Impact of interconnection photovoltaicwind system with utility on their reliability using a fuzzy scheme

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Impact of interconnection photovoltaic/wind system with utility on their reliability using a fuzzy scheme

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Abstract

Reliability analysis has been considered as an important step in any system design process. A reliable electrical power system means a system which has sufficient power to feed the load demand during a certain period or, in other words, has small Loss of Load Probability (LOLP). LOLP is defined as an expected fraction of load not met by its power needs from electrical power system during its lifetime. Photovoltaic (PV)/Wind Energy System (WES) Hybrid Electric Power System (PV/WES HEPS) differs considerably from the Utility Grid (UG) in its performance and operating characteristics. With the interconnection of PV/WES as a HEPS into the UG, the fluctuating nature of the energy produced by these systems has a different effect on the overall system reliability than that of the fluctuating nature of energy produced by UG. Therefore, this paper presents a complete study, from reliability point of view, to determine the impact of interconnecting PV/WES HEPS into UG. Four different configurations of PV/WES/UG have been investigated and a comparative study between these four different configurations has been carried out. The overall system is divided into three subsystems, containing the UG, PV and WES. The generation capacity outage table has been built for each configuration of these subsystems. These capacity outage tables of UG, PV/UG, WES/UG and PV/WES/UG are calculated and updated to incorporate their fluctuating energy production. This paper also presents a fuzzy logic technique to calculate and assess the reliability index for each HEPS configuration under study.

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1. Introduction

As energy demands around the world increase, the need for a renewable energy source that will not harm the environment has increased. Some projections indicate that the global energy demand will almost triple by 2050 [1,2]. Renewable energy sources currently supply somewhere between 15% and 20% of the total world energy demand. PV and WES are the most promising as future energy technologies. A 30% contribution to world energy supply from renewable energy sources by year 2020 as proposed in Ref. [2] would reduce the energy related CO$_2$ emission by 25%. The index used to measure generation reliability is probabilistic estimates of the ability of a particular generation configuration to supply the load demand. Generator units may be unavailable due to failures, this is called “forced unavailability”, or due to preventive maintenance, this is called “planned unavailability”. Both types of unavailability may be treated stochastically, but the planned unavailability is often treated deterministically. The uncertainty in the generation capacity is due to failures (outages) of generator units [3]. The reliability analysis for renewable system uses a capacity outage probability table, which is an array of capacity levels and the associated probabilities of existence. This is obtained by combining availability and unavailability of the generating units using basic probability concepts. From the individual probability table, we prepared a cumulative probability table. The probability tables for PV, WES and PV/WES HEPS are modified hour by hour to include the effect of fluctuation in generation capacity. Finally, these tables are combined to evaluate the loss of load probability using Fuzzy algorithm. Also, the impact of the interconnection of PV/WES HEPS on their reliability has been analyzed.

2. Methodology

2.1. Probabilistic modeling and reliability index

Probabilistic reliability index serves as an accurate and consistent basis for assessing reliability of power systems, where components outage and load demand are of stochastic
nature [4]. The reliability analysis for renewable system uses a capacity outage probability table, which is an array of capacity levels and the associate probabilities of existence. This is obtained by combining the generating units availability and unavailability using basic probability concepts. From the individual probability table, we prepare cumulative probability table. The basic elements used to evaluate generation adequacy are shown in Fig. 1. The system is deemed to operate successfully as long as there is sufficient generation capacity to supply the load [5].

The cumulative probability of a particular capacity outage state of \( X \) MW after adding a two-state unit of capacity \( C \) MW with forced outage rate, \( \gamma \), is given [6,7] as

\[
P(X) = (1 - \gamma)^*P'(X) + \gamma^*P'(X - C),
\]

where \( P'(X) \) and \( P(X) \) denote the cumulative probabilities of the capacity outage state of \( X \) MW before and after the unit is added. \( P(X) \) is also the probability of capacity outage being \( \geq X \).

