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Optimal Reliability Study of Grid-Connected PV Systems Using Evolutionary Computing Techniques

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ABSTRACT Integrating renewable energy sources (RESs) into electrical power systems has gotten highly noticeable among researchers and those interested in electrical energy production due to the increase in energy demands, fossil fuel exhaustion, and ecological effects. PV-based renewable energy generation is one of the essential RESs that has appeared and had played a vital role in electrical power systems recently due to their advantages. In this regard, this paper presents a multi-objective computation problem for optimal siting and the design of grid-tied PV systems to achieve optimum generating reliability, considering some states of different generation probabilities. The proposed paper studies the evaluation of the grid-tied PV systems reliability, the states of generation probabilities, the generation buses availabilities, the capacities of the generation's system in or out of service for each failure state, and the frequency and mean duration of generation failure states. The presented multi-objective computation problem is optimized using a modified adaptive accelerated particle swarm optimization (MAACPSO) algorithm. The effectiveness of the proposed method is demonstrated through IEEE_EPS_24_bus integrated with PV systems. Results revealed the ability of MAACPSO to solve the multi-objective optimization problem presented, consequently supporting the system reliability.

INDEX TERMS Failure rate, optimum reliability, particle swarm optimization, PV system, probability failure, reliability evaluation, repair rate, system reliability.

LIST OF ABBREVIATIONS

AFD	Average frequency duration
AID	Average interruption duration
A	Grid availability
$\mathbf{C_i^{(t)}}$	Acceleration coefficient at iteration t and is equal to 1 or 2
C_1 and C_2	Acceleration coefficients "appropriate value ranges for C_1 and C_2 are from 1 to 2
C_{i0}	Initial values of inertia weight factor and acceleration coefficients respectively with i = 1or 2
$\mathbf{F_{(m)}^{(t)}}$	Mean value of the best positions related to all particles at iteration t
FFSi	Failure frequency of i state
IEEE_EPS_24_bus	Electric power system RTS_24 bus
LOLE	Loss of load expectation
LOLP	Loss of load probability
MAACPSO	Modified adaptive accelerated coefficients particle swarm optimization
MDS_i	Mean duration of states
MCT	Markov chain technique
$\mathbf{P_{PVF}^{Min}}$	Minimum power capacity for PV system
PSO	Particle swarm optimization
Pr	States of system's probabilities
PV	Photo voltaic
P_{PVF}	Power capacity for PV system
P_{PV}	PV power capacity

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r_1 and r_2	Random factors which are in the range [0], [1]
RDS_i	Rate of departure of i state
R_{total}	Total system reliability
T	Transition matrix
T	Current iteration number
$T_{(i)}$	Duration of capacity loss in percent
$T_{(max)}$	Maximum iteration number
TVAC	Time-varying acceleration coefficients
TVIW	Time-varying inertia weight
TID	Total interruption duration
$\mathbf{V}_{(i)}^{(t+1)}$	Velocity of particle i at (t + 1) in the modified search space
$\mathbf{V}_{(i)}^{(t)}$	Velocity of particle i at iteration t
W	Inertia weight factor
W(t)	Inertia weight factor
$W_{(max)}$	Maximum weight which appropriate value is 0.9
$W_{(min)}$	Minimum weight which appropriate value is 0.4
$\mathbf{X}_{(i)}^{(t)}$	Current position of particle (i) at iteration (t)
$\mathbf{X}_{(i)}^{(t+1)}$	Current position of particle (i) at iteration (t+1) in the modified search space
λ_i	Failure rate for component i
λ_{total}	System failure rate

I. INTRODUCTION

Renewable energies have many economic and environmental advantages, which has led to an increase in researchers' interests in studying these types of energies. Researchers in the renewable energy field focus on selecting the type, size and location of each source from the available renewable energy sources (RESs), studying the possibility of increasing the RESs capacities and penetration into the classical electrical power systems to reduce both the electricity production cost and the pollution problems beside increasing the system reliability and stability. There are many types of RESs such as solar PV, wind, fuel cell, and biomass, to name a few, that have been used a lot in generating electric power for on-grid and off-grid applications [1]–[3].

Some PV off-grid applications for charging electric vehicle batteries with wireless and wired mode [4], [5]. The authors compared the results with those obtained by experimental prototype design. The results show that the homogeneity of simulated results with the experimental results. Another application for feeding smart buildings was presented in [6].

Grid-tied RESs systems can encounter some failures during operation, which decreases the reliability and the availability of these systems. This requires attention to study the reliability of Grid-tied RESs systems in detail to reach the best (optimum) designs for such systems in terms of cost and location, taking into account some indices [7]. Some studies provided detailed analyses about the effects of adding some RESs to the power grid, as distributed generation (DG) in terms of reliability [8].

Rathore and Patidar [9], presented the reliability assessment of off-grid standalone microgrids system with PV, wind, and pumped storage hydro (PSH) system in India using Monte Carlo simulation technique. Guo *et al.* [10], evaluated the nodal reliability indices for hybrid AC-DC power system and the reliability performance of consumers at each node by using a multi-state model. The results showed the important role of reliability assessment to determine the risks of the hybrid AC-DC power system. Ballireddy and Modi [11], presented a hybrid optimization technique to assess the reliability indices of power systems by installing wind farms and using ant lion optimization technique and Monte Caro simulation. The work was demonstrated on the IEEE reliability test system (IEEE RTS 79). The authors' approach succeeded in evaluating the established model reliability indices. Reddy and Momoh [12], used Monte Carlo simulation for IEEE 30 bus system and genetic algorithm to optimize the scheduling strategy of the system taking into account the impact of the wind turbine, PV system, and load forecasts. The results showed that, with just a marginal increase in the cost of day-ahead generation schedule, a good reduction for mean adjustment cost in real-time is obtained. Another study about minimizing the power losses in grid-connected RESs considering reliability improvement with an optimal sitting of some RESs was presented in [13], [14]. An optimal generation cost and minimization of transmission losses for IEEE 30 and 300 bus systems using multi-objective optimal power flow technique [15]. Other Monte Carlo simulation applications for optimal scheduling of some hybrid systems with different configurations were presented in [16]–[18].

Wind and PV RESs have been the most widely used among different RESs in electric power generation until now [19], [20]. Generating power from the PV has many advantages over wind energy, like relatively simple technologies and the lack of impact of the local environment, which leads to an increasing focus on the PV energy production as shown in the annual growth of RESs, Fig.1 [19]. By 2021, the expected power generated from PV systems is 1 TW [20]. To accomplish this expectation, the reliability of grid-tied PV systems should be considered and enhanced.

Some studies are based on using the PV systems only as a RES. Hong *et al.* [21], presented a methodology for evaluating the impact of PV as a DG with random simulation and assessing the reliability indices by using the equivalent energy function method. The results showed the effectiveness of using PV for saving on energy cost. Raghuwanshi *et al.* [22], presented the reliability indices assessment of the standalone photovoltaic with water pumping system using Markov model combined with frequency duration technique. Abunima and Teh [23], proposed a new failure rate model for PV considering the changing environmental weather, PV system structure, and

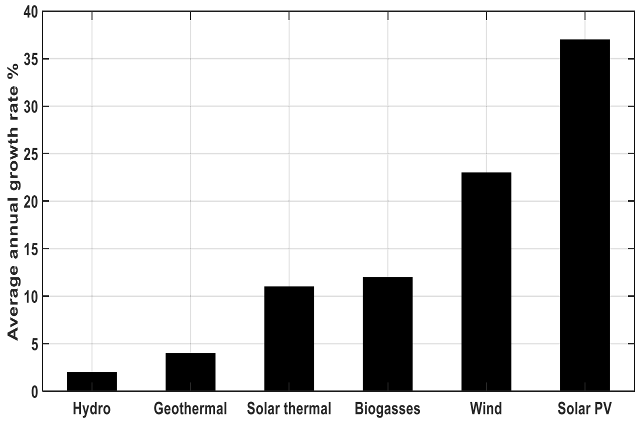

FIGURE 1. Annual growth rate of some RESs.

system components. The results showed that monthly failure rate values are significantly different from conventional values. Oktoviano Gandhi *et al.* [24], presented the reviews of the technical impacts of PV integration into power systems. Factors contributing to those impacts and the level and timeframe at which they occur are carefully analyzed. The reliability of a large-scale PV system integrated into a distribution network was assessed and improved as given in [23], [25]–[27].

