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Research Article

Reliability Analysis and Bess Impact for Two Different Systems: Pv - Inverters and PV - MGP

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Abstract

The integration of solar photovoltaic power with Battery Energy Storage System (BESS) has recently increased. The deployment of a battery energy storage system for the photovoltaic (PV) application has been increasing at a fast rate. Since PV technology was established and launched it used a DC to AC inverter to convert direct current to alternative current for grid connection, this units which consists of electronic elements has poor reliability aspect and since PV systems use large amount of these inverters, the total system reliability is low. In our research we propose a new configuration for reliability analyses of converting direct current to alternative current using Motor Generator Pair (MGP). MGP's reliability is higher from standard inverter, moreover, one MGP replacing a dozen inverters which improves the total system reliability.

In particular, this research presents reliability analysis of two different configuration of systems for reliability analysis and comparing them. To find the reliability indices, an analysis was conducted using a Multi-State System (MSS) using Markov processes, a Universal Generating Function (UGF) and a z-transform. The results show that there is a significant improvement in reliability indices for the MGP alternative. To find the Loss of Load Probability (LOLP) parameter, an analysis was conducted for eleven different values of load factors, the results demonstrated a significant improvement in system reliability achieved by integrating an energy storage system. These findings demonstrate the effectiveness of the storage system in optimizing a photovoltaic system, especially in improving reliability in scenarios with low load factors. For the first proposed system with standard 25 inverters without BESS the obtained LOLP is 0.5750 for standard load L1while with BESS LOLP is 0.0401, for the second proposed system that consist of MGP the obtained LOLP without BESS is 0.5666 while the LOLP with BESS is 0.038. These improvements in LOLP reflects the role of the BESS in improving the reliability of the system.

Keywords: Multi-State System, Universal Generating Function, Reliability Analysis, Power Storage Motor Generator Pair, Photovoltaic System

Introduction

The limitations of global fossil and nuclear fuel resources have made it necessary to urgently search for alternative sources of energy. As a result, there is a need to find a new way to balance supply and demand without relying on coal and gas-fueled generators [1]. Renewable energy resources (RERs) have demonstrated themselves to be sustainable, efficient, reliable, and environmentally friendly. These favorable attributes have led to a rapid increase in installed capacities of RERs on a global scale. The integration of RERs into existing power grids can be effectively achieved through the implementation of microgrid technology. In microgrids, Distributed Generation (DG) units are placed in close proximity to customer loads, ensuring continuous power supply at load points during grid failures or network faults. This setup helps reduce power outages for customers, ultimately enhancing system reliability [2].

In this evolving landscape, ensuring the continuity and quality of service has become a crucial operational requirement that is regulated and monitored. To meet these requirements, various proposals have emerged to assess the performance of distribution systems using probabilistic models. These models not only consider stochastic parameters like failure and repair rates of components but also incorporate the modeling of DG intermittence. Traditional reliability indices for distribution systems need to adapt to quantify the performance of these networks and evaluate service continuity conditions in light of DG integration. This evaluation is efficiently carried out using computational algorithms based on analytical or Monte Carlo simulation (MCS) techniques. Early publications focused on calculating the probability, frequency, and duration of failures, later incorporating switch actions. These evaluations were initially performed through analytical methods employing various techniques such as state enumeration, minimum cut sets, and Markov models [3]. Reliability plays a crucial role as a key performance indicator in the planning, design, and operation of a power system. Power utilities utilize reliability metrics to assess the performance of the power system both during its conceptualization and operational phases. Studies have shown that failures in the distribution system account for as much as 80% of the power supply unavailability at load points compared to other segments of the electric power system. These failures have localized effects and result in significant economic losses for consumers due to the sensitive and sophisticated nature of their equipment. Customer failure surveys conducted by distribution network operators highlight the importance of regularly assessing the reliability of the distribution system. The presence of unreliable power supply from the distribution system despite a reliable generation and transmission system underscores the need for increased focus on reliability assessments in the distribution power system.