The above expression is initialized by setting

\[
P_0(X) = 1.0 \quad \text{for} \quad X \leq 0 \quad \text{and} \quad P(X) = 0.0 \quad \text{otherwise}.
\]

Forced outage rate, \( \gamma \), is given by the following equation [5]:

\[
\gamma = \frac{\text{Forced outage in hours}}{\text{Forced outage in hours} + \text{In services hours}}.
\]

Eq. (1) can be modified as follows to include multi-state unit representations [6,7]:

\[
P(X) = \sum_{i=1}^{n} p_i * P'(X - C_i),
\]

where \( n \): the total number of units states; \( C_i \): the capacity outage of state \( i \) for the unit being added; \( p_i \): the probability of existence of the unit state \( i \) and is defined as follows [6,7]:

\[
p_i = \sum_{r=k}^{n} \binom{n}{r} * \gamma^r * (1 - \gamma)^{n-r},
\]
where \( k \): minimum number of units required to the system succeed. The term \( \binom{n}{r} \) is defined as follows:
\[
\binom{n}{r} = \frac{n!}{(n-r)! \cdot r!}.
\] (5)

The overall probability that the load demand will not be met is called LOLP is computed as
\[
\text{LOLP} = \sum_{r=k}^{n} p_i \cdot P(L_j > C_i),
\] (6)

where \( L_j \): forecast peak load at hour \( j \); \( P(L_j > C_i) \): probability of loss of load at hour \( j \);
LOLP: loss of load probability at hour \( j \) for state \( i \).

2.2. Fuzzy logic application on reliability study of renewable energy

There are many methods for sizing PV system, WES and PV/WES/UG HEPS. The first group of these methods is intuitive methods. They are used as a first approach, but they are very inaccurate. The second group of these methods is denominated numerical method and uses system simulations. They are more accurate than the intuitive methods. Lastly, there are methods which use equations to describe the system under study as a function of reliability. These are called analytical methods. FL techniques have superseded conventional technologies in many scientific applications and engineering systems. Fuzzy techniques are applicable in various areas such as control, pattern recognition, quantitative analysis, planning, and prediction. The applications of fuzzy technique are increasing so rapidly that it is not possible to offer a limited list of them. An efficient reliability scheme based on FL technique, is suitable for sizing the PV system, WES and PV/WES/UG HEPS. The reliability proposed makes use of an ANFIS. In order to use the FL technique, the input parameter of each configuration should be determined precisely. The input data for each configuration under study can be obtained from power for one module for PV system, power for one wind turbine generator and load power at a given site. FIS employs the theory of fuzzy sets and fuzzy if-then rules to derive an output of LOLP. Typically, an FIS scheme performs its action in several steps including:

- Fuzzification (comparing the input values with membership functions to obtain membership values of each linguistic term).
- Fuzzy reasoning (firing the rules and generating their fuzzy or crisp consequents).
- Defuzzification (aggregating rule consequents to produce a crisp output) [8,9].

The investigations described here have been carried out for a Sugeno-type FIS structure as shown in Fig. 2, where the output of each rule \((y_1, y_2, \ldots, y_n)\) is a linear combination of input variables \((x_1, x_2, x_3, x_4)\) plus a constant term, the inner nodes \((R_1, R_2, \ldots, R_N)\) represent the rules and the final output LOLP is the weighted average of each rule’s output:
\[
\text{LOLP} = \frac{w_1y_1 + w_2y_2 + \cdots + w_ny_n}{w_1 + w_2 + \cdots + w_n},
\] (7)
\[
y_k = a_kx_1 + b_kx_2 + c_kx_3 + d_kx_4 + f_k,
\] (8)
\[ w_k = \mu_{i_k}(x_1)\mu_{j_k}(x_2)\mu_{k_k}(x_3)\mu_{l_k}(x_4), \]  

where \( \mu_{i_k}(x_i) \in \{\mu_{\text{Low}}, \mu_{\text{Medium}}, \mu_{\text{High}}\} \) membership functions for linguistic terms low, medium, high associated with the \( i \)th input signal, \( w_j \)—weighting factor for the \( j \)th rule consequent [9]. The membership function maps each input element of \( x_1, x_2, x_3 \) and \( x_4 \) to a membership value between 0 and 1.

The membership functions \( \mu_{i_k}(x_i) \) and \( y_{i_k} \) represent the fuzzy sets which describe the antecedent’s consequents. There are many membership function types. The selection of the membership functions and their boundaries should express the performance of the FL algorithm.

### 3. Applications of probabilistic modeling and results

A new computer program has been designed to calculate the LOLP index for ElZafaranna site, located on the western coast of the Suez Gulf, latitude 29.07°N and longitude 31.36°E, Egypt. The flowchart of this program is shown in Fig. 3. The inputs data of this program are:

1. hourly radiation, kW/m²;
2. hourly wind speed, m/s;
3. characteristic of PV module;
4. characteristic of wind turbine;
5. hourly load demand, W.

