Integrating Photovoltaic Inverter Reliability into Energy Yield Estimation with Markov Models

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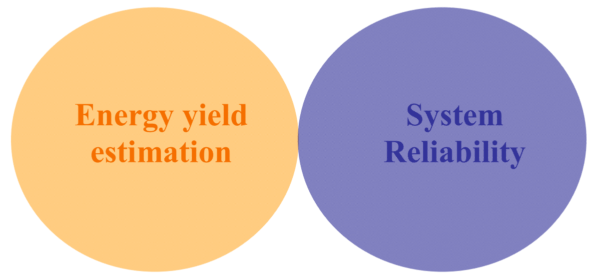
***Abstract*— Markov reliability models to estimate Photovoltaic (PV) inverter reliability are proposed for utility-interactive systems. These are then extended to generate a unified PV energy-yield model. The integrated reliability-energy yield framework is superior to conventional methods as it accounts for inverter failures and repairs. The proposed analytical framework is utilized to compare conventional central inverter architectures to emerging architectures that employ microinverters. Case studies applied to a 9 kW residential system indicate that over a 25 year period, in typical operating conditions, microinverters provide higher energy yield as compared to a conventional system. Additionally, the analysis demonstrates that the energy yield is more sensitive to the repair time compared to the mean time to failure of the inverters.**

Keywords-Photovoltaic energy conversion, Markov reliability models, utility-interactive inverters, energy yield estimation.

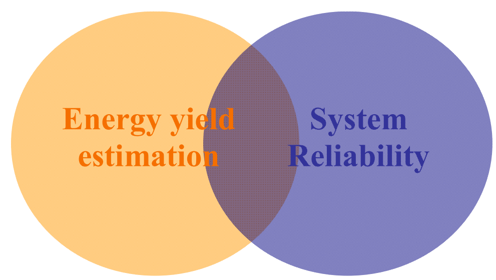
I. Introduction

Photovoltaic systems have gained prominence as economically viable, clean, renewable sources of energy. Typical PV installations are classified as residential, commercial or utility-scale, based on power level. Additionally, PV systems may be grid-tied or stand alone (with battery back up), while hybrid systems (grid-tied with battery backup) are also not uncommon.

Energy yield and system reliability are key metrics of performance in PV energy systems. Involved analytical models (including Markov methods in some cases) to estimate PV energy yield have been proposed [1]-[3]. Reliability of PV modules and balance-of-system components is an equally dominant concern owing to the high fixed costs in typical installations. Detailed reliability studies pertaining to PV modules, inverters, batteries, and other balance-of-system components are available in the literature [4]-[8]. An effort to explore the undeniable link between energy yield and system reliability has been lacking. This work seeks a unified approach to estimate PV energy yield while acknowledging system reliability. In essence, we are interested in models that would help in moving from a non-unified view to one that better acknowledges the undeniable link in these critical metrics. The goal of the proposed work is illustrated in Fig. 1.



(a) Non-unified view of key PV system metrics



(b) Unified view of PV system metrics

Figure. 1. Proposed models seek a unified view of energy yield and system reliability (b) as an alternative to a simplistic, non-unified perspective (a)

In this paper, we propose the use of Markov reliability models to provide practicing engineers with unified tools that integrate reliability into energy yield estimation. While combinatorial reliability models have been proposed to make similar arguments [9], Markov models are employed in this work as they can incorporate state-dependent failure rates and handle different failure modes and repair strategies [10]-[11].

A particularly interesting application of the proposed models is to compare different PV system architectures and evaluate emerging technologies. In recent years, the number of stand-alone installations has been overtaken by grid-tied systems [12]. Congruently, the number of residential grid-tied systems has been steadily increasing. In 2008, residential systems constituted 27% of all new grid-tied PV installations [12]. Another relevant paradigm shift in the PV arena is the increased assimilation of power electronic circuits directly with PV modules. Conventional installations where large PV arrays were typically connected to central power converters (Fig. 2) are giving way to distributed systems (Fig. 3). For instance, an emerging architecture that is expected to dominate the residential PV market consists of PV modules coupled with dedicated dc-ac inverters, commonly referred as microinverters. Each module produces power at ac-mains voltage, and a central inverter is unnecessary [13]-[15] (Fig. 3). Using the proposed analytical models, informed comparisons can be made between the traditional (central inverter) and emerging (distributed microinverters) system architectures.