Enhancements in this area can significantly reduce the duration and frequency of power outages experienced by consumers [4]. The reliability of the power grid supplying electricity in the present market using conventional sources of energy is comparatively high. On the other hand, renewable energy sources will not be as reliable as conventional energy sources. Renewable sources require more reserves, they are less flexible, and their generation varies suddenly with the change in weather conditions. They also use more electronics components, which have a higher failure rate, thereby decreasing their reliability and resiliency. Ref [5] based on the quantity and type of power conversion units and their interconnection method, the PV-battery system can be categorized into DC- and AC-coupled setups. The reliability of each configuration is directly impacted by the quantity of components and their electrical load. The reliability indices were calculated with no consideration on multi-state systems and z transform. Ref [6] conducts a reliability analysis of a standalone photovoltaic system designed to power electric loads in remote areas inaccessible to the low voltage distribution network. The analysis involves characterizing the electric load behavior using a Monte Carlo approach to consider the stochastic variations in electrical energy demand. The reliability indices were calculated with no consideration on electronic component & multi-state systems and z transform. Ref [7] evaluating the reliability of a distribution system incorporating microgrids, a substantial amount of computation time is required to guarantee the convergence of a Monte Carlo method used for estimating key indices. This process involves employing multi-state models for the system's various components. To enhance the efficiency and precision of the reliability assessment, particular emphasis is placed on utilizing multi-state models for distributed generation resources, with a focus on the battery energy storage system. Although reliability indices were calculated with consideration on multi-state systems there was no consideration on z transform. Ref [8] explores ways to improve PV inverter reliability by implementing battery system control. The PV inverter is identified as a particularly vulnerable component in PV systems, often leading to unexpected failure events. By integrating battery systems, the PV system gains greater control flexibility. This allows for a reduction in the load on PV inverters by storing excess PV energy in the battery rather than curtailing it. This presents an opportunity to enhance PV inverter reliability without compromising total energy production. The reliability indices were calculated with no consideration on multi-state systems and z transform. Ref [9] suggest improve stability problems for the future power grid due to lack of inertia cause by renewable energy connected to the grid. Improving stability problem achieved by using synchronous motor & synchronous generator pair. Ref [10] suggest improve inertia response and droop control for grid changing frequency using synchronous motor & synchronous generator pair since renewable energy sources does not contain rotating elements. Ref [11] is also suggest improve inertia response and droop control for grid changing frequency but they suggest DC-link voltage control methods using dc motor and synchronous generator pair. Ref [12] utilize DC motor & AC generator pair instead of conventual inverter to improve the reliability of PV system due to high temperatures condition which rise mor then 50 deg of Celsius that cause damage to the inverter. None of the 9 to 12 considered nor calculated the reliability indices of PV & MGP systems.

In this article we will focus on Grid-Connected PV system generation combined whit BES system installed on a business's rooftops in Israel to generate electricity for their operations. We compare performance and reliability estimation between two systems, a standard PV system and an MGP system instead of standard inverters.

Methodology

Multi-State Models for Component in Power Generating System and the UGF Method

Multi-state system reliability modeling is used to evaluate the performance and reliability of systems that can operate is several states characterized by different performance levels [13,14]. The UGF technique enables the determination of the overall system performance distribution of entire system based on the performance distributions of its constituent elements [15]. The UGF technique, is a straightforward universal approach of obtaining the discrete distribution of functions of random variables in a form of probability mass function (pmf). The UGFs representing the pmf of statistically independent random variables G_i can be defined as polynomials:

$$\boldsymbol{u_{i(z)} = \Sigma_{n_i=0}^{N_i} P_{i,n_i} Z^{g_{i,n_i}}} \qquad (1)$$

where $\boldsymbol{g_i, n_i}$ is the $\boldsymbol{n_i}$-th realization G_i, $\boldsymbol{N_i}$ is the number of such realizations and $\boldsymbol{P_{i,ni}} = \boldsymbol{Pr}(G_i = \boldsymbol{g_{i,ni}})$ is the realization probability. To obtain the UGF representing the pmf of function $\vartheta(G_1(t), \ldots G_J(t))$, the following composition operator is used