It is assumed here that the load demand varies monthly. Therefore, there are 12 daily load curves through the year i.e. \( 12 \times 24 = 288 \) h through the year. Fig. 4 shows the load demand for January, April, July and October [1]. The outputs of this program are:

1. hourly power from PV system, W;
2. hourly power from WES, W;
3. LOLP values for each hour for UG, PV/UG HEPS, WES/UG HEPS and PV/WES/UG HEPS at different penetration values under condition of using ASE-300 DGF/17 solar cell module type with rating 300 W and T600-48 Wind turbine generator type with rating 600 kW.
3.1. Capacity outage table for the configuration of UG only

One of the most commonly used methods of determining the required generation for LOLP calculations is the generation capacity outage table [7]. The generation capacity outage table is based on the independent behavior of different units where each has its own unavailability. The power system in this study consisted of 20 generating units each with...
5 MW of capacity to feed the load demand. The forced outage rate of each unit is 0.05, i.e. it has an availability of 0.95 [10]. The nominal installed capacity of the system is 100 MW based on maximum load. The capacity outage distribution of the system is shown in Table 1 which indicates the amount of capacity out of service (column 2) and available
(column 3) for each state, the probability of each state (column 4) and the cumulative probability (column 5) that is the probability that more than that capacity is out of service. An example, the probability that 25 MW or more is out of service is 2.573E−3. By applying Eqs. (2) and (5) combined with load demand shown in Fig. 4. From methodology of probabilistic modeling, we found the LOLP each hour per month. From summation of LOLP for each hour during each month, we can get total LOLP for each month for UG alone as shown in Fig. 5 which indicates the total LOLP for UG alone during year is equal to 2.181018301377 h with percentage reliability equal to (288/2.1810)/288 × 100 = 99.242%.

3.2. Capacity outage table for the configuration of PV/UG HEPS

The fluctuating nature of the energy produced by PV system has a different effect on the overall system reliability than that of the energy produced by UG. Therefore, the EFOR\textsubscript{pv} has been calculated every month. The EFOR\textsubscript{pv} equal to the maximum PV energy output for any period to the total PV energy during this period is shown in the following equation [11]:

\[
\text{EFOR}_{\text{pv}} = 1 - \frac{\text{Maximum of PV energy}}{\text{Total of PV energy}}. \tag{10}
\]

The sliding window approach has been applied here which allows for variability in PV power output throughout time. From the computer program the EFOR\textsubscript{pv} for all months of the year is shown in Fig. 6. On the other hand, the hourly LOLP for each hour during each month has been found by probabilistic modeling. Figure 5 displays the total LOLP for each month for PV/UG HEPS. From this figure it can be seen that the total LOLP during each month was improved when load demand was fed from PV/UG HEPS. For example, LOLP during April was 0.0968992 h when load was fed from UG, on the other hand during April LOLP was 0.073406492 h when load was fed from PV/UG HEPS. The yearly LOLP when the load feed form PV/UG HEPS is equal to 1.64259304 h with percentage reliability equal to (288−1.64259)/288 × 100 = 99.4296%.

![Fig. 5. Total hourly LOLP values for all months during the year.](image-url)
3.3. Capacity outage table for the configuration of WES/UG HEPS

In order to estimate the LOLP of WES/UG HEPS, the EFOR_{w} was calculated as shown in the following equation [11]:

\[
\text{EFOR}_{w} = 1 - \left( \text{Maximum energy of WES} / \text{Total energy of WES} \right).
\] (11)

From designed computer program, monthly value of EFOR_{w} of the year is shown in Fig. 6. Figure 5 displays the total hourly LOLP value for each month of the year for UG alone and WES/UG HEPS. From this figure it can be seen that the total LOLP for each month improved when load demand was fed from WES/UG HEPS. For example, the value of LOLP during April was 0.0968992 h when load was fed from UG, on the other hand the value of LOLP during April was 0.0283574 h when load was fed from WES/UG HEPS. The total yearly LOLP value for WES/UG HEPS was equal to 1.504018 h with percentage reliability equal to \((288/1.5040)/288 \times 100 = 99.477\%\).