Su *et al.* [25] and Li *et al.* [26], proposed a reliability evaluation for PV systems that are integrated with RDS. This study investigated the distribution reliability indices with aging period consideration and islanding operation and added some new reliability indices. The results showed that the unreasonable reliability evaluation procedure had a major impact on the reliability evaluation and the accuracy of reliability evaluation had an essential effect on the distribution system operation and future planning. Spertino *et al.* [27], proposed a reliability evaluation for maintenance view, analyzed the availability of off-grid of 10 PV systems with various configurations of the inverter, and assessed the annual energy loss and PV plants availability. The results showed that the interest in the PV systems maintenance increased availability and reduced PV energy losses. Abunima and Teh [23], presented a realistic PV reliability model system considering the time failure rates with the various influences environmental factors through the months of a year. The results show that the monthly rates of failure are different from the conventional yearly rate and fluctuated around the annual rates.

Some factors should be considered while studying the reliability of grid-tied RES. Samy et.al [28] had considered the loss of power supply probability during the designing of hybrid RES. Some studies considered the number of light load hours as a percentage of hours per year, loss of load probability (LOLP). Some modify this factor as a time interval, not as a percentage, loss of load expectation (LOLE) [29].

Actually, the LOLP/LOLE does not indicate loss of load but rather a deficiency in the available generating capacity. The generation system planners have to assess the generation system reliability and determine the amount of power capacity required to obtain a specified level of LOLP. As the load demand grows over time, the generation units should be increased so that the LOLP/LOLE does not exceed the required criterion [29].

These factors listed before for the reliability investigation and optimum design of grid-tied RESs, besides the non-linearities in the system components and uncertainties, make this multi-objective optimization problem is difficult to be handled by linear programming techniques [30]. Many evolutionary computing techniques were presented to solve such multi-objective no-linear optimization problems. From these evolutionary techniques, harmony search [31], multi-objective particle swarm optimization algorithm [28], Harris Hawks optimization [32], and modified adaptive accelerated particle swarm optimization (MAAPSO) [30]. The MAAPSO is converting the well-known PSO technique into an adaptive one by self-adaptation of some PSO parameters. MAACPSO was used to minimize the errors between the peak load forecasting values and their actual values and performance compared to other optimization techniques: PSO, genetic algorithms, and evolutionary programming. Results reveal the system performance when using MAACPSO surplus when using the other optimization techniques in terms of fast, high-quality results, accurate solutions, and flexibility to integrate with other algorithms [33]. Another comparison is given in [30] to show the efficacy of the MAACPSO over PSO, crazy PSO, adaptive accelerated coefficients PSO, and adaptive weighted PSO in terms of fewer setting parameters and in terms of less time to conversion.

This paper presents the reliability evaluation and improvement of high-level grid-tied PV systems. This study is applied to a hierarchical level I of electric IEEE_EPS_24_bus.

The main contribution of this work is to design high-level grid-tied PV systems optimally, considering several economic and technical aspects that are:

1- Optimal sitting of the PV systems through proposing one, two, three, or four PV systems, 1.5 MW each.
2- The states of generation probabilities
3- The frequency of generation failure states
4- The mean duration of generation failure states
5- The capacities of generators that are in/or out of service for each failure state.
6- The impact of changing the value of repair rates with different failure rate values on system availability.
7- The impact of changing the number of installed PV plants.
8- Some reliability indices, like AFD, AID, TID, LOLP, and LOLE.

This multi-objective optimization problem is performed by combining three techniques, block diagrams technique MCT, and MAACPSO.

II. SYSTEM STRUCTURE AND ANALYTICAL TECHNIQUES

The PV cell absorbs solar radiation and converts it to DC electric power. The PV module is an assembly of PV cells mounted in a framework for installation. Each panel has its characteristics that depend on the temperature and

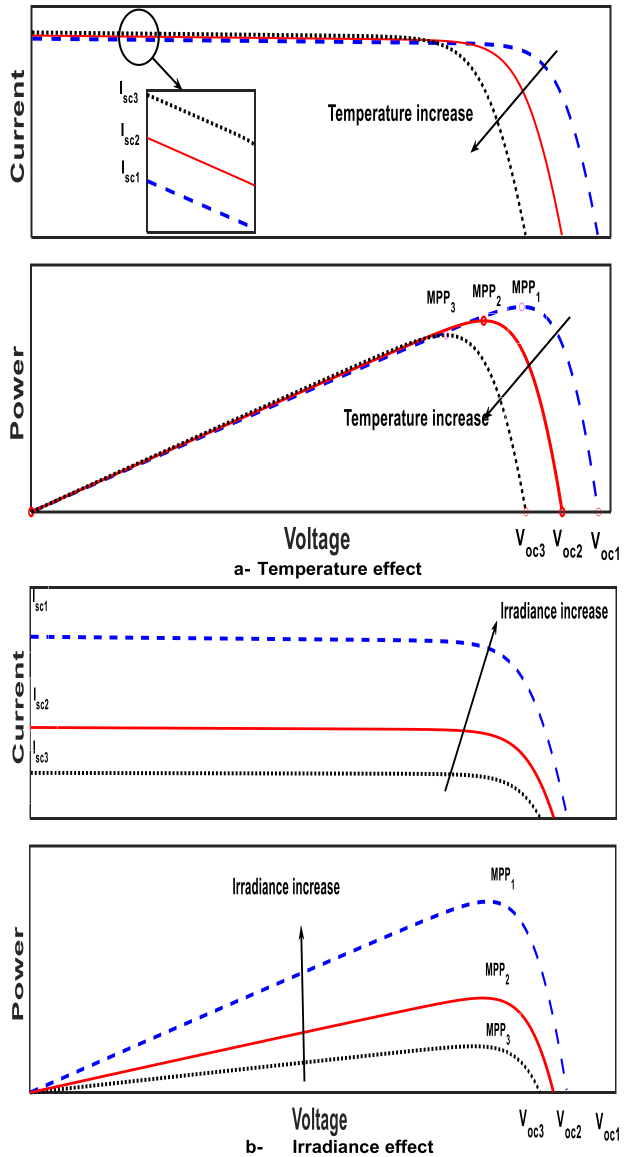

FIGURE 2. PV panel characteristics.

the irradiance. Each panel has short-circuited current (I_{sc}), open-circuit voltage (V_{oc}) and maximum power point (MPP). These characteristics are called the PV panel/cell characteristics and formulated in I-V and P-V curves shown in Fig.2. These characteristics are affected by the environmental conditions that are the temperature, Fig.2-a and the irradiance, Fig.2-b.

Several panels are connected together to form the PV plant. In this study, the maximum output power of the PV plant used in this study is 1.5 MW [34]. With 100 PV plants connected in parallel, the PV system's total generated power is 150 MW.

In this part, the analytical techniques used for the optimal design of generation power system reliability of IEEE_EPS_24_bus integrated with one, two, three, or four PV systems will be presented.

This work's main idea is to design a large-scale grid-tied PV system optimally, considering some reliability aspects. This optimal design is performed by minimizing a multi-objective function using MAACPSO.

There are more uncertainty parameters in electrical power systems such as consumer loads, energy price, and PV system supply. The generated power of the PV system depends on sun irradiation. Sun irradiation is commonly characterized by Beta distribution function [35]. The parameters of the beta distribution are named by alpha (α) and beta (β) [35]. Handling of these uncertainty parameters is very important. The uncertainty PV system power generation handled in most literature preview used uni-modal distribution functions which are modeled by Weibull, beta, and log normal probability density functions [17], [35]. The assumed setting of the parameters of beta distribution are $\alpha = 6.38$, $\beta = 3.43$, and the weight parameter in range 0, 1] [35]. In the proposed paper, the uncertainty of solar PV plants is considered $\pm 20\%$ [17], [35].

The objective functions are a complete generation system reliability, increasing the generation bus availability, AFD, AID, and TID while reducing the generation bus unavailability, generation system LOLP, and generation system LOLE.

This study aims to improve the reliability of a grid-tied PV system considering several factors to be a comprehensive study. These factors are the value of failure and repair rates for each power system component, the number of PV plants for each PV system, the rating capacity output for each PV system, and the PV system's installed location in the power system. When these factors are implemented in the objective functions, the system will be more complex and difficult to be handled by any optimizer algorithm. In order to simplify the implementation of these factors in the optimization problem presented in this paper, the block diagram technique and MCT are utilized.

