Performance of Utility Interconnected Photovoltaic Inverters Operating Beyond Typical Modes of Operation

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Abstract – The high penetration of utility interconnected photovoltaic (PV) inverters can affect the utility at the point of common coupling. Today's utility interconnection standards are evolving to allow voltage and frequency support, and voltage and frequency ride-through capability. With multi-MW-sized PV plants and multitudes of small commercial and residential systems coming online each year, the interconnection standards are allowing distributed energy resource equipment to provide reactive power to supplement existing voltage-regulating devices and ride-through voltage and frequency anomalies. These new interconnection requirements, coupled with the high dc-to-ac ratios, are becoming more common with declining PV module costs and are changing the modes of operation for utility-interconnected PV systems. This report investigates the effects these modes of operation have on the inverter performance, array utilization, and power quality while focusing on conversion efficiency.

Index Terms **-- distributed, frequency, efficiency, photovoltaic, voltage support, frequency support.**

I. INTRODUCTION

The installation rate of photovoltaic (PV) utility interconnected systems continues to break records in the US with over 1800 MW [1] of installed PV in FY11 and over 1900 MW in the first 3 quarters of FY12; the total installation for FY12 is expected to exceed 3000 MW of utility interconnected PV systems. The amount of PV distributed energy resource (DER) systems now represents a significant part of the renewable generation mix and performs well with other resources while only injecting real (watts) power, but as penetration continues to grow this may not be the case.

In California, the largest US PV renewable market, the FY12 installed systems have been split between the PV system classes: residential, commercial, and utility scale. Each PV system class has specific attributes including: economics, performance, controllability, and all classes could offer more capabilities for mitigating the adverse impact of intermittent DER on the reliability and stability of the utility grid. With the strong PV market growth projection, existing codes and standards need to be updated to address new DER system modes of operation.

The utility interconnection standards described in IEEE 1547 [2] are evolving to allow voltage and frequency support, voltage and frequency ride-through capability. The proposed changes to the interconnection standard have encouraged the development of new capabilities that fully exercise DER attributes.

A consortium of stakeholders is investigating the issues associated with integrating large numbers of PV systems into the distribution system while maintaining utility stability and reliability requirements. The impact of these systems is greatest for large commercial and utility-scale installations, and therefore the majority of the efforts to investigate variability-mitigating capabilities are targeting these systems. The specific types of variability mitigation being proposed and developed include the following:

- ramp control,
- power curtailment,
- volt/var,
- frequency/watt,
- power smoothing with storage,
- power shifting with storage,
- voltage ride through, and
- frequency ride through.

Implementing any of these modes of operation may cause the inverters to operate outside their design ranges or may affect the inverter's power conversion efficiency, array utilization capabilities, the power quality, and/or device reliability. The method of determining the inverters' performance is described in the California Energy Commission (CEC) Sandia Inverter Performance Protocol [3] document—a procedure detailing the input and output variable requirements for determining the inverters' efficiency and maximum power rating.

II. CEC INVERTER PERFORMANCE PROTOCOL

The method used to determine the power conversion efficiency of an inverter aims to vary two parameters: dc voltage and power level, while monitoring the ac output power of the device. The CEC performance protocol utilizes three dc voltage levels and six power levels to calculate the efficiency matrix. These two parameters directly affect the efficiency of the inverter; therefore these are the two parameters that are adjusted to evaluate the unit under test. A draft inverter performance protocol, released on October 2004, was adopted by the CEC for evaluating PV inverter performance and certification by a nationally recognized testing laboratory (NRTL). Compliance with the power conversion, tare loss, and maximum continuous power rating sections is required to be named in the California PV inverter eligibility list.

A. Efficiency

Section 5.5 of the protocol provides the minimum testing requirements to determine the CEC weighted efficiency rating for an inverter. This test is presently conducted under normal operating conditions, i.e., the inverter operating at unity power factor (displacement power factor). A distinction between displacement power factor and power factor must be noted because of the effects this can have on device under test (DUT) efficiency. The displacement power factor associates the phase angle relationship between the ac line voltage and inverter current and is describe in the following equation:

$$pf_{dis} = \cos(\varphi). \qquad (1)$$

The losses associated with a conductor depend on the resistance and the square of the current flowing through the conductor, i.e., $I^2 \cdot R$ losses.