3.4. Capacity outage table for the configuration of PV/WES/UG HEPS

The techno-economic design of this configuration has been carried out in Ref. [1]. This design was based on the following equation:

\[
P_{\text{gtotal}}(t) = \alpha \cdot P_{\text{pv}}(t) + (1 - \alpha) \cdot P_{\text{WES}}(t),
\] (12)

where \(P_{\text{gtotal}}\): the total generated power from PV/WES HEPS; \(P_{\text{pv}}(t)\): the generated power from PV system, W; \(P_{\text{WES}}(t)\): the generated power from WES, W; \(\alpha\): the penetration level of PV system, 0, 0.1, 0.2, 0.3,….1.

If \(P_{\text{gtotal}} > \text{load demand}\), then the surplus energy is fed to the UG. If \(P_{\text{gtotal}} < \text{load demand}\), then the deficit energy will be taken from the UG. From this study it was found that the most economic penetration level is equal to 0.28. The EFOR_{pvw} can be calculated as follows:

\[
\text{EFOR}_{\text{pvw}} = 1 - \left( \text{Maximum of } P_{\text{gtotal}} \text{ energy} / \text{Total of } P_{\text{gtotal}} \text{ energy} \right).
\] (13)
Using a proposed computer program the monthly $\text{EFOR}_{\text{pvw}}$ values through the year has been estimated at penetration level equal to 0.28. Figure 6 shows the relation between $\text{EFOR}_{\text{pvw}}$ and year months at penetration ratio equal to 0.28. The LOLP values for PV/WES/UG HEPS at different penetration levels have been estimated as shown in Fig. 7, which indicates the minimum LOLP value for this configuration occurs at penetration level equal to 0.28, i.e. the PV will feed 28\% of the load demand; and WES will feed the remaining 72\% of the load demand. The yearly LOLP value for PV/WES/UG HEPS was equal to 1.223 h with percentage reliability equal to $(288-1.223)/288 \times 100 = 99.575\%$.

4. Application of FL and results

4.1. Configuration of PV/UG

In order to use the ANFIS technique for this configuration, the input parameters limit should be determined precisely. The input parameters are hourly load demand and hourly power generated from PV system. The output is LOLP. The ANFIS consists of five layers of nodes performing different operations on incoming signals. The nodes in particular layers are responsible for determination of membership grades for each linguistic term, executing the rules and generating the weighted output. The membership function $\mu_{ik}(\alpha_i)$ with its grade of membership in fuzzy sets associates for this configuration are shown in Figs. 8 and 9. The parameters of the ANFIS have been adjusted via training (similar as for neural network schemes). The training set of input–output patterns and testing set have generated a new computer program as shown in Fig. 3. Each row of training data is a desired input/output pair of the target system to be modeled. Each row starts with an input vector and is followed by an output value. The training data
set consisted of 180 samples and the testing set 108 samples. A hybrid training algorithm being a combination of the least squares method and back-propagation gradient descent method was used here to prepare the FIS for the LOLP calculation. ANFIS from Matlab converts the trained data points to rules and fuzzy sets [12]. The membership functions are Gaussian membership functions and rules are design tools that give opportunity to calculate LOLP. The Max–Min inference method and average weight defuzzification strategy are used.

There are 90 rules which are sufficient to assign a LOLP using ANFIS. Some of these rules are as follows:

1. If (input1 is in1mf1) and (input2 is in2mf1) then (output is out1mf1) (1)
2. If (input1 is in1mf1) and (input2 is in2mf2) then (output is out1mf2) (1)
3. If (input1 is in1mf1) and (input2 is in2mf3) then (output is out1mf3) (1)
4. If (input1 is in1mf1) and (input2 is in2mf4) then (output is out1mf4) (1)
5. If (input1 is in1mf1) and (input2 is in2mf5) then (output is out1mf5) (1)
6. If (input1 is in1mf1) and (input2 is in2mf6) then (output is out1mf6) (1)
7. If (input1 is in1mf1) and (input2 is in2mf7) then (output is out1mf7) (1)
8. If (input1 is in1mf1) and (input2 is in2mf8) then (output is out1mf8) (1)
9. If (input1 is in1mf1) and (input2 is in2mf9) then (output is out1mf9) (1)
10. If (input1 is in1mf2) and (input2 is in2mf1) then (output is out1mf10) (1)
89. if (input1 is in1mf10) and (input2 is in2mf8) then (output is out1mf89) (1)
90. If (input1 is in1mf10) and (input2 is in2mf9) then (output is out1mf90) (1)

The output of LOLP value predicted using ANFIS is shown in Fig. 10. The difference between exact solution by probabilistic model and FIS predicted is very small as shown in Fig. 11. Thus we only see one curve as shown in Fig. 10. Once the yearly LOLP value has been obtained, it is very easy to design the configuration of PV/UG.