A. BLOCK DIAGRAM TECHNIQUE

The block diagram technique is used to minimize the number of system components' rates, either failure or repair. The group representing the failure rates for the system's components in a graphical representation model [36]. The model is divided into groups that are connected in series or parallel. The following equation can calculate the total failure rate for the model.

1) IN CASE OF PARALLEL

$$\mathrm{R(t)} = e^{-\lambda t} \tag{1}$$

$$\mathrm{R_{total}} = 1 - \prod_{i=1}^{n} (1 - R_n) \quad \text{For i} = 1, \ldots, \text{n} \tag{2}$$

$$\begin{aligned} \frac{1}{\lambda total} = &\left[\frac{1}{\lambda 1} + \frac{1}{\lambda 2} + \ldots.. + \frac{1}{\lambda n}\right] \\ &- \left[\frac{1}{\lambda 1 + \lambda 2} + \frac{1}{\lambda 1 + \lambda 3} + \ldots.. + \frac{1}{\lambda 1 + \lambda n}\right] \\ &+ \left[\frac{1}{\lambda 1 + \lambda 2 + \lambda 3} + \frac{1}{\lambda 1 + \lambda 2 + \lambda 4} \right.\\ &\left. + \ldots.. + \frac{1}{\lambda 1 + \ldots\ldots + \lambda n}\right] \\ &- \ldots\ldots\ldots\ldots.. + \left[(-1)^{\mathrm{n}+1}\left(\frac{1}{\sum_1^n \lambda n}\right)\right] \end{aligned} \tag{3}$$

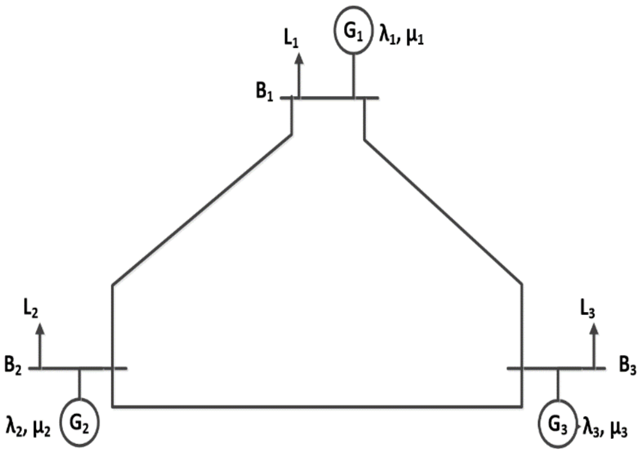

FIGURE 3. Three-generation components system.

2) IN CASE OF SERIES

$$R_{total} = \prod_{i=1}^{n} R_i \quad \text{For } i = 1, \ldots, n \tag{4}$$

$$\lambda_{total} = \sum_{i=1}^{n} \lambda_i \quad \text{For } i = 1, \ldots, n \tag{5}$$

After reducing the system's component number and assessing the whole generation system reliability, MCT's role is to analyze the system probability, availability, unavailability, and reliability indices.

B. MARKOV PROCESS TECHNIQUE

The MCT calculates all the states of the system's probabilities by presenting the transition between states [37]. To calculate the system's probabilities, the MCT starts by establishing a transition matrix and representing all states' transitions. These transitions between the states are represented by failure or repair mode.

To illustrate the role of MCT in the optimization problem presented in this paper, a simple three-bus system is utilized as depicted in Fig. 3.

The system has three generators G1, G2, and G3. Each generator has failure and repair rates $\lambda 1$, $\mu 1$, $\lambda 2$, $\mu 2$, $\lambda 3$, and $\mu 3$, respectively. As Markov process, the probability cases number is equal to 2^3 cases [37]. In an electrical power system, the generator's failure and repair are represented by on-state and off-state, respectively. The on-state is represented by 0, and the off-state is represented by 1.

The Markov equation can be represented as:

$$[Pr]\,[T] = [0] \tag{6}$$

The transition matrix creates by entering the failure and repair rates which represent the change between states as shown in the following equation (7), as shown at the bottom of the page.

Transitions of failure mode between states are represented in the upper triangle part of the matrix and the transitions of failure mode between states are represented in the lower triangle part of the matrix [38]. Each element in the diagonal is equal to minus the sum of its row's elements as Markov assumption [38].

To calculate the Pr matrix, the transpose of Markov matrix is needed. The transpose of matrices is represented in the following equation (8), as shown at the bottom of the next page.

As Markov assumption, the sum of all states of system's probabilities is equal to one [37] (9) and (10), as shown at the bottom of the next page.

By solving the Markov equation, the system's probabilities can be determined.

The Pr8 represents the complete shutdown of the generation system and unacceptable state. The system's availability and reliability are calculated by the following equations [39].

$$\text{Availability} = Pr1 + Pr2 + Pr3 + Pr4 + Pr5 + Pr6 + Pr7 \tag{11}$$

$$\text{System unavailability} = \sum_{n=2}^{8} Pr_n \tag{12}$$

FFS_i can be calculated by the following equations [40].

$$FFS_i = RDS_i \times Pr_i \tag{13}$$

MDS_i can be calculated by the following equation [40].

$$MDS_i = 1/RDS_i \tag{14}$$

The mean duration for each state is the time duration for the failure state [29]. The proposed method assumed all probability of determined capacity in an outage for each failure state is the loss of load. By calculated the MDS_i and probability of determining capacity in an outage for each failure state, LOLP and LOLE can be calculated [29].

The LOLP definition is the loss of power supply probability as a percentage of hours per year. It can be calculated by

$$[Pr]x\begin{bmatrix} -(\lambda1+\lambda2+\lambda3) & \lambda1 & \lambda2 & 0 & \lambda3 & 0 & 0 & 0 \\ \mu1 & -(\mu1+\lambda2+\lambda3) & 0 & \lambda2 & 0 & \lambda3 & 0 & 0 \\ \mu2 & 0 & -(\mu2+\lambda1+\lambda3) & \lambda1 & 0 & 0 & \lambda3 & 0 \\ 0 & \mu2 & \mu1 & -(\mu2+\mu1+\lambda3) & 0 & 0 & 0 & \lambda3 \\ \mu3 & 0 & 0 & 0 & -(\mu3+\lambda1+\lambda2) & \lambda1 & \lambda2 & 0 \\ 0 & \mu3 & 0 & 0 & \mu1 & -(\mu3+\mu1+\lambda2) & 0 & \lambda2 \\ 0 & 0 & \mu3 & 0 & \mu2 & 0 & -(\mu3+\mu2+\lambda1) & \lambda1 \\ 0 & 0 & 0 & \mu3 & 0 & \mu2 & \mu1 & -(\mu3+\mu2+\mu1) \end{bmatrix} = [0] \tag{7}$$

the sum of all mathematical expectations for all generation units as, [29]:

$$LOLP = \sum_{i=1}^{n} P_i \times t_i \tag{15}$$

The LOLE definition is the loss of power supply probability as a time interval of hours per year and can be calculated as the following equation [29].s

$$LOLE = \sum_{i=1}^{n} P_i (t_i - t_{(i-1)}) \tag{16}$$

As the three-bus test system is used to show the effectiveness of using MCT in the reliability study of a grid-tied PV system, the dimension of the transition matrix is 2^3x 2^3, in this thee-bus system. In the case of a large interconnected system with n- number of generators, the dimension will be 2^nx 2^n that will make the optimization process complicated in addition to the extended time taken to complete the optimization process.

C. MAACPSO ALGORITHM

Kennedy and Eberhart presented particle swarm optimizer (PSO) in 1995. This algorithm is a population-based optimization and simulated the social behavior of the flocking of birds [30]. In PSO, the individuals are called particles and they change their state with time. The particles fly around in the multidimensional space. During the flight, each particle adjusts its position according to its own experience, p_{best}, and according to a neighboring particle's experience, g_{best}. Figure 4 shows the best position and its neighbor [30].