Non-Unity Power Factor Efficiency Modeling Results

Sandia is collaborating with Northern Plains Power Technologies to model the anticipated losses associated with power electronic devices commanded to operate with a non-unity power factor.

- The losses in an inverter are expected to rise as power factor drops for several reasons, including:For a fixed real power (W) output level, as the inverter's power factor drops, the inverter must source more current. Thus, conduction (I^2R) losses and inverter switching losses ($\propto I$) will both increase.
- As the power factor drops, more current will flow through the inverters' antiparallel diodes instead of through the main switching devices. These diodes tend to have higher voltage drops and losses than the main switches.
- At lower power factors, the level of ripple on the DC bus is expected to rise. This ripple creates actual losses, because of the increased current flow through parasitic series resistances in DC filter elements, and it may also create a loss in terms of energy harvest as the DC operating voltage may not stay precisely on the maximum power point. This mechanism is not considered in this section because, as noted above, it is not a "loss" in the conventional sense.

Figure 1 shows the Matlab Simulink model used for the analysis associated to non-unity power factor operation and Figure 2 shows the controls diagram.

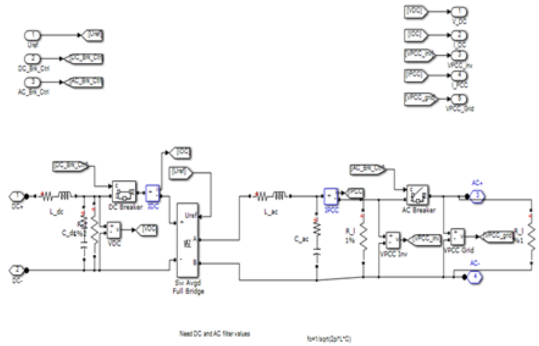

Figure 1. MatLab Simulink component model diagram

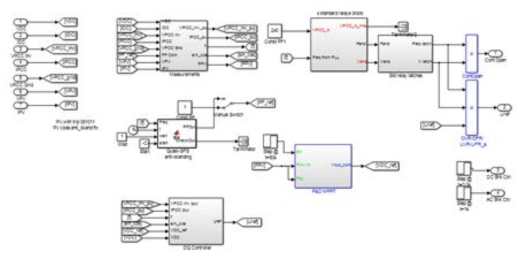

Figure 2. MatLab Simulink controls model diagram

Figure 3 shows the efficiencies of a 250 kW inverter while sinking and sourcing VArs, as predicted by the model. In these results, the PV array was replaced with a DC power supply, so that MPPT "losses" were not included. As expected, the efficiency decreases as the power factor drops. The reduction in efficiency is slightly greater when sinking VArs than when sourcing, because when the PV inverter is sourcing VArs it pushes its output terminal voltage up slightly, which requires the converter to source less current for the same power and reduces I^2R losses.

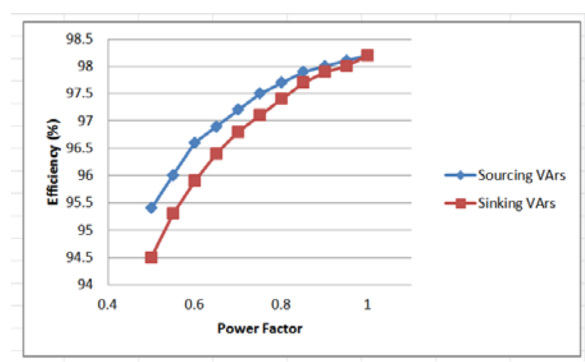

Figure 3. Efficiencies of a modeled 250 kW PV inverter as a function of power factor, while sinking or sourcing VArs.

Non-Unity Power Factor Efficiency Characterization using Laboratory Experiments

Sandia National Laboratories Distributed Energy Technologies Laboratories (DETL) has been collaborating with several industry partners to document the inverters conversion efficiency characteristics when the inverter is operating at non-unity power factor.

PV inverters have two distinct methods to operate in a non-unity power factor mode. One method to achieve non-unity power factor requires varying the ac line voltage and the *smart* inverter will act accordingly to compensate for the change in ac line voltage. Following a draft Sandia Interoperability Test Protocol [4], the voltages V1, V2, V3, V4 and the reactive power Q1, Q2, Q3, Q4 are set to follow the profile shown in Figure 4.