Fig. 10. Output of LOLP value using ANFIS for the configuration PV/UG HEPS.

Fig. 11. The difference between ANFIS and probabilistic model for the configuration PV/UG HEPS.
The yearly value of LOLP obtained by ANFIS was 1.6426 h. To get this value for the configuration of PV/UG HEPS we need 709770 modules from ASE-300 DGF/17 solar cell module type to feed the load demand with maximum demand 100 MW.

The FIS-based reasoning unit itself has the following design parameters:

- Type—Sugeno.
- Gaussian membership functions.
- Nine and 10 linguistic terms for each input membership function.
- 90 linear terms for output membership functions.
- 90 rules (resulting from number of inputs and membership function terms).
- Fuzzy operators: product (and), maximum (or), product (implication), maximum (aggregation), average weight (defuzzification).

4.2. Configuration of WES/UG

The input parameters in this configuration are hourly load demand and hourly power generated from WES. The output is LOLP. The membership function $\mu_{ik}(x_i)$ with its grade of membership in fuzzy sets associates for this configuration are similar to Figs. 8 and 9 but with different number of membership function. The parameters of the ANFIS for this configuration were also adjusted via training (similar to as for neural network schemes). Each row of training data is a desired input/output pair of the target system to be modeled. Each row starts with an input vector and is followed by an output value. The training data set consisted of 180 samples and the testing set 108 samples. A hybrid training algorithm being a combination of the least squares method and back-propagation gradient descent method was used here to prepare the ANFIS for the LOLP calculation. ANFIS from Matlab converts the trained data points to rules and fuzzy sets [12]. The membership functions are Gaussian membership functions and rules are design tools that give opportunity to calculate LOLP. The Max–Min inference method and average weight defuzzification strategy are used. There are 120 rules which are sufficient to assign a LOLP using ANFIS. Some of these rules are as follows:

1. If (input1 is in1mf1) and (input2 is in2mf1) then (output is out1mf1) (1)
2. If (input1 is in1mf1) and (input2 is in2mf2) then (output is out1mf2) (1)
3. If (input1 is in1mf1) and (input2 is in2mf3) then (output is out1mf3) (1)
4. If (input1 is in1mf1) and (input2 is in2mf4) then (output is out1mf4) (1)
5. If (input1 is in1mf1) and (input2 is in2mf5) then (output is out1mf5) (1)
6. If (input1 is in1mf1) and (input2 is in2mf6) then (output is out1mf6) (1)
7. If (input1 is in1mf1) and (input2 is in2mf7) then (output is out1mf7) (1)
8. If (input1 is in1mf1) and (input2 is in2mf8) then (output is out1mf8) (1)
9. If (input1 is in1mf1) and (input2 is in2mf9) then (output is out1mf9) (1)
10. If (input1 is in1mf2) and (input2 is in2mf10) then (output is out1mf10) (1)
11. If (input1 is in1mf2) and (input2 is in2mf11) then (output is out1mf11) (1)
12. If (input1 is in1mf2) and (input2 is in2mf12) then (output is out1mf12) (1)
13. If (input1 is in1mf2) and (input2 is in2mf13) then (output is out1mf13) (1)
...
The output of LOLP value predicted using ANFIS is shown in Fig. 12. The difference between exact solution by probabilistic model and FIS predicted is very small as shown in Fig. 13. Once the yearly LOLP value was obtained, it is very easy to design any configuration from WES/UG. The yearly value of LOLP obtained by ANFIS was 1.65041 h. To get this value for the configuration of the WES/UG HEPS we need 300 wind turbines from T600-48 Wind turbine generator type with rating 600 kW to feed the load demand with maximum demand 100 MW.

The FIS-based reasoning unit itself has the following design parameters:

- Type—Sugeno.
- Gaussian membership functions.
- Ten and 12 linguistic terms for each input membership function.
- 120 linear terms for output membership functions.
- 120 rules (resulting from number of inputs and membership function terms).
- Fuzzy operators: product (and), maximum (or), product (implication), maximum (aggregation), average weight (defuzzification).