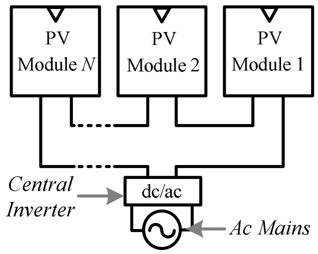


Figure 2. Traditional central inverter system architecture

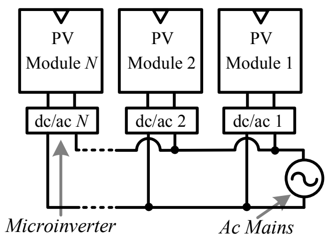


Figure 3. Emerging microinverter system architecture

The remainder of this paper is organized as follows. In Section II, the PV system analyzed in the case study is introduced and Markov models that describe system reliability are derived. Analytical models to estimate energy yield over the system's lifetime are integrated into the reliability analysis. In Section III, two applications of the proposed method are presented. First, case studies to estimate system reliability and energy yield are presented for central and distributed PV architectures. Additionally, the sensitivity of energy yield to inverter failure and repair rates is also probed. Conclusions are highlighted in Section IV.

II. Markov Models for Reliability Assessment and Energy-Yield Estimation

A. *PV system employed in case studies*

The models described in this work are presented for the Gable Home: a net-zero, passive, solar-powered house constructed by the University of Illinois for the U. S. Department of Energy's 2009 Solar Decathlon [16]. The 9 kW grid-tied PV electrical system consists of forty 225 W mono-crystalline modules split into two sub arrays. The dc power sourced by the PV modules is converted to mains-compatible ac power by two 5 kW grid-tied inverters. The use of two inverters ensures that the terminal voltage and current sourced by each sub array falls within the maximum power point tracking regime of the inverters under all ambient conditions. A block diagram of the PV electrical system is shown in Fig. 4.

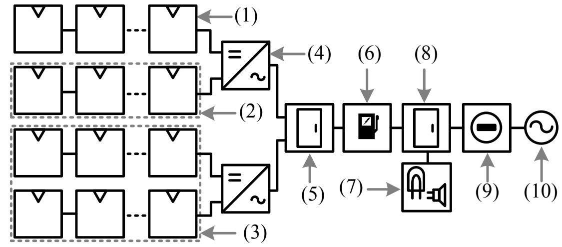


Figure 4. Block diagram of PV electrical system in the Gable Home [16]

B. *Markov reliability model*

A simple Markov model can be drafted to characterize the reliability of the central inverters in the Gable Home PV system. The state-transition diagram corresponding to this model is shown in Fig. 5. Each node in the diagram is a state in the Markov process, and represents the number of functional inverters. Transitions between states occur as a result of inverter failures and subsequent repairs. The failure and repair rates of the central inverters are denoted as λ_C and μ_C, respectively.

To facilitate the discussion on distributed systems employing microinverters, we consider a hypothetical 9 kW system for the Gable Home, where each PV module is installed with a dedicated microinverter. That is, instead of the two central inverters, each of the forty PV modules is assumed to be coupled with an appropriately rated microinverter. The Markov model for this system follows similar to the central architecture and is illustrated in Fig. 6. The failure and repair rates of the microinverters are denoted as λ_D and μ_D, respectively.

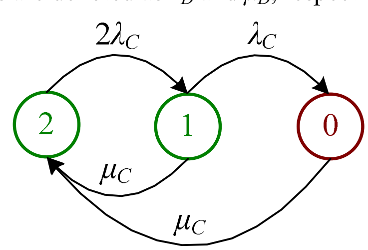


Figure 5. Markov reliability model for central inverter architecture

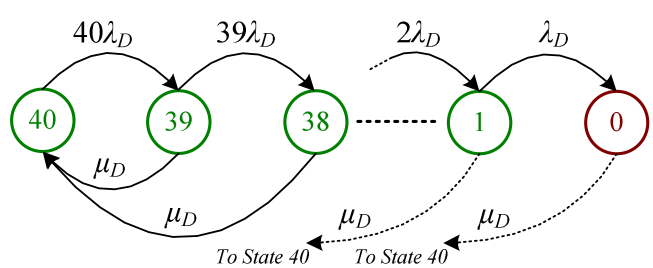


Figure 6. Markov reliability model for distributed inverter architecture

The repair strategy assumed in this analysis presumes that in each failed state, all faulty inverters are simultaneously repaired (or replaced) to restore the system to full functionality. Other repair strategies and state-dependent repair rates could alternately be modeled by modifying the transitions (and associated repair rates) between states. For instance, in Fig. 7(a), repairs are shown to occur at different rates. Conceivably, the time taken to repair two inverters could be longer than that to repair a single inverter, in which case, $\mu_2 < \mu_1$. Figure 7(b) illustrates a different repair strategy which might be applicable in certain installations. Note that this model does not capture the reliability of PV modules and other balance-of-system components (although, these could be incorporated into the model in a straightforward manner).