$$\mathrm{U(z)} = \otimes_{\vartheta}\left(u_1(z), \ldots u_J(z)\right) =$$
$$= \otimes_{\vartheta}\left(\sum_{n_1=0}^{N_1} P_{1,n_1} Z^{g_{1,n1}}, \ldots, \sum_{n_J=0}^{N_J} P_{J,n_J} Z^{g_{J,nJ}}\right) =$$
$$= \sum_{n_1=0}^{N_1}\sum_{n_2=0}^{N_2} \cdot\cdot \sum_{n_J=0}^{N_J}\left(\prod_{i=1}^{J} P_{i,n_i} Z^{\vartheta\left(g_{1,n1},\ldots g_{J,nJ}\right)}\right) \quad (2)$$

The polynomial U(z) represents all the possible mutually exclusive combinations of realizations of the independent variables $G_1(t),\ldots G_J(t)$ by relating the probability of each combination to the value of function $\vartheta(G_1(t),\ldots G_J(t))$ for this combination. Eventually, this polynomial takes the form $\mathrm{U(z)} = \sum_{i=0}^{I} P_1 Z^{g_i}$,which represents the pmf of $\vartheta(G_1(t),\ldots G_J(t))$ [16]. In solar generation, there are two different sources of randomness: one is the external solar Irradiation and the other is the internal mechanical degradation of the hardware elements. We assume that they are independent from each other.

PV systems usually consist of many independent branches connected in parallel, which correspond to a multi-state system. If random variables G1 and G2 represent productivities of two units working in parallel, the pmf of the random variable representing the cumulative performance of these components can be obtained by operator $\otimes_+$: $u(z) = u_1(z) \otimes_+ u_2(Z)$=

$$\sum_{i=0}^{N_1}\sum_{j=0}^{N_2} P_i P_j Z^{(g_i+g_j)} \quad (3)$$

If random variables G1 and G2 represent productivities of two units working in series such that the overall system performance is a multiplicative accumulation of their individual contributions, the pmf of the random system performance can be obtained using the operator $\otimes_X$ [17]. $\mathrm{u(z)} = u_1(z) \otimes_{\boldsymbol{X}} u_2(z) =$

$$\sum_{i=0}^{N_1}\sum_{j=0}^{N_2} P_i P_j Z^{(g_i \mathrm{x} g_j)} \quad (4)$$

PV System and BESS Power Output Modelling

For PV systems, there are two sources of randomness: the variable solar irradiation, and the mechanical availability of the system. The PV system consists of the following inner components: PV modules constructed in strings, Power optimizers (DC-DC converter), DC Fuses, DC Switches, inverters, and the AC Circuit Breakers. All these components are connected in series but in parallel branches, which implies that a fault in one of them leads to overall string failure but not to a whole system failure.

We introduce two mutually independent random variables G^{IR} and G^{MA} that represent the PV output power corresponding to the irradiation levels and the maximum power the mechanical state of the system allows to generate.

The pmfs of the variables G^{IR} and G^{MA} can be represented by UGFs

$$\boldsymbol{u_{IR}}(\mathrm{Z}) = \boldsymbol{\Sigma}_{\mathrm{i}=0}^{\boldsymbol{N_{IR}}} \boldsymbol{P_i} Z^{g{i}^{IR}} \quad (5)$$

And

$$\boldsymbol{u_{MA}}(\mathrm{Z}) = \boldsymbol{P_0^{MA}} Z^{g0^{\boldsymbol{MA}}} + \boldsymbol{P_1^{MA}} Z^{g1^{\boldsymbol{MA}}} \quad (6)$$

Where $\boldsymbol{N_{IR}}$ is the total number of considered irradiation levels, $\boldsymbol{g_0^{MA}} = 0$ and $\boldsymbol{g_1^{MA}}$ is the maximal power the system can generate in its working state. The mechanical states of an individual PV string consist of two states because it either function in perfect mode or it can totally malfunction. The failure and the repair rates of a PV string is taken as 0.00013/hr and 0.0270/hr respectively [17].