To assess the inverter's ability to provide reactive power during variations in line voltage, a programmable ac simulator is used to linearly ramp the voltage to the desired levels. Inverter performance is monitored with a data acquisition system (DAS) that captures steady-state inverter ac line voltage (s), current(s), apparent, real, and reactive powers, and power-quality parameters at a once-per-second rate. The DAS monitors the reactive power generated as the voltage varies beyond the V2–V3 hysteresis band. The increase in reactive power decreases the power factor and the non-unity power factor operation is achieved.

This mode of operation is especially desirable by utilities because reactive power can assist the utility in meeting voltage-regulation requirements. This function can be initiated autonomously by monitoring the voltage at the point of common coupling or from a voltage signal at a different location. The volt/var function can also be implemented via a communicated sequence of commands, which determine the level of var generation.

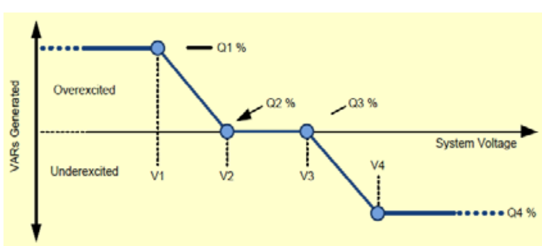

Figure 4. V1–V4: the adjustable voltage percentages and Q1–Q4: the adjustable reactive power percentages

Figure 5 shows the test results from the implementation of the volt/var advanced inverter function on an inverter. For this test, the irradiance was held constant to limit the inverter to 50% of is rated output power. As the voltage deviates from nominal and exceeds a programmed percentage of nominal, the inverter generates reactive power according to preprogrammed Q1–Q4 levels. Figure 5 shows the effect of the var generation has on the conversion efficiency.

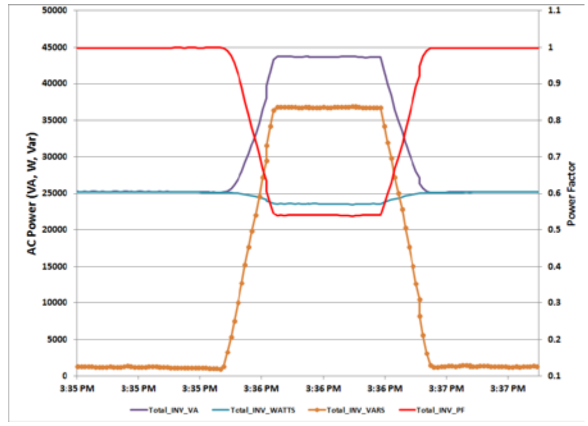

Figure 5. Inverter power delivery during implementation of volt/VAr advanced inverter function VV11

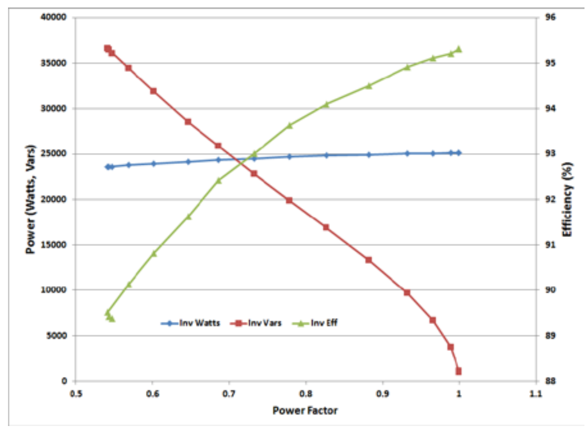

Figure 6. Inverter efficiency vs power factor during volt/var

The second method to achieve the non-unity power factor operation is described in the Sandia Interoperability Test Protocol section INV3—Adjust Power Factor. This describes the methods used to set the power factor and this function can be autonomously implemented or the desired power factor can be communicated using commands mapped into inverter control commands per IEC 61850-90-7 [6].

This method assumes reactive power priority and this prioritization has more significance as the DER operates close to rated power. Prioritization is needed to deliver the desired power factor, yet at low power levels, power factor is undefined. Prioritization of real power can have a limiting effect on the power factor if the inverter is operating near rated power. If power factor has priority, then real power production may be sacrificed to meet the desired power factor requirements. Figure 7 shows the results of an inverter operating at ~50% of rated power and the power factor is varied from unity to 0.5 and Figure 8 provides a graph showing the conversion efficiency and the significance of operating in non-unity power factor mode. Note how closely Figures 3 and 8 match.