4.3. Configuration of PV/WES/UG

Here the penetration ratio for PV system is equal to 0.28 and the WES equal to 0.72. The LOLP under this condition was the lowest LOLP. The input parameters in this configuration are hourly load demand and hourly power generated from PV system, hourly power generated from WES. The output is a LOLP. The membership function \( \mu_k(x_i) \) with its grade of membership in fuzzy sets associates for this configuration are similar to Figs. 8 and 9 but with different number of membership functions. The training data set consisted of 180 samples and the testing set 108 samples. ANFIS from Matlab converts the trained data points to rules and fuzzy sets [12]. The membership functions are Gaussian membership functions and rules are design tools that give opportunity to calculate LOLP. The Max–Min inference method and average weight defuzzification strategy are used.

There are 210 rules which are sufficient to assign a LOLP using ANFIS. Some of these rules are as follows:

1. If (input1 is in1mf1) and (input2 is in2mf1) and (input3 is in3mf1) then (output is out1mf1) (1)
2. If (input1 is in1mf1) and (input2 is in2mf1) and (input3 is in3mf2) then (output is out1mf2) (1)
3. If (input1 is in1mf1) and (input2 is in2mf1) and (input3 is in3mf3) then (output is out1mf3) (1)
4. If (input1 is in1mf1) and (input2 is in2mf1) and (input3 is in3mf4) then (output is out1mf4) (1)
5. If (input1 is in1mf1) and (input2 is in2mf1) and (input3 is in3mf5) then (output is out1mf5) (1)
6. If (input1 is in1mf1) and (input2 is in2mf1) and (input3 is in3mf6) then (output is out1mf6) (1)
7. If (input1 is in1mf1) and (input2 is in2mf1) and (input3 is in3mf7) then (output is out1mf7) (1)
8. If (input1 is in1mf1) and (input2 is in2mf2) and (input3 is in3mf3) then (output is out1mf8) (1)
9. If (input1 is in1mf1) and (input2 is in2mf2) and (input3 is in3mf4) then (output is out1mf9) (1)
10. If (input1 is in1mf1) and (input2 is in2mf2) and (input3 is in3mf5) then (output is out1mf10) (1)

↓

199. If (input1 is in1mf6) and (input2 is in2mf7) and (input3 is in3mf4) then (output is out1mf209) (1)
210. If (input1 is in1mf6) and (input2 is in2mf7) and (input3 is in3mf5) then (output is out1mf210) (1)
The FL algorithm predicted LOLP for any value of penetration ratio. Overall, the output for 108 samples from FL is shown in Fig. 14. The difference between fuzzy technique and probabilistic model as shown in Fig. 15. From Figs. 14 and 15 it can be seen that, the results indicate good performance of the FL as well as the probabilistic model. The yearly value of LOLP obtained by ANFIS in this configuration was 1.233 h. To get this value for the configuration of the PV/WES/UG HEPS we need 183085 modules from ASE-300 DGF/17 solar cell type and 218 wind turbines from T600-48 Wind turbine generator type with rating 600 kW to feed the load demand with maximum demand 100 MW.

The FIS-based reasoning unit itself has the following design parameters:

- Type—Sugeno.
- Gaussian membership functions.
• Six, five and seven linguistic terms for each input membership function.
• 210 linear terms for output membership functions.
• 210 rules (resulting from number of inputs and membership function terms).
• Fuzzy operators: product (and), maximum (or), product (implication), maximum (aggregation), average weight (defuzzification).

5. Conclusions

This paper presents a complete reliability study to determine the impact of interconnecting PV/WES HEPS into UG. From results detailed above, the following salient conclusions can be drawn:

1. Introducing PV with penetration ratio 0.28 into WES/UG combination decreases LOLP from 1.63 to 1.223 h.
2. A new proposed method to evaluate the reliability index (LOLP) for each configuration under study using FL algorithm has been proposed. The results obtained show that the proposed method gives good estimations.
3. Simulations by FL show that the LOLP curves generated by the proposed method fit the curves generated by the probabilistic model.
4. The proposed methodology for generating LOLP curves based on FL can be used for sizing PV/UG power system, WES/UG power system or PV/WES/UG HEPS.

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