Therefore: $\boldsymbol{u_{MA}}(\mathbf{Z}) = 0.994 * Z^1 + 0.006 * Z^0$
Following [17] we obtain the total UGF representing the pmf of the output PV power as:

$$u_{PV}(z) = u_{IR}(z) \otimes_{\boldsymbol{X}} u_{MA}(z) =$$
$$\sum_{i=0}^{N_{IR}-1} \sum_{j=0}^{N_{MA}-1} P_i^{IR} P_j^{MA} Z^{g_i^{IR} * g_j^{MA}} \quad (7)$$

The BESS behavior is determined by two random variables: G^{OP}, which determines the possible output power of the BESS depending on the amount of accumulated energy and G^{BS}, which determines maximum output power of the BESS depending on its mechanical state (availability). Similar to (5)-(7) we obtain

$$\boldsymbol{u_{OP}}(\mathrm{Z}) = \boldsymbol{\Sigma}_{\mathrm{i=0}}^{\boldsymbol{N_{OP}}} \boldsymbol{P_i} Z^{gi^{OP}} \qquad (8)$$

$$\boldsymbol{u_{BS}}(\mathrm{Z}) = \boldsymbol{P_0^{BS}} Z^{g0^{BS}} + \boldsymbol{P_1^{BS}} Z^{g1^{BS}} \ldots + \boldsymbol{P_n^{BS}} Z^{g\mathrm{n}^{BS}} \qquad (9)$$

And

$$\boldsymbol{u_{BESS}(z) = u_{OP}(z) \otimes_X u_{BS}(z)} = \sum_{i=0}^{N_{OP}-1} \sum_{j=0}^{1} P_i^{OP} P_j^{BS} Z^{\varphi_x(g_i^{OP} * g_j^{BS})} \qquad (10)$$

In this study, we perform the analysis for PV system which consists of 25 identical strings connected in parallel with joint BESS and we compare the analysis to proposed new system which consists of two MGP systems instead of standard 25 inverters. It is assumed that the PV and BESS mechanical states are mutually independent from each other. Based on this assumption, we can obtain the UGF representing the total power of 25 PV strings system as [17]:

$$\boldsymbol{u_{PV}(z)}=\boldsymbol{u_{IR}(z) \otimes_X u_{MA}(z)} = u_{IR}(z) \otimes_{\boldsymbol{X}} \begin{bmatrix} u_{MA}^1(z) \otimes_+ u_{MA}^2(z) \otimes_+ \\ \ldots . u_{MA}^{25}(z) \end{bmatrix} \qquad (11)$$

The overall UGF representing the total power of 25 strings with standard inverters integrated with the BESS is obtained as:

$$u_{G1} = u_{PV} \otimes_+ u_{BESS} \qquad (12)$$

Having the system generation power distribution represented by the UGF (12) in the form

$$\boldsymbol{u_{G1}}(\mathrm{Z}) = \boldsymbol{\Sigma}_{\mathrm{j=1}}^{\mathrm{n}} \boldsymbol{P_j} Z^{g_j} \qquad (13)$$

and the load distribution is represented by the UGF

$$\boldsymbol{u_{Load}}(\mathrm{Z}) = \boldsymbol{\Sigma}_{\mathrm{i=1}}^{\mathrm{n}} \boldsymbol{S_i} Z^{n_i} \qquad (14)$$

One can calculate the LOLP index using the following operator $\otimes_W$ [13,14]:

$$\mathrm{LOLP} = u_{G1}(z) \otimes_{\boldsymbol{W}} u_{Load}(z) = \boldsymbol{\Sigma}_{\mathrm{j=1}}^{\mathrm{n}} \boldsymbol{P_j} Z^{g_j} \otimes_{\boldsymbol{W}} \boldsymbol{\Sigma}_{\mathrm{i=1}}^{\mathrm{n}} \boldsymbol{S_i} Z^{n_i} = \boldsymbol{\Sigma}_{\mathrm{j=1}}^{\mathrm{n}} \boldsymbol{\Sigma}_{\mathrm{i=1}}^{\mathrm{l}} \boldsymbol{P_j S_i} Z^{w(g_{j,} n_i)} \qquad (15)$$