The velocity of each agent can be calculated as:

$$V_i^{(t+1)} = WV_i^{(t)} + C_1 r_x \left(P_{best(i)}^{(t)} - X_{(i)}^{(t)}\right) + C_2 r_2 x \left(g_{best(i)}^{(t)} - X_{(i)}^{(t)}\right); \quad W, C_1, C_2 \geq 0 \tag{17}$$

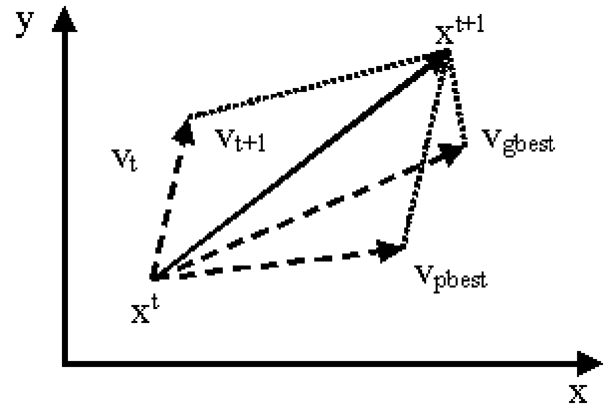

FIGURE 4. Concept of a searching point by PSO.

A certain velocity gets gradually close to p_{best} and g_{best}. By using the previous equation, the velocity and the current position can be calculated as [30]:

$$X_{(i)}^{(t+1)} = X_{(i)}^{(t)} + V_{(i)}^{(t+1)}; \quad i = 1, 2 \ldots, n \tag{18}$$

$$W = W_{max} - \frac{W_{(max)} - W_{(min)}}{t_{(max)}} * t \tag{19}$$

The element W controls the influence of the previous history of the velocities to the current one. It is adapted according to (20-25)

The components C_1 and C_2 pull each particle toward p_{best} position, which is the cognitive element of velocity and g_{best} position, which is the social element velocity. The position is updated based on (18). The inertia of the variable time (t) can determine a good solution at a faster rate. Still, the ability to catch the optimal solution is poor due to the lack of diversity at the search end.

$$\begin{bmatrix} -(\lambda1+\lambda2+\lambda3) & \mu1 & \mu2 & 0 & \mu3 & 0 & 0 & 0 \\ \lambda1 & -(\mu1+\lambda2+\lambda3) & 0 & \mu2 & 0 & \mu3 & 0 & 0 \\ \lambda2 & 0 & -(\mu2+\lambda1+\lambda3) & \mu1 & 0 & 0 & \mu3 & 0 \\ 0 & \lambda2 & \lambda1 & -(\mu2+\mu1+\lambda3) & 0 & 0 & 0 & \mu3 \\ \lambda3 & 0 & 0 & 0 & -(\mu3+\lambda1+\lambda2) & \mu1 & \mu2 & 0 \\ 0 & \lambda3 & 0 & 0 & \lambda1 & -(\mu3+\mu1+\lambda2) & 0 & \mu2 \\ 0 & 0 & 0 & 0 & \lambda1 & 0 & -(\mu3+\mu2+\lambda1) & \mu1 \\ 0 & 0 & 0 & \lambda3 & 0 & \lambda2 & \lambda1 & -(\mu3+\mu2+\mu1) \end{bmatrix} x\,[Pr] = [0] \tag{8}$$

$$Pr1 + Pr2 + Pr3 + Pr4 + Pr5 + Pr6 + Pr7 + Pr8 = 1 \tag{9}$$

$$\begin{bmatrix} 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 \\ \lambda1 & -(\mu1+\lambda2+\lambda3) & 0 & \mu2 & 0 & \mu3 & 0 & 0 \\ \lambda2 & 0 & -(\mu2+\lambda1+\lambda3) & \mu1 & 0 & 0 & \mu3 & 0 \\ 0 & \lambda2 & \lambda1 & -(\mu2+\mu1+\lambda3) & 0 & 0 & 0 & \mu3 \\ \lambda3 & 0 & 0 & 0 & -(\mu3+\lambda1+\lambda2) & \mu1 & \mu2 & 0 \\ 0 & \lambda3 & 0 & 0 & \lambda1 & -(\mu3+\mu1+\lambda2) & 0 & \mu2 \\ 0 & 0 & 0 & 0 & \lambda1 & 0 & -(\mu3+\mu2+\lambda1) & \mu1 \\ 0 & 0 & 0 & \lambda3 & 0 & \lambda2 & \lambda1 & -(\mu3+\mu2+\mu1) \end{bmatrix} [Pr] = \begin{bmatrix} 1 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \end{bmatrix} \tag{10}$$

Due to the fitness value of G_{best} and P_{best}, C_1 and C_2 differ adaptively and (17) changed to the following equation [30].

$$V_{(i)}^{(t+1)} = W^{(t)}V_{(i)}^{(t)} + C_1^{(t)} r_1 x(p_{best(i)}^{(t)} X_{(i)}^{(t)}) + C_2^{(t)} r_2 x(g_{best(i)}^{(t)} X_{(i)}^{(t)}) \quad (20)$$

$$W^{(t)} = W_O^{(t)} \exp(-\alpha_w\, t) \quad (21)$$

$$C_1^{(t)} = C_{1O} \exp(-\alpha_c\, t\, k_c^{(t)}) \quad (22)$$

$$C_2^{(t)} = C_{2O} \exp(\alpha_c\, t\, k_c^{(t)}) \quad (23)$$

$$\alpha_c = -\frac{1}{t_{max}} \ln\left(\frac{C_{2O}}{C_{1O}}\right) \quad (24)$$

$$K_c^{(t)} = \frac{F_m^{(t)} - g_{best(i)}^{(t)}}{F_m^{(t)}} \quad (25)$$

$\alpha_w \alpha_w$ is determined for starting and last W values in the same way as α_c [30].

The modification in PSO algorithm described in (17-25), can be achieved through the following:

The two accelerating coefficients, at each iteration, are updated as:

$$C_2^{(t)} = 4 - C_1^{(t)} \quad (26)$$

$$C_1^{(t)} = C_{1O} \exp(-\alpha_c\, t\, k_c^{(t)}) \quad (27)$$

It's supposed to be less calculation for C_1 and C_2 and the fastest solution [30].

The objective functions in the proposed technique are increasing the generation system reliability presented in (1) and improved the system reliability indices given in (11)-(16). These system reliability indices are enhanced by increasing the total system reliability.

The process starts by recording and tabulating the data related to each generator in the network. These data include the capacity, failure and repair rates of each generator. Each generator's capacity is known in the generation station, either from the generator's nameplate data or from the manufacture datasheets. At the same time, the repairing and failure rates are recorded and tabulated by the maintenance team in the power station. These data are available for some typical systems like IEEE 14-bus and 24-bus systems [41]–[45].

The block diagram technique, Markov process, and MAACPSO algorithm in the optimal reliability study presented in this paper can be summarized through the block diagram shown in Fig.5.

The proposed algorithm can be described in the following steps:

1- The capacity, failure and repairing data for each generator in the system are tabulated.
2- The PV data, including failure rating, repair rating, size and location, are tabulated.
3- The generating and PV data represent the input to the block-diagram technique.
4- The block-diagram technique assesses the total system failure rate, system repair rate, and system reliability and reduces system components to lower numbers.

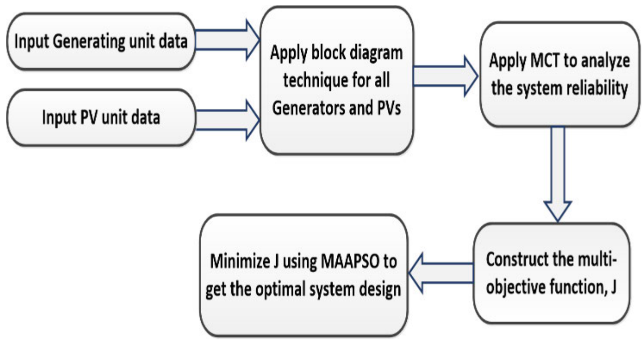

FIGURE 5. The block diagram of the proposed method.

5- MCT technique block efficiently evaluates failure probability states and assesses the system reliability indices. This evaluation is performed by constructing zeros and ones matrix, transition states matrix, and Markov equation.
6- A multi-objective function that includes the PV system data used, the generation system's data, the system reliability, and reliability indices is formulated.
7- Finally, the formed multi-objective function is optimized using MAACPSO algorithm to evaluate system reliability and assess the system reliability indices.