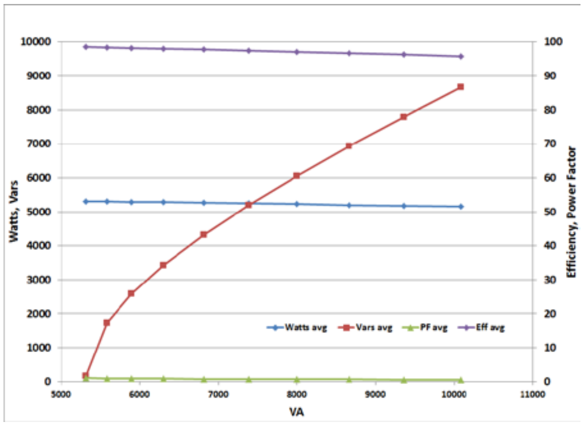

Figure 7. Inverter power delivered during commanded power factor

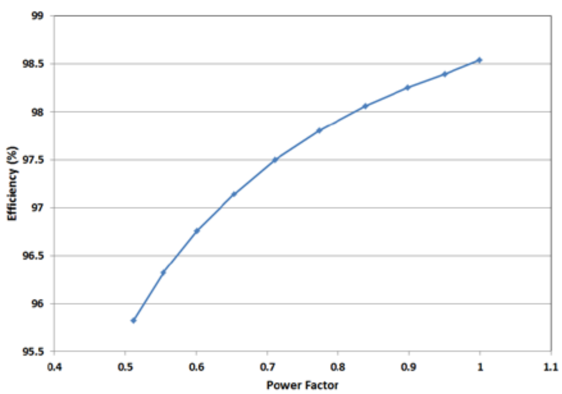

Figure 8. Inverter efficiency during commanded power factor operation

It has been established that generation can be more efficient at higher power factors; therefore, the data collected during CEC inverter efficiency testing should be enhanced to include non-unity power factor operations (pf<1). Table 1 shows the dc voltage and power levels currently tested in the protocol. Figure 9 shows an example of the influence of dc voltage levels and power levels on the efficiency of most inverter designs.

Table 1. Efficiency Test Conditions

Test 1	Vdc	Vac	Inverter AC Output Rated Power Level(kW) at PF=1					
			100%	75%	50%	30%	20%	10%
A	V_{min} =	V_{nom} = Vac						
B	V_{nom}=	V_{nom} = Vac						
C	V_{max} =	V_{nom} = Vac						

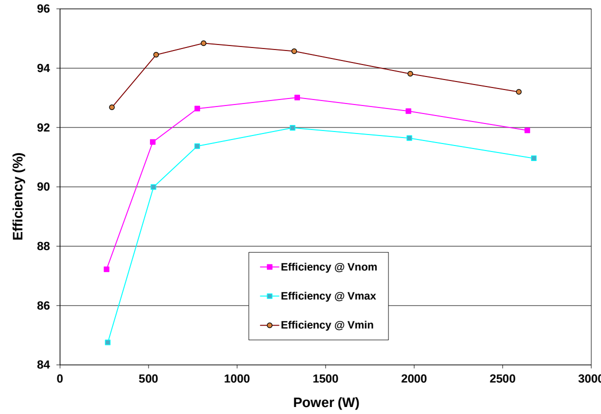

Figure 9. Efficiency curves using parameters from Table 1

By expanding the efficiency evaluation to include power factor as a variable (e.g., four tables, one for each of these power factors: 0.95, 0.9, and 0.85), a thorough assessment on the effects can be determined. These proposed data sets will provide the information to determine the peak, nominal average, and the weighted efficiency values.

The weighting values correlate to the percentage of the time the inverter is expected to operate in that power level. The following equation is used in the CEC protocol to tabulate weighted inverter efficiency:

$$\eta_{Wtd} = F_1\eta_{10} + F_2\eta_{20} + F_3\eta_{30} + F_4\eta_{50} + F_5\eta_{75} + F_6\eta_{100} \quad (5)$$

where: η_{10}, η_{20}, η_{30}, measured efficiency values at 10%, 20%, 30%, etc. of rated power

and F_1, F_2, F_3, etc. are the weighting factors and are equal to the following percentages: $F_1 = 0.04$, $F_2 = 0.05$, $F_3 = 0.12$, $F_4 = 0.21$, $F_5 = 0.53$, $F_6 = 0.05$.

