or failed interconnections. Diode dependent power losses are due to electrical property mismatches between diodes which lead to electrical imbalances. These losses occur for mismatched cells in either parallel or series interconnected arrays. This is due to the fact that series connected strings have a constant current and parallel connected strings have a constant voltage (Lasnier, F. 1990, Rauschenbach, H.S. 1980).

The network assembly software component allows the user to select

- network size and configuration;
- diodes from the database to be used in the assembly;
- diode placement method.

The network assembly tool links to the database, allowing the user to select diodes for evaluation in a network. The user may place diodes in network locations manually through the GUI or select from a number of automatic placement options, including heuristic, random or systematic.

Electrical Circuit Analysis Software

The electrical circuit analysis software, Saber® (Synopsys, Inc.), is used to

- specify network size and configuration parameters;
- perform DC analysis of the network.

Network size and configuration are specified through a graphical user interface. For the results presented here, the following network interconnection characteristics were chosen (Figure 2):

- series resistance (R_s) between diodes of 0.9 m Ω ;
- shunt resistance (R_{sh}) between diodes of 0.1 m Ω .

The output of the DC analysis includes the network I-V curve and key electrical measures such as short-circuit current, open circuit voltage, and maximum power. Output files are produced to allow further analysis of simulation studies.

Relational Database

The database contains the properties of both "virtual" diodes created by the simulation system and measured characteristics of the diodes in physical inventory. Manufacturing, module fabrication, and testing information is also contained in the database. The relational design (Ramakrishnan and Gehrke, 2000) allows the database to be easily expanded to accommodate new information that must be captured as the TPV technology is developed.

SENSITIVITY STUDIES AND RESULTS

Two initial studies are described below that address the sensitivity of diode variability to network performance for small-scale networks. The first study investigates the fundamental relationship between network efficiency and the current mismatch between series-connected diodes. The second study investigates diode selection and placement in a network of two parallel strings of four series-connected diodes for a physical construction. Figure 2 shows the electrical connections, including shunt and series resistances.

Figure 2 - Electrical Connections for Eight-Diode Network

The TPV simulation system was used for "virtual module assembly" to identify optimal diode configurations prior to assembly. The system aided in the selection of diodes and was used to evaluate the performance of several arrangements of diodes prior to physical assembly.

Effect of Diode Mismatch in Series Connected Strings

In the construction of highly efficient, small-scale TPV networks, diode selection and placement was investigated prior to physical assembly and test. This evaluation yielded both a fundamental understanding of the sensitivity of network performance to diode mismatch, and guidelines for selecting and placing diodes in an array. Initially, networks were constructed to evaluate network performance and assembly techniques. The networks were configured as two parallel-connected strings with each string composed of four series-connected diodes.

Current matching between series-connected diodes is believed to be a major factor contributing to a high performing array of series-connected devices. The variability in diode electrical characteristics is determined by the diode manufacturing process. A simulation study was performed to quantify the effects of diode mismatch. In this study, the electrical characteristics of 2000 diodes were simulated based on the prototypical values given in Table 1.

Diode Parameter	Units	Range
Saturation Current Density (J_s)	A/cm ²	[1×10^{-5} , 5×10^{-5}]
Series Resistance (R_s)	m Ω	[0.0, 12.0]
Ideality Factor (n)	-	[1.0, 1.1]
Shunt Resistance (R_{sh})	Ω	[1.0, 13.0]
Light Generated Current Density (J_L)	A/cm ²	[2.0, 2.8]
Breakdown Voltage (V_b)	V	[0.1, 0.9]
Breakdown Parameter (b)	-	[2.0, 6.0]
Active area	cm ²	0.431

Table 1 - Diode Characteristics

Five hundred networks of four series-connected diodes each were simulated. Networks containing strings of four series-connected diodes were chosen for laboratory testing. Diodes were randomly selected for placement in a string. A DC analysis was performed for each network; diode mismatch was measured as the maximum pairwise difference in the short circuit currents (I_{sc}) of the individual diodes in the network.