Figure 6 shows the developed method's flowchart, which combined the blocks diagram technique, Markov process, and MAACPSO algorithm.

In the proposed study, the penalty factors associated with each violated constraint are bounded to the objective function to force a solution to stay in the feasible solution space. The respected constraints values in the proposed method are:

$$P_{PV} = 1.5 \text{ MW} \quad (28)$$

$$P_{PVF}^{Min} = 50 \text{ MW} \quad (29)$$

$$\sum\nolimits_{i=1}^{n} P_{PVF} \leq 300 \text{ MW} \quad (30)$$

III. STUDY CASES

Figure 7 shows the IEEE electrical power system with 24 buses (IEEE_EPS_24_bus). This system has 24 buses with two voltage levels (138 KV and 230 KV), 5 power transformers 230/138 KV, 9 cables, 29 transmission lines, and 10 generators [41]–[43]. The capacity of generation units for the IEEE_EPS_24_bus system is given in table (1) [41]–[43]. The failure and repair rates of generation units and PV plants are shown in table (2) [44], [45].

This study focuses on assessing the reliability of a grid-tied PV system. The reliability of the system will be evaluated through four cases that have a different number of PV systems. The proposed paper studied installing one PV system in the first case, installing two PV systems in the second case, installing three PV systems in the third case, and installing four PV systems in the fourth case. These cases are named IEEE_EPS_24 bus_1_PV, IEEE_EPS_24 bus_2_PV, IEEE_EPS_24 bus_3_PV, and IEEE_EPS_24 bus_4_PV, respectively.

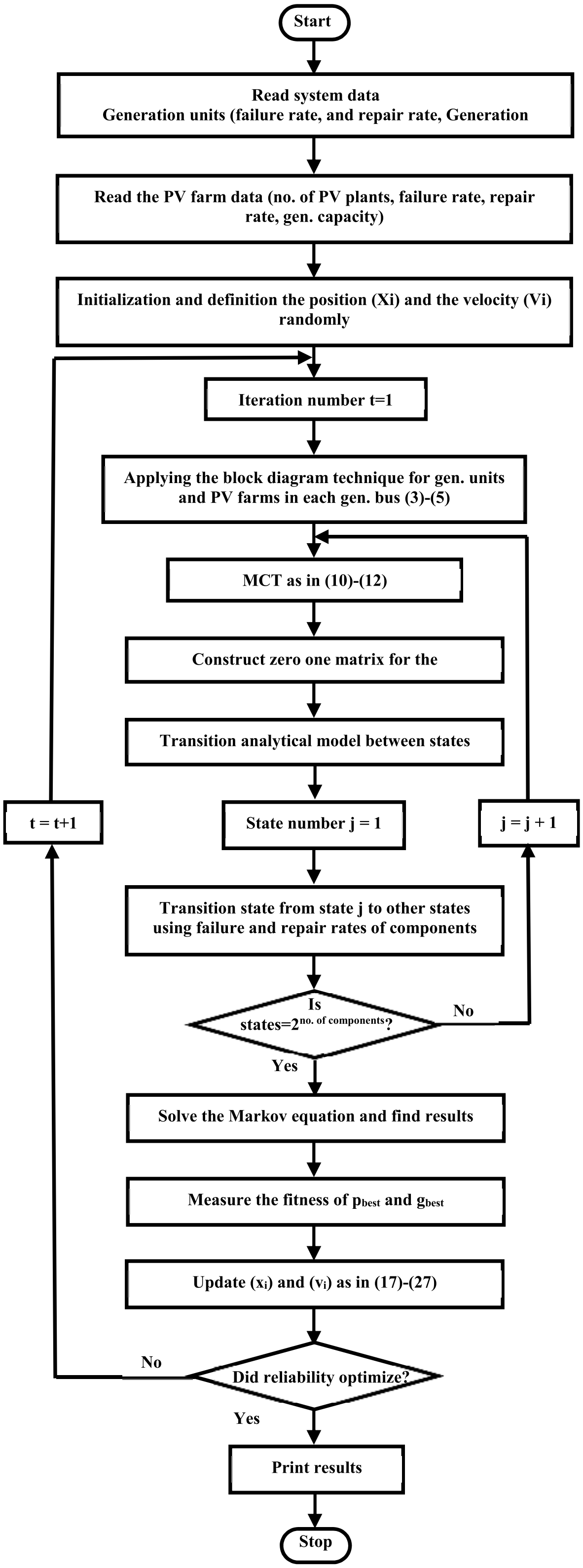

FIGURE 6. Flow chart for proposed algorithm.

The block technique is used for reducing the number of generation units from the largest number to the possible lowest number for easy evaluation. The system without PV systems has 32-generation units; therefore, the probability failure number is equal to 2^{32} states. Using the block diagram technique, the generation units have been reduced to only 10 components; therefore, the probability's failure will be equal to 2^{10} states.

The installed PV system capacities, location, PV plants No., and PV plants output are illustrated in table 3 for each study case.

TABLE 1. Capacity and location for generation unit of the system [45].

Bus No.	Unit Capacity (MW)						Total capacity
	Unit 1	Unit 2	Unit 3	Unit 4	Unit 5	Unit 6	
Bus 1	20	20	76	76	-	-	192
Bus 2	20	20	76	76	-	-	192
Bus 7	100	100	100	-	-	-	300
Bus 13	197	197	197	-	-	-	591
Bus 15	12	12	12	12	12	155	215
Bus 16	155	-	-	-	-	-	155
Bus 18	400	-	-	-	-	-	400
Bus 21	400	-	-	-	-	-	400
Bus 22	50	50	50	50	50	50	300
Bus 23	155	155	350	-	-	-	660

TABLE 2. System specification for generation unit [44], [45].

System components	Capacity of gen. unit	λ	μ
IEEE system gen. units	12	0.00034	0.0166
	20	0.00222	0.02
	50	0.000505	0.05
	76	0.00051	0.025
	100	0.000833	0.02
	155	0.00104	0.025
	197	0.00105	0.02
	350	0.00087	0.01
	400	0.000909	0.00667
PV pant	1.5	0.1	(1/30)

A. ONE PV SYSTEM INSTALLATION (IEEE_EPS_24 BUS_1_PV

The proposed technique studies the reliability evaluation of the generators of IEEE_EPS_24 bus with installed one PV system (first model) at bus 9, two PV system at buses 4 and 9 (second model), three PV system at buses 3, 4, and 9 (third model), and four PV system at buses 3, 4, 8, and 9 (fourth model). In addition, the proposed technique analyzes the impact of PV systems on the generation system reliability evaluation and an optimum capacity of the PV system for optimum reliability indices. In the first model, the optimum PV system capacity is 300 MW that is installed at bus 9, which results in an optimum voltage profile as proved in [44]. The max. power capacity of each PV plant is 1.5 MW [46], [47]. The failure and repair rates for PV plants for this power capacity are 0.1 failure/yr and (1/30) hr,