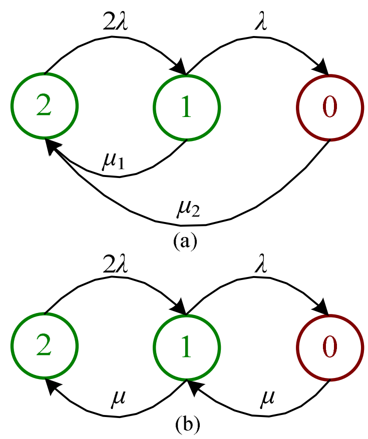


Figure 7. Alternate Markov models that include: (a) State-dependent failure rates, (b) Different repair strategy

In the discussion that follows, we will analyze the Markov models described in Figs. 5-6. A Markov process is a collection of random variables indexed in time and taking values in some set called the state space. A Markov process satisfies the Markov property, which is to say that the future evolution of the process only depends on its current state. The differential equations that govern the probability of being in some state at a given time are called the Chapman-Kolmogorov equations. The Chapman-Kolmogorov equations for the models shown in Figs. 5-6 are given by

$$\dot{p}_i(t) = \begin{cases} -(i\lambda+\mu)p_i(t)+(i+1)\lambda p_{i+1}(t) & 0 \le i \le N-1 \\ -i\lambda p_i(t)+\mu\sum_{m=1}^{N-1} p_m(t) & i = N \end{cases} \quad (1)$$

where λ is the failure rate, μ is the repair rate and $p_i(t)$ is the occupational probability of state i. Note that the above equations apply to both the central and distributed systems. The number of inverters in the system is denoted as N. Initially (t=0), the system is assumed to have all inverters operational. This translates to the following initial conditions for (1)

$$p_i(0) = \begin{cases} 0 & 0 \le i \le N-1 \\ 1 & i = N \end{cases}. \quad (2)$$

The steady-state occupational probability of a given state, p_i*, provides an estimate of the fraction of time the PV system functions with i inverters. The steady-state occupational probabilities can easily be obtained from (1) by setting the derivatives to zero. It is important to note that this set of equations is under determined, so it is necessary to add the normalization equation

$$\sum_{i=1}^{N} p_i{}^* = 1\,. \quad (3)$$

C. Markov reliability-Energy yield model

The Markov model outlined above can now be expanded to estimate the PV energy yield. Such a method is more inclusive than conventional techniques that do not factor in failures and repairs. For the distributed system architecture, the energy produced by the system, E_{DIST}, can be estimated as the sum of the energy produced in each state, i, E_i

$$E_{DIST} = \sum_{i=0}^{N} E_i = \sum_{i=0}^{N} i.P_{MODULE}.CF.T.\eta_{DIST}.p_i^* \quad (4)$$

where P_{MODULE} is the rated dc power of each module, CF is the capacity factor for the location, T, is the time period over which the study is performed, η_{DIST} , is the efficiency of the micro inverter, and p_i* is the steady-state occupational probability of state i, obtained by solving (1). Similarly, the energy produced by the central architecture, E_{CENT}, can be computed as:

$$\begin{aligned} E_{CENT} &= \sum_{i=0}^{N} E_i = \sum_{i=0}^{N} iP_{ARRAY}CF.T.p_i^*.\eta_{CENT} \\ &= \sum_{i=0}^{N} iP_{ARRAY}CF.T.p_i^*(k\eta_{DIST}) \end{aligned}. \quad (5)$$

The power rating of the array, P_{ARRAY}, is one half the system rating. The efficiency of the central-inverter architecture is denoted as η_{CENT}. For the purpose of comparison, it is expressed as a fraction of the efficiency of the distributed architecture ($\eta_{CENT} = k\eta_{DIST}$). Distributed architectures are bound to enjoy higher conversion efficiency, as they implement maximum power point tracking for each module, have lesser dc wiring and can harvest more energy when the modules are partially shaded. Hence, in the case studies that follow, we assume that $k < 1$.

III. Applications of the Proposed Analytical Method

A. Comparison of central and distributed systems

The Markov models presented thus far are utilized to compare the energy yield and the system reliability of the central inverter architecture installed in the Gable Home, and the hypothetical PV system built with microinverters. Table I lists the relevant parameters utilized in the case study. The period of evaluation is 25 years, which is the warranted lifetime of the modules. This justifies the exclusion of PV module failure in the reliability analysis.