Where

$$W(g_{j,} n_i) = \begin{cases} 1 & if \quad g_j < n_i \\ 0 & if \quad g_j \geq n_i \end{cases} \qquad (16)$$

Data Acquisition

For this study, solar radiation measurements are conducted by Solar Power company, the measurement type used is called Base Measurement System (BMS) that provides solar radiation data from instruments at the Beit Dagan meteorological station, Israel. The latitude, longitude, and elevation of the site are 31.99° N, 34.91° W, and 50 m, respectively. In our model we use an actual 700kWp solar power system that exists on a business roof and consists from 25 inverters with a power of 28 kW each. We will combine this system with a 920kWh BESS energy supply for a full load cover during the night as presented in Figure 1.

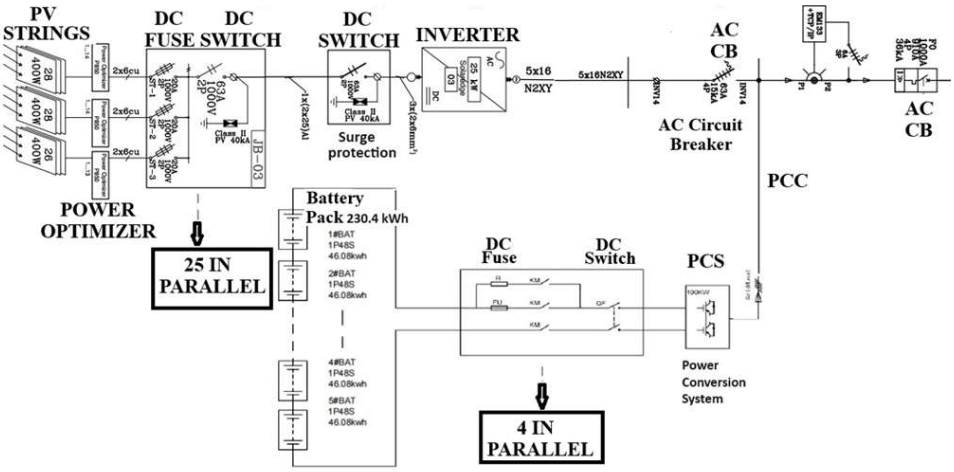

Fig. 1. Option 1 true detailed electrical architecture 700 kWp PV + BESS

To improove reliability we propose a second option wich consists from two sets of MGP systems instead of 25 standard inverters, each MGP system power is 420kW, the MGP consists of Brushless DC Motor (BLDC) & Permanent Magnet Synchronous Generator (PMSG) presented in Figure 2.

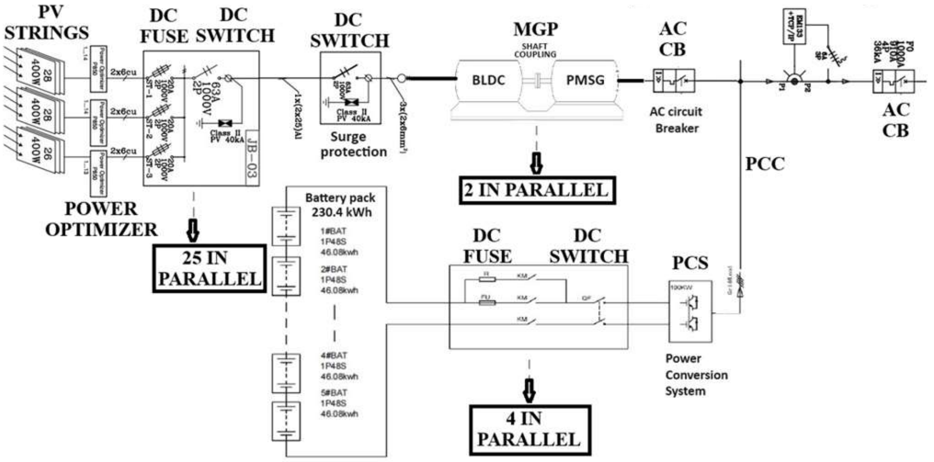

Fig. 2. Option 2 electrical architecture 700 kWp PV + MGP+ BESS

Table.1 presents the states of PV radiation and power output:

State number	State probability	Hour of a day	Total system annual average daily [kWh]	One string annual average daily [kWh]
1	0.4166	19:00 – 05:00	0	0
2	0.2083	05:00-07:00,16:00 – 19:00	40	1.6
3	0.2083	07:00 – 10:00,14:00-16:00	280	11.2
4	0.1666	10:00 – 14:00	440	17.6

Table 1: Annual daily average generated energy of the PV without BESS

Reliability Analysis

Calculations of the Reliability Indices for the First Option Standard PV system + BESS via UGF

For the calculation we will use equations mentioned in chapter 2 and MATLAB software. Based on these probabilities we obtain the UGF of the total generation power output include the solar irradiance and mechanicals states for option 1 without BESS using z transform. To simplify the calculations the string's mechanical states was taken as two mechanical states (all the string is working or all is failed). Probabilities of working and failed states occupancy are 0.994 and 0.006, respectively.

According to (11) we obtain the UGF of power generated by 25 strings is:

$$\boldsymbol{u_{PV}(z)}=\boldsymbol{u_{IR}(z)} \otimes_X \boldsymbol{u_{MA}(z)} = u_{IR}(z) \otimes_{\boldsymbol{X}} [u_{MA}^1(z) \otimes_+ u_{MA}^2(z) \otimes_{+\ldots} u_{MA}^{25}(z)] = (0.4166*Z^0+0.2083*Z^{\mathbf{1.6}} + 0.2083 * Z^{\mathbf{11.2}} + 0.1666 * Z^{\mathbf{17.6}}) \otimes_{\boldsymbol{X}}[(0.994*Z^1+0.006*Z^{\mathbf{0}}) \otimes_+(0.994*Z^1+ 0.006* Z^{\mathbf{0}}) \otimes_+ (0.994*Z^1+0.006*Z^{\mathbf{0}}) \otimes_+ \ldots \boldsymbol{21\ times} \ldots \otimes_+ (0.994*Z^1+0.006*Z^{\mathbf{0}})] = (\text{ we consider only the terms that are multiplied with e-5 and bigger, since the other terms is negligible and do not affect the results})= u_{PV}(z) = 1.4333\mathrm{e}-01 * \mathrm{z}^{440.0} + 2.1629\mathrm{e}-02 * \mathrm{z}^{422.4} + 1.5667\mathrm{e}-03 * \mathrm{z}^{404.8} + 7.2503\mathrm{e}-05 * \mathrm{z}^{387.2} + 1.7920\mathrm{e}-01 * \mathrm{z}^{280.0} + 2.7043\mathrm{e}-02 * \mathrm{z}^{268.8} + 1.9588\mathrm{e}-03 * \mathrm{z}^{257.6} + 9.0651\mathrm{e}-05 * \mathrm{z}^{246.4} + 1.7920\mathrm{e}-01 * \mathrm{z}^{40.0} + 2.7043\mathrm{e}-02 * \mathrm{z}^{38.4} + 1.9588\mathrm{e}-03 * \mathrm{z}^{36.8} + 9.0651\mathrm{e}-05 * \mathrm{z}^{35.2} + 4.1660\mathrm{e}-01 * \mathrm{z}^{0.00}$$

UGF for BESS and Load

For BESS, the operation state probabilities are obtained by using charging and discharging profile, this profile depends on load profile, capacity of the PV system and weather. For simplify the calculation the load will be taken as steady load of 280kW during the day from 07;00 to 16:00 and it drops to a steady value of 140kW between 16:00 to 19:00, then it drops to 65 kW between 19:00 – 24:00, during the night the load stands at 14 kW from 24:00 to 07:00. BESS probability operation stats are: $\overline{Pr_{op}} = \frac{17.5}{173.75}, \frac{75}{173.75}, \frac{81.25}{173.75}$ ={ 0.1007,0.4316 ,0.5683} Probabilities of working and failed states occupancy are 0.988 and 0.012, respectively.