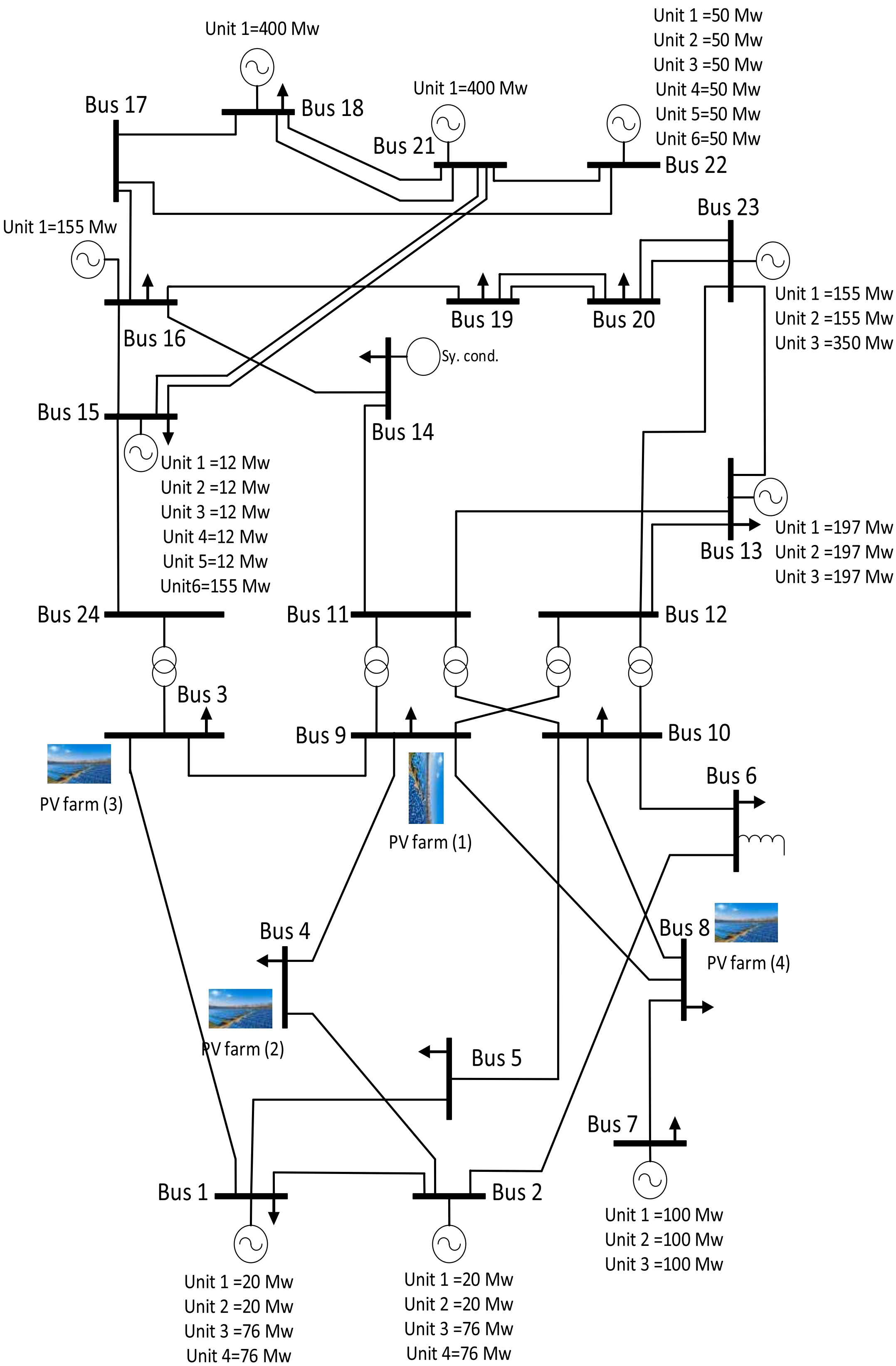

FIGURE 7. Single line diagram of IEEE_EPS_24 bus and generation unit data.

respectively [46], [47]. The 200 PV plants are required to construct the proposed PV system as shown in table (3). The system has 232 generation units and PV plants; therefore, the probability failure number is equal to 2^{232} (infinity

TABLE 3. Sitting and setting of PV System.

Case name	PV system No.	±20 % uncertainty in PV system capacity (MW)	PV system location	PV plants No.	PV Plant power output (MW)
First model	PV 1	300	Bus 9	200	1.5
Second model	PV 1	150	Bus 9	100	1.5
	PV 2	150	Bus 4	100	1.5
Third model	PV 1	100	Bus 9	67	1.5
	PV 2	100	Bus 4	67	1.5
	PV 3	100	Bus 3	67	1.5
Fourth model	PV 1	50	Bus 9	34	1.5
	PV 2	150	Bus 4	100	1.5
	PV 3	50	Bus 3	34	1.5
	PV 4	50	Bus 8	34	1.5

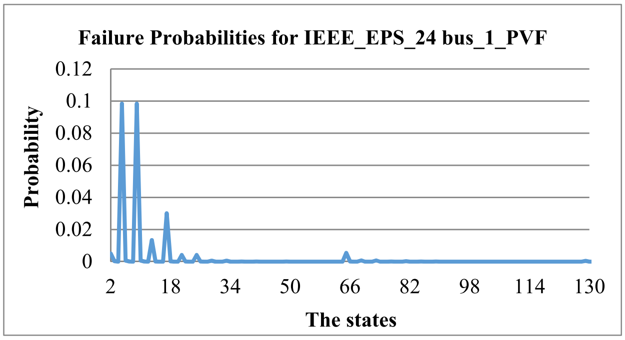

FIGURE 8. **Probability failures for IEEE_EPS_24 bus_1_PV for states from (2 to 130).**

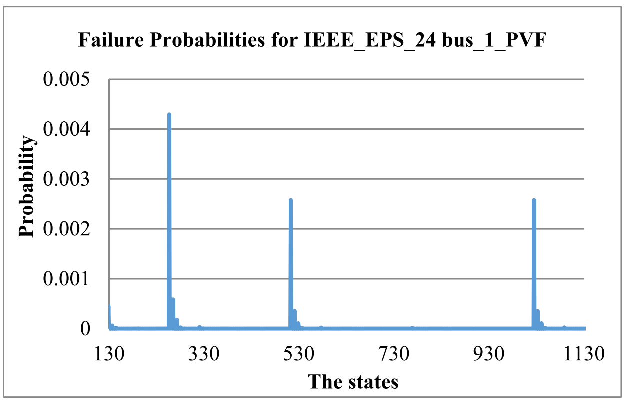

FIGURE 9. **Probability failures for IEEE_EPS_24 bus_1_PV for states from (130 to 1130).**

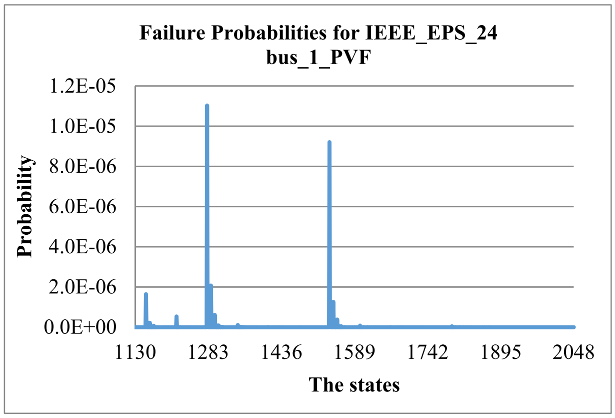

FIGURE 10. **Probability failures for IEEE_EPS_24 bus_1_PV for states from (1130 to 2048).**

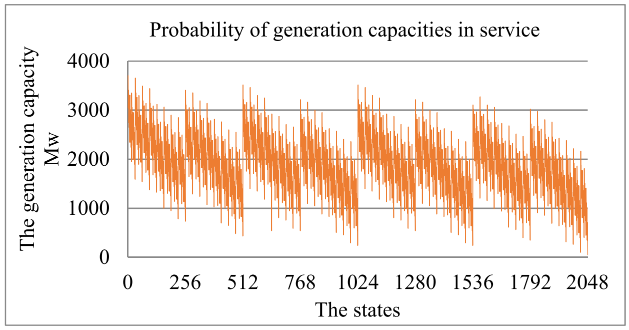

FIGURE 11. **Probability of generation capacity states in service.**

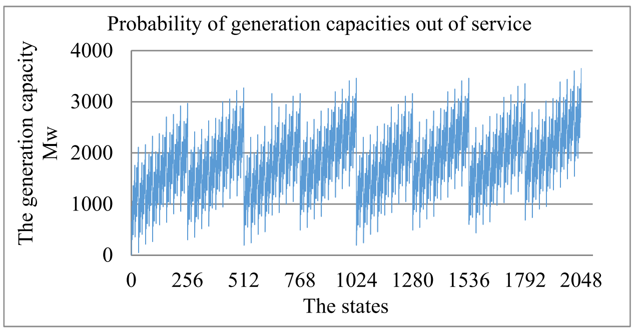

FIGURE 12. **Probability of generation capacity states out of service.**

number). By applying the block diagram technique, the generation components have been reduced to only 11 components. Therefore, the probability's failure will be equal to 2^{11} states. By applying the proposed MCT and solved Markov equation, 2048 failure probabilities have resulted and the failure probability from state 2 to 2048 are shown in Figs. (8-10). The maximum failure probability is 0.7221 at state number 1 in which all the generators are in service and PVs are in operating mode and the minimum failure probability is $4.4141e^{-25}$ at state number 2048 and in which all the generators are out of service.