These methods will be updated to include the three power factors under consideration. Laboratory evaluations will determine how varying power-factor operations affect the overall inverter performance. This information is important (a) in determining whether the inverter has sufficient heat mitigation, (b) to better predict PV system power delivery, and (c) the evaluations will provide data for enhancing inverter performance models.

B. Maximum Power Point Tracking (MPPT)

Effectively harvesting available PV power from the array is a key inverter performance characteristic that is essential to properly characterize and document. Inverter manufacturers have invested time and money to optimize this function, and many articles have been written on new MPPT algorithms that enhance energy harvest with different module technologies and fill factors. MPPT algorithms are typically implemented in the inverter, or can be distributed at the multistring, string, or even at the module level. Distributed MPPT capabilities are implemented in dc-dc converters, better known as power optimizers, and these devices function to reduce the module mismatch, shading issues, and system losses.

The EN50520:2010 test procedure [5] is used in Europe to determine the overall efficiency of utility interconnected PV inverters. The document specifies a MPPT test procedure using a PV simulator to control a variable array IV characteristic. By subjecting inverters to a repeatable array IV characteristic the MPPT efficiency can be compared. The test procedure has two different time-varying irradiance curves, one to represent low-to-medium irradiance variability, and another to represent a medium-to-high variability in irradiance, shown in Figure 10. This curve contains varying ramp rates on the incline and declining edge of the curve. Table 2 contains the voltage variation limits allowed for the varying irradiance conditions.

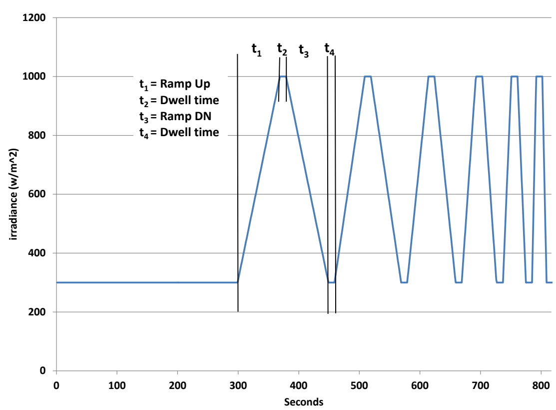

Figure 10. Irradiance profile for small & medium irradiance intensities

Table 2. IV Characteristic Requirements for the PV Simulator

	cSi-technology	Thin Film Technology	Tolerance
$\frac{\lvert U_{MPP}\rvert_{G\ =\ 200W/m^2}}{\lvert U_{MPP}\rvert_{G\ =\ 1000W/m^2}}$	0.95	0.98	± 1 %
$\frac{U_{MPP\ ,\ STC}}{U_{OC\ ,\ STC}}$	0.8	0.72	< 1 %
$\frac{I_{MPP\ ,\ STC}}{I_{SC\ ,\ STC}}$	0.9	0.8	< 1 %

MPPT efficiency is determined by calculating the theoretical energy provided by the PV source (simulator) and the energy used by the DUT within a measuring period. The following equation is used to determine MPPT efficiency:

$$\eta_{MPPT} = \frac{\int_0^{T_M} P_{DC}\,(t) * dt}{\int_0^{T_M} P_{MPP}\,(t) * dt} \qquad (6)$$

where:

P_{DC} (t) instantaneous power drawn by DUT

P_{MPP}(t) instantaneous theoretical MPPT power.