According to (10) we obtain the UGF of BESS generated by 4 sets in parallel as:

$$\boldsymbol{u_{BESS}(z)} = \boldsymbol{u_{OP}(z)} \otimes_X \boldsymbol{u_{BS}(z)} = u_{OP}(z) \otimes_{\boldsymbol{X}} [u_{BS}^1(z) \otimes_+ u_{BS}^2(z) \otimes_+ \ldots \otimes_+ u_{BS}^4(z)] = (0.1007*Z^{17.5} +0.4316*Z^{\mathbf{75}} + 0.4676 * Z^{\mathbf{81.25}}) \otimes_{\boldsymbol{X}}[(0.988*Z^1+0.012*Z^{\mathbf{0}}) \otimes_+(0.988* Z^1+0.012*Z^{\mathbf{0}}) \otimes_+ (0.988*Z^1+0.012*Z^{\mathbf{0}}) \otimes_+ (0.988*Z^1+0.012*Z^{\mathbf{0}})]= (\text{ we consider only the terms that are multiplied with e-5 and bigger, since the other terms is negligible and do not affect the results})=$$

$\boldsymbol{u_{BESS}(z)}$ =4.4556e-01*z^325+4.1125e-01 *z^300+2.1646e-02*z^243.75+1.9980e-02*z^225+ 3.9437e-04*z^162.5 + 3.6401e-04 * z^150+ 9.5953e-02*z^70+4.6617e-03*z^52.5+8.4929e-05*z^35.

By combining the UGFs of PV and BESS, according to (12) we obtain the composite generation u-function for the complete first system:

$$\boldsymbol{u_{G1}}(\mathbf{z}) = \boldsymbol{u_{PV}}(\mathbf{z}) \otimes_+ \boldsymbol{u_{BESS}}(\mathbf{z}) = \left(\frac{4.166\times10^{-1}z^0+9.0651e-05* z^{35.2}+\cdots+1.4333e-01 * z^{440.0}}{13\ items}\right) \otimes_+ \left(\frac{\mathbf{8.4929}\boldsymbol{e}\mathbf{-05}z^{35}+\cdots+\mathbf{4.4556}\boldsymbol{e}\mathbf{-01}\ z^{325}}{9\ items}\right)=$$

LOLP Calculation for First Option Without BESS with Standard Load L

The load profile is characterized by 4 distinct states according factory demands. According to (15) we obtain the load UGF:

$$u_{Load}(z) = 0.2916*Z^{14} + 0.2083*Z^{65} + 0.125 * Z^{\mathbf{140}} + 0.375*Z^{\mathbf{280}}$$

$$u_{LLF_1}(z) = \boldsymbol{u_{PV}(z)} \otimes_{\boldsymbol{W}} u_{Load}(z) = (1.4333e-01 * z^{440.0} + 2.1629e-02 * z^{422.4} + 1.5667e-03 * z^{404.8} + 7.2503e-05 * z^{387.2} + 1.7920e-01 * z^{280.0} + 2.7043e-02 * z^{268.8} + 1.9588e-03 * z^{257.6} + 9.0651e-05 * z^{246.4} + 1.7920e-01 * z^{40.0} + 2.7043e-02 * z^{38.4} + 1.9588e-03 * z^{36.8} + 9.0651e-05 * z^{35.2} + 4.1660e-01 * z^{0.0}) \otimes_{\boldsymbol{W}} (0.2916*Z^{14} + 0.2083*Z^{65} + 0.125 * Z^{\mathbf{140}} + 0.375*Z^{\mathbf{280}}) = 0.4247z\hat{}0 + 0.5750\, z\hat{}1$$

$$\text{LOLP} = u'_{LLF1}(1) = 0.5750$$

This means that 57.5% of the time the load will be unsupplied.