TABLE I – PARAMETERS EMPLOYED IN CASE STUDIES

Symbol	Quantity	Value
P_{ARRAY}	Rated power of array	4.5 kW
T	Time period	25 years
CF	Capacity factor	19.17 %
η_{DIST}	Dc-ac conversion efficiency	95.5 %

The failure rate of the central inverters, λ_C, is assumed to be 1/10 yr^{-1}, and the repair rate, μ_C, is assumed to be 365/20 yr^{-1}. That is, on average, it is assumed that it can take up to 20 days to replace all faulty inverters and restore the system to full functionality. The energy yield of the central architecture, E_{CENT}, is plotted as a function of k in Fig. 8. Figure 9 depicts the energy yield of the distributed architecture, E_{DIST}, as a function of repair rate, μ_D, for a failure rate, $\lambda_D = \lambda_C = 1/10$ yr^{-1}. Figure 10 plots E_{DIST} as a function of inverter failure rate, λ_D, for a repair rate, $\mu_C = \mu_D = 365/20$ yr^{-1}. The results indicate that for the same failure rate, the central architecture has to be at least 98.91% as efficient as the distributed architecture to match its energy yield, with average repair times varying between 10 and 60 days. Similarly, for the same repair rate, the central architecture has to be at least 99.47% as efficient as the distributed architecture to match its energy yield, with the microinverters allowed to fail anywhere between once in five and once in twenty five years.

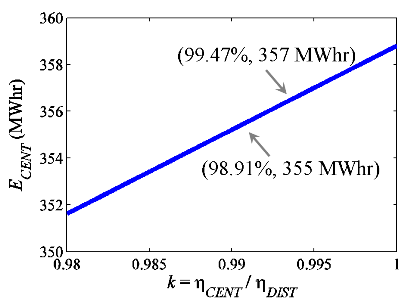


Figure 8. Energy yield, E_{CENT}, of central system as a function of system efficiency

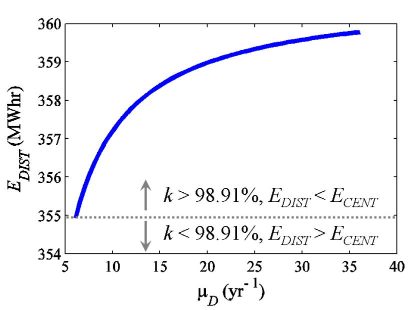


Figure 9. Efficiency requirements that ensure $E_{CENT} > E_{DIST}$ for the same repair rates, $\mu_C = \mu_D$

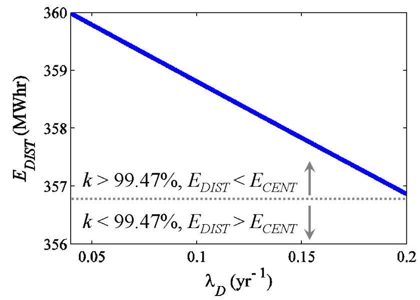


Figure 10. Efficiency requirement that ensure $E_{CENT} > E_{DIST}$ for the same failure rates, $\lambda_D = \lambda_C$

B. *Energy yield sensitivity*

In this study, we examine the influence of failure and repair rates on energy yield for the distributed architecture. Figure 11 depicts the energy yield of the distributed architecture as a function of average time to microinverter failure and average repair time. Energy yield is noted to be more sensitive to the repair time as compared to the mean time to failure of the microinverters. Conceivably, alternate repair strategies (such as those highlighted in Fig. 7) will provide different results. An interesting study would be to evaluate the sensitivity of energy yield to the failure and repair rates for a wide variety of repair strategies so that an optimal strategy can be chosen for a given system.

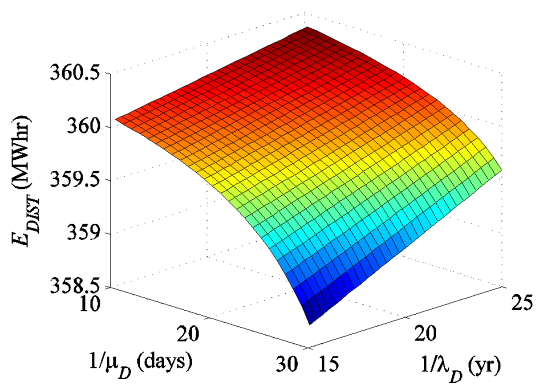


Figure 11. Energy yield of distributed architecture as a function of failure and repair rates

IV. CONCLUSIONS

A systematic method to integrate PV inverter reliability into energy-yield estimation is proposed with Markov reliability models. The suggested approach is more inclusive than conventional techniques, as inverter failures and repairs over the lifetime of the system are acknowledged. Case studies that compare central and distributed system architectures are analyzed using the proposed technique. The models can easily be extended to include the reliability of the PV modules and other balance-of-system components.

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