Figure 11 shows the inferred states of the probability of generation's power capacities, which remained in service for each probability state. In the first probability state, all generations are in service and the system has been in a full generation. Fig.12 shows the inferred states of the probability of generation's power capacities which get out of service for each state. In the last probability state, all generations are out of service and the system has been in the blackout.

Figure 13 shows the calculated failure's probability and the availability of each generation's bus. The maximum failure probability of generation's bus is equal to 0.09867 at generation's bus 9 and the minimum value is equal to 0.000812 at

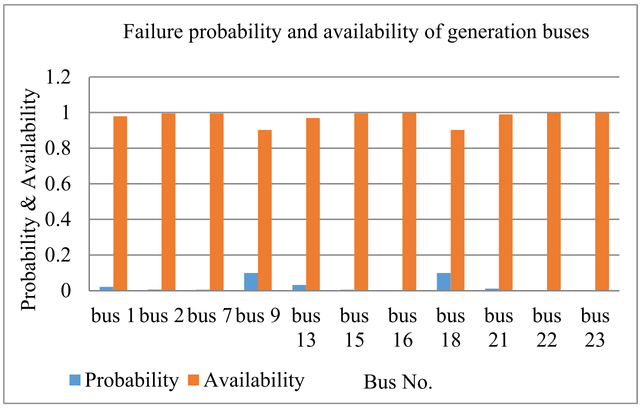

FIGURE 13. Failure probabilities and availability for generation buses.

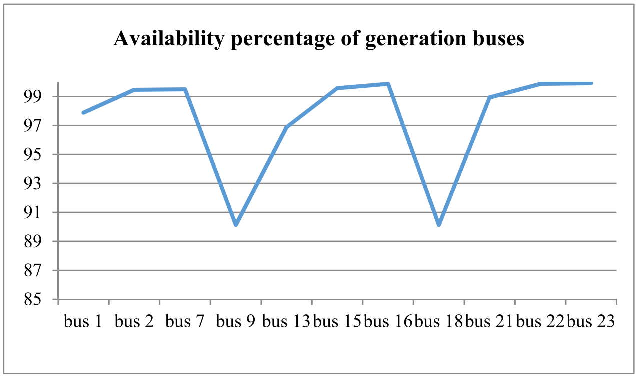

FIGURE 14. Availability percentage of generation buses.

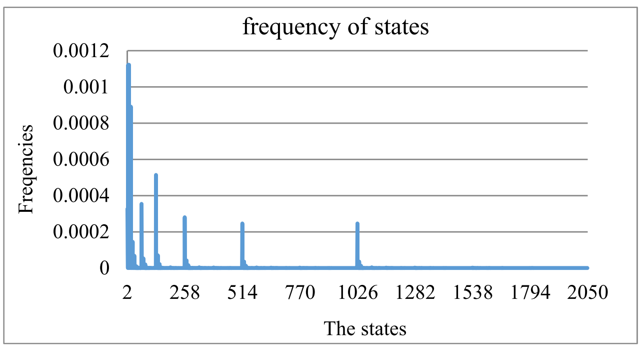

FIGURE 15. The frequency of failure probability states from (2 to 2048).

generation's bus 23. The maximum bus availability is equal to 0.99919 at generation's bus 23 and the minimum value is equal to 0.901334 at bus 9. The availability percentage of generation buses are shown in Fig.14. The assessed generation system reliability, with one installed PV with bus 9 by the proposed technique, is equal to 0.74084.

The maximum probability failure frequency and corresponding mean duration are equal to 0.004073 and 177.2879 at bus 1respectively. The minimum values of these are equal to 8.5632e^{-25} and 0.51547 at bus 2048, respectively, as shown in Fig.15.

The impact of changing the value of repair rates with different failure rate values on system availability is depicted in Fig. 16. The figure represents the relation between the

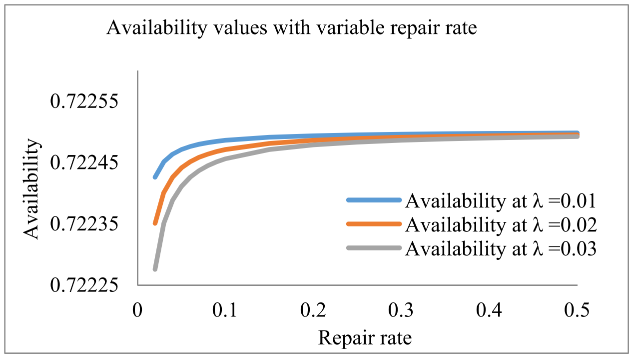

FIGURE 16. The relation between the availability and repair rate with constant failure rate.

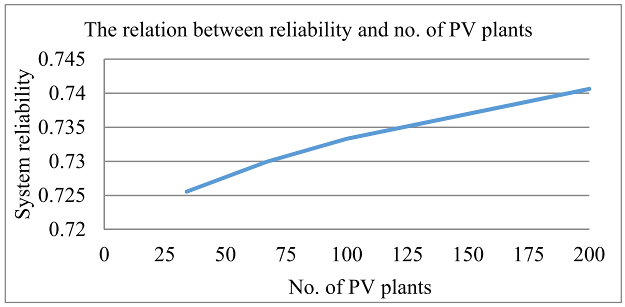

FIGURE 17. The relation between the reliability and number of pv plants.

availability of generation system and repair rate when the failure rate values were 0.01, 0.02, and 0.03. In this case, the generation system's availability increased by increasing the repair rate when the failure rate is constant and the relationship takes a curve relation similar to the logarithm curve. By changing the failure rate, the availability slope curve changed.

The relation between generation reliability and the number of PV plants used in the PV system will be investigated through Fig. 17. The reliability of the generation system increased by increasing the number of PV plants and PV system capacity. At the number of PV plants is equal to 34 units and the PV system capacity is approximately equal to 50 MW, the generation system reliability is equal to 0.72555. At the number of PV plants is equal to 67 units and the PV system capacity is approximately equal to 100 MW, the generation system reliability is equal to 0.72996. At the number of PV plants is equal to 100 units and the PV system capacity is equal to 150 MW, the generation system reliability is equal to 0.7333. At the number of PV plants is equal to 200 units and the PV system capacity is equal to 300 MW, the generation system reliability is equal to 0.7406. It can notice from the results that the generation system reliability increased by increasing the number of PV.

B. TWO PV SYSTEM INSTALLATION (IEEE_EPS_24 BUS_2_PV)

This part of the proposed study studies the reliability evaluation of the generation side for IEEE_EPS_24 bus_2_PV, which has two PV systems (second model) and analyzes the

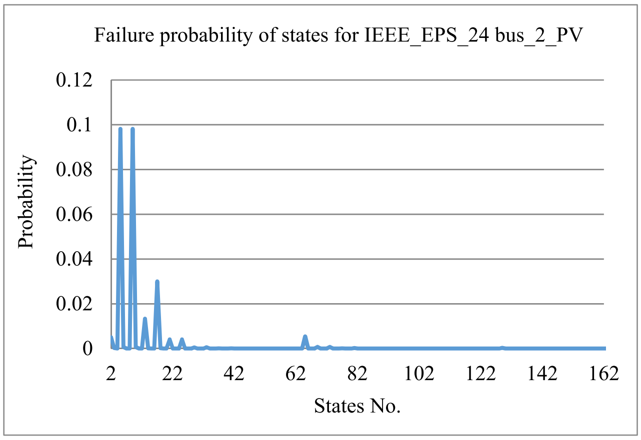

FIGURE 18. Probability failures for IEEE_EPS_24 bus_2_PV for states from (2 to 162).

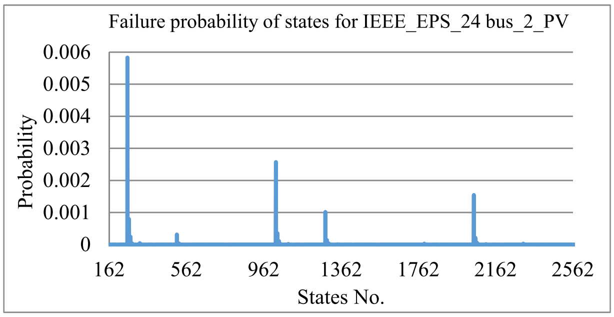

FIGURE 19. Probability failures for IEEE_EPS_24 bus_2_PV for states from (162 to 2562).