LOLP Calculation for First Option BESS Included

$$\boldsymbol{u_{LLF2}(z)} = \boldsymbol{u_{G1}(z)} \otimes_{\boldsymbol{W}} \boldsymbol{u_{Load}(z)} = u_{G1}(z) \otimes_{\boldsymbol{W}} (0.2916*Z^{14} + 0.2083*Z^{65} + 0.125 * Z^{\mathbf{140}} + 0.375*Z^{\mathbf{280}}) = 0.9593\, z\hat{}0 + 0.0401\, z\hat{}1$$

$$\text{LOLP} = u'_{LLF2}(1) = 0.0401$$

This means that 4% of the time the load will be unsupplied.

Results and Discussion

Using the model and data presented above we obtained the LOLP of first system with and without BESS 0.0401 and 0.5750 respectively. Table 2 and Figure 3 presents the LOLP improvement achieved by introducing the BESS for different load factors for both systems.

LOLP CULCULATION		
	First option 25 standard inverters	**Second option 2 MGP**
LOLP without BESS for L1 = [14,65,140,280] kW	**0.5750**	**0.5666**
LOLP without BESS for L2 =2L1= [28,130,280,560]kW	**0.7083**	**0.7058**
LOLP with BESS for L1 = [14,65,140,280] kW	**0.0401**	**0.038**
LOLP with BESS for L2=2L1 = [28,130,280,560]kW	**0.2757**	**0.2760**

Table 2 LOLP calculations for two options

It can be seen that the integration of BESS into PV system provides a notable enhancement in system reliability. The analysis reveals that BESS significantly contributes to reducing LOLP, with the most substantial benefits observed for lower load factors.

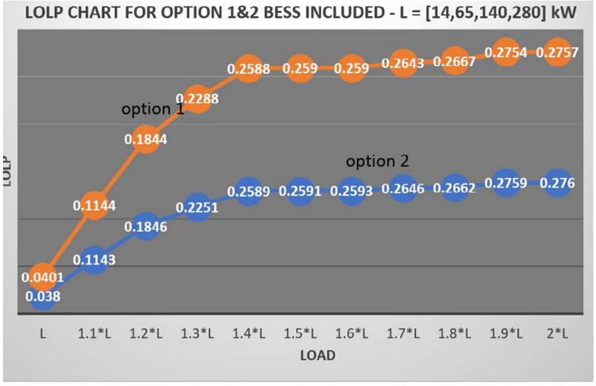

Figure 3 LOLP calculations for two options BESS included

Conclusion

This research demonstrates the substantial benefits of integrating BESS into PV systems, particularly in terms of enhancing system reliability measured by the LOLP. Through analysis across ten different load factors, the study provides evidence that BESS integration improves the reliability of PV power systems. The results indicate that BESS consistently reduces LOLP across various load factors, with the most significant enhancements observed at lower load factors. Specifically, the integration of BESS led to improvements in LOLP of up to 93% at a 100% load factor (L1) and 52% at 200% load factor (2*L1). This substantial reduction demonstrates the critical role of BESS in mitigating the variability and intermittency associated with Poore Weather generation conditions.

The research highlights the strategic importance of incorporating BESS into PV systems to achieve more reliable and stable renewable energy generation. This study also provides a comprehensive evaluation of the reliability of PV systems with integrated BESS, comparing conventional inverters to MGPs. Key conclusions include: Enhanced Reliability with MGPs - the proposed MGP-based system is more reliable due to its simplified architecture and added grid stability. Practical Implications - the study highlights the potential of MGPs to enhance the performance of renewable energy systems, making them a viable alternative to traditional inverters.

Future Directions

Further research should incorporate economic analyses, explore hybrid configurations, and investigate advanced control strategies for system optimization. These findings contribute to advancing the design and implementation of more reliable and efficient PV systems globally.

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