Figure 3 shows the results for 500 simulated 1x4 networks. Network efficiency decreases and becomes more variable as diode current mismatch increases.

Figure 3 – Network Efficiency vs. Current Mismatch for Simulated 4 Series-Connected Diode Networks

The quantification of network efficiency and diode mismatch provides a useful means to develop diode matching guidelines for network assembly. These results coupled with experimental goals of the network assembly suggested a threshold of 0.05 amps in I_{sc} mismatch. The eight diodes selected from the inventory had short circuit currents within 0.05 amps. This provided a reasonable trade off between diode selection and network losses. In other circumstances, a different threshold may be appropriate.

Diode Selection and Placement in an Eight Diode Network

The primary goal in constructing a small-scale network was to demonstrate that electrically connecting high performing diodes would result in a highly efficient network. Maximizing TPV module performance requires optimizing the selection and placement of TPV diodes within a network. As the number of diodes increases, the selection and placement of diodes becomes more complicated. Using simulation allows “virtual network assembly” to identify optimal diode configurations for network fabrication.

Simulation studies were conducted prior to assembling an eight diode network to evaluate diode selection and placement. Forty-seven diodes from the available inventory were identified as candidates for network assembly. These candidates had high levels of electrical performance and were within the dimensional tolerances required by the assembly technique. From this group, eight diodes were to be chosen for fabrication into a network.

The maximum pairwise I_{sc} difference between series connected diodes was applied as the primary diode matching criterion. A secondary matching criterion was applied which balances voltage across the parallel connections between the two strings. The application of these two matching criteria resulted in the selection of the final group of eight diodes. The system was used to evaluate the sensitivity of network performance to the placement of the eight diodes prior to physical assembly.

Figure 4 shows the power producing portion of the I-V curves for the simulation and as-built test results. Table 2 illustrates the close agreement obtained between the modeled and as-built results at key electrical parameters. These results provide confidence that the TPV diode networks are performing as expected compared to modeled results. This suggests that the simulation methodology can be used to investigate the fundamental behavior of TPV networks and reduce the amount of hardware testing required and its associated costs. This will be particularly beneficial as large-scale TPV systems are designed.

	Open Circuit Voltage (volts)	Short Circuit Current (amps)	Fill Factor	Maximum Power (watts)
Simulation	1.20	2.31	70.1	1.95
As-built	1.24	2.38	69.9	2.07

Table 2 - Summary of simulated and laboratory results

Figure 4 - Comparison of simulation and test results

Following the hardware test, a simulation study was conducted to assess the impact of the diode matching criteria on network efficiency. In this study, 200 simulated modules were evaluated by randomly selecting and placing eight diodes from the original pool of 47 candidate diodes. Figure 5 shows the distribution of network efficiencies obtained (normalized to the efficiency of the as-built configuration). The observed network efficiencies showed a 3% range. The as-built configuration, which used diode matching criteria, ranked at the 95th percentile of the distribution. This study will be used to improve the diode matching heuristics by evaluating the electrical characteristics of the configurations in the nine networks whose network efficiencies exceeded that of the as-built configuration. In addition, the configurations of the networks with lowest efficiencies will be evaluated to better understand arrangements that should be avoided.

Figure 5 - Distribution of Network Efficiency for 200 Networks with Randomly Selected Diodes

CONCLUSIONS

Simulation has proven to be a valuable tool in advancing the development of TPV energy conversion systems. Custom-designed simulation software has enabled computational engineering studies that support the fabrication and testing of TPV diode networks. The quantification of the sensitivities of network performance to various diode and system variables guides the design and assembly of TPV networks. In particular, investigation of the effects of diode variability on network efficiency has contributed to high performing small-scale networks through the selection of diode matching tolerances.

The combination of network modeling and laboratory testing provides an efficient means to evaluate the effects of the many factors which govern network performance. Additional simulation studies must be performed to investigate the sensitivity of network performance to non-uniform illumination and diode failure. Quantification of the influence of these operational factors is needed to design TPV networks that will perform reliably at the required power rating over system design life.

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