The theoretical MPPT power at irradiance (*Irr*) and cell temperature (T) for Sandia's simulator (Ametek Programmable Power TerraSAS) is calculated from the power at STC conditions (P_{ref}). P_{ref} is

$$Pref = \max(I \times V)\ at\ STC$$

$$I(V) = Isc\left(1 - C1\left(exp\left(\frac{V}{C2 \times Voc}\right) - 1\right)\right)$$

where *C1* and *C2* are:

$$C1 = \left(1 - \frac{Imp}{Isc}\right)\left(exp\left(\frac{-Vmp}{C2 \times Voc}\right)\right)$$

$$C2 = \frac{\left({}^{Vmp}/_{Voc}\right) - 1}{log\left(1 - {}^{Imp}/_{Isc}\right)}.$$

P_{MPP} is then calculated as:

$$P_{MPP} = P_{ref}\frac{Irr}{Iref}\left(1 + \frac{\beta}{100}(T - Tref)\right),$$

Where P_{ref} is calculated above, *Irr* is the irradiance, *Iref* is the reference irradiance (1000 W/m^2), β is the temperature coefficient for dc power (%/°C), *T* is the cell temperature (°C) and *Tref* is the reference temperature (25°C).

To compare dynamic MPPT efficiency for a collection of inverters, Sandia tested seven inverters according to the test protocols described in Section 4.4 of EN50530-2010. Four of the inverters were from the same manufacturer (identical make and model) (A1–A4). The other three were single inverters from different manufacturers. The inverters were connected to the simulator and each irradiance profile (low-to-medium and medium-to-high) was repeated a number of times to ensure consistent results.

One of the challenges of the test was to synchronize the irradiance profiles and the measured dc power in time, all collected at 1-sec intervals. To do this, we first plotted the measured output power vs. time to visually estimate the start time for each test. Next, we adjusted this start time estimate by iteratively time-shifting the measured power until we minimized the variance in the linear regression of measured power and input irradiance. The initial estimate minus the time adjustment resulting in this minimum was considered the start time of each test. Once the tests were synchronized with the irradiance inputs, we calculated the theoretical P_{MPP} from the equations above using array parameters defined in Table 3.

Table 3. Array parameters used to drive PV simulator.

Isc (A)	Imp (A)	Voc (V)	Vmp (V)
8.5	7.8661	440	363.87

The MPPT efficiency results are presented in Table 4. The low-to-middle (LTM) irradiance test was run 11 times and the medium-to-high (MTH) test was run 3 times. We report means and standard deviations for each inverter.

Table 4. MPPT efficiency for LTM and MTH conditions

Inverter	Mean (%) η_{MPPT} (Low)	Stdev (%)	Mean (%) η_{MPPT} (High)	Stdev (%)
Inverter A1	99.998	0.001408	99.997	0.000697
Inverter A2	99.992	0.001467	99.992	0.000609
Inverter A3	99.989	0.001522	99.992	0.000837
Inverter A4	99.991	0.001351	99.992	0.000642
Inverter B	99.950	0.000284	99.936	0.021217
Inverter C	99.986	0.000063	99.994	0.000108
Inverter D	99.968	0.000556	99.981	0.000713

III. CONCLUSION

The advanced functions being performed by inverters are addressing the concerns due to the high penetration of a variable DER but the impact of these new functions may adversely affect PV system performance. Laboratory testing and model development activities performed at Sandia National Laboratories will estimate these impacts.

The following three functions were investigated.

A. Reactive Power Generation/MPPT

Providing voltage regulation capabilities will typically require the inverter to operate at a non-unity power factor, and this will have an impact on the conversion efficiency of the inverter. This reduction in efficiency will have an impact on how inverters efficiencies are quantified. MPPT efficiency performance evaluations will be performed at non-unity power factor to document effects.

B. High DC/AC Ratio

The high dc/ac ratio of the PV system will affect the maximum power voltage (V_{mp}) at which the inverter operates and the amount of time spent at that voltage and power level. An analysis of the effects on the weighted values correlating to the dc/ac ratio will be demonstrated and the high ratio effect on MPPT will be evaluated.

C. MPPT Evaluation

The MPPT algorithms developed by inverter manufacturers have done very well at harvesting almost all available power. The effects of reactive power generation increases the ripple on the dc voltage, which can potentially complicate the measurement accuracies. With high dc/ac ratio's MPPT efficiencies are no longer valid but quantification of these effects need to be assessed.

The results from these evaluations will provide data needed to make more accurate performance assessments of PV systems that are operating with these types of conditions or functions. The information will provide data needed for refinements to PV and inverter performance models.

ACKNOWLEDGEMENT

Sandia National Laboratories is a multi-program laboratory managed and operated by Sandia Corporation, a wholly owned subsidiary of Lockheed Martin Corporation, for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000. This work was funded by the US Department of Energy Solar Energy Technologies Program.

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