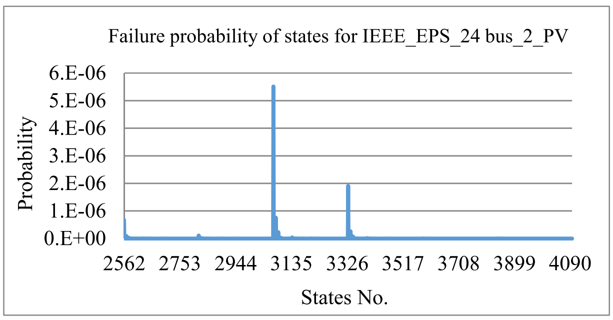

FIGURE 20. Probability failures for IEEE_EPS_24 bus_2_PV for states from (2562 to 4096).

impact of PV systems on system reliability evaluation. The total optimum PV systems capacity is 300 MW [44]. This power capacity is divided into buses 4 and 9. 100 PV plants are required to construct each PV system as shown in table 3. This system has 232 generation components; therefore, the probability of failure is equal to infinity. By applying the block diagram technique, the generation components have been reduced to only 12 components, hence the probability's failure will be equal to 2^{12} states. By applying the proposed MCT and solved Markov equation, 4096 failure probabilities are shown in Figs. (18-20).

It is noticed from the inferred results of this case that; the maximum failure probability's value is equal to 0.72035 at state No. 1 and the minimum value is equal to $1.85e^{-26}$ at state No. 4096. The failure's probability and availability percentage of generation buses are clearly illustrated in Figs. (21-22). It is noticed from the figures that; The maximum bus availability is equal to 0.9999997 at bus 22 and the minimum value is equal to 0.8565 at bus 7. The maximum bus probability is equal to 0.1435 at bus 7 and the minimum value is equal to $2.937e^{-7}$ at bus 22.

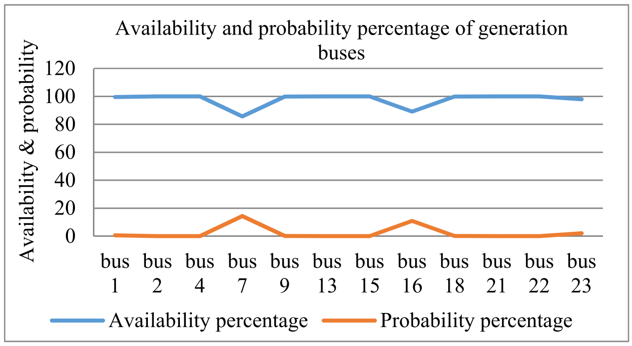

FIGURE 21. Availability and probability percentage of generation buses.

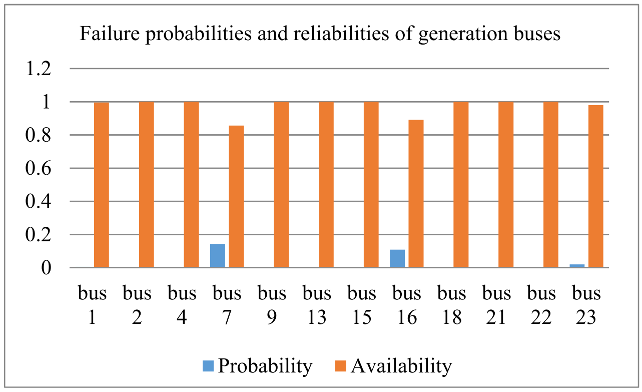

FIGURE 22. Availabilities and probabilities for generation buses.

The calculated generation system reliability with two installed PV systems with buses 4 and 9 by the proposed technique is equal to 0.7521.

The maximum probability failure frequency, in this case, is equal to 0.00563 at state 1 and the corresponding mean duration is 128.0453. The minimum value of probability failure frequency is equal to $2.174e^{-25}$ at bus 4096 and the corresponding mean duration is 0.1354.

The proposed technique also studies the reliability assessment of the generation side for IEEE_EPS_24 bus_3_PV with three PV systems (third model) and IEEE_EPS_24 bus_4_PV with four PV systems (fourth model). The optimum PV system capacity is 300 MW installed with IEEE_EPS_24 bus system at bus 3, 4, and 9 in case of the third model. 67 PV plants are required to construct the model to bus 3, 4, and 9 as illustrated in table (3). The system generation reliability assessed for the model and found equal to 0.75035.

The optimum PV system capacity installed with IEEE_EPS_24 bus system at bus 3, 4, 8, and 9 to construct the fourth model. 34, 100, 34, and 34 PV plants installed to bus 3, 4, 8 and 9, respectively, as illustrated in table (3) [44].

TABLE 4. Sitting and setting of pv systems and optimum reliability for models (The best of 10 run).

	No. of PV plants at bus 3	No. of PV plants at bus 4	No. of PV plants at bus 8	No. of PV plants at bus 9	System reliability
2nd model	-	34	-	166	0.75765392
3rd model	34	130	-	36	0.75620958
4th model	34	98	34	34	0.75587128

TABLE 5. The comparison between reliability indices for models.

Reliability indices	1st model	2nd model	Optimum 2nd model
System reliability	0.7408	0.7521	0.7577
AFD [48]	0.01038316	0.01545053	0.01980198
AID [48]	0.67318351	1.08620151	1.13583118
TID	2759.37922	4452.20511	4655.6371
System availability	0.27795	0.279655	0.281821
System unavailability	$1.87e^{-01}$	$3.53e^{-05}$	$3.60e^{-05}$
LOLP [29]	1.73895111	1.61308078	1.59169005
LOLE [29]	17.950849	15.2681942	13.223795

The system generation reliability assessed for the model and found equal to 0.755958.

C. OPTIMUM CAPACITIES OF PV SYSTEMS INSTALLATION

This part presents the optimal reliability indices for the last three models with two, three, or four PV systems. The optimal capacity and location of the PV system will be determined for each model. The model constraints considered in this study as are the total PV systems capacity is 300 MW as illustrated in table (3), the total power capacity for each PV panel must be 1.5 MW, the minimum power generation form the PV system is 50 MW, and the number of PV systems are two, three, or four for second, third, and fourth model, respectively [44].

By applying the proposed MAACPSO method 10 times to each of the last three models, the best results are tabulated in Table 4. The optimum system reliabilities are 0.75765392, 0.75620958, and 0.755871284 for the second, third, and fourth models, respectively. The sitting and setting of PV systems in the second model are 34 connected with bus 4 and 166 connected with bus 9. The sitting and setting of PV systems in the third model are 34 connected with bus 3, 130 connected with bus 4, and 36 connected with bus 9. The sitting and setting of PV systems in the fourth model are 34 connected with bus 3, 98 connected with bus 4, 34 connected with bus 8, and 34 connected with bus 9.

From these results, the best system generation reliability is 0.75765392 in the second model that contains two PV systems. Comparing the reliability indices between the first, second, and optimization case of the second model is illustrated in table (5).

From these results, the best system availability value is 0.281821 in case of the optimum model, the best LOLP value is 1.59169005 in case of the optimum model, and the best LOLE value is 13.223795 in case of the optimum model.

IV. CONCLUSION

This study focused on the probability analysis and reliability assessment of the components of grid-tied PV systems through IEEE 24 system with four different models; each has a different number of PV systems. Three combined algorithms were utilized in the proposed method, and these algorithms are the block diagram technique, Markov process technique, and the MAACPSO optimization algorithm. The block diagram technique succeeded in reducing a large number of system components to only a few components. The effectiveness of Markov process succeeded in assessing the whole generation system's reliability, reliability indices, maximum and minimum of failure probabilities' frequency, mean duration corresponding to maximum and minimum of failure probabilities' frequency, maximum and minimum failure probabilities, and maximum and minimum of the generation's buses availability. While MAACPSO is used to optimize a multi-objective, function proposed in this study.

Besides, there are some meaningful conclusions about the reliability assessment of the system that are:

1) When used one PV system with a maximum power capacity of 300 MW is installed at bus 9, the generation system reliability is assessed by the proposed technique and found equal to 0.74084.
2) In the first model, the availability of the generation system increased by increasing the repair rate when the failure rate is constant. By changing the failure rate, the slope of the reliability curve changed.
3) The generation system reliability is equal to 0.7256 in the first model and the number of PV plants equal to 34 units. At the number of PV plants is equal to 67 units, the generation system reliability is equal to 0.72996. At the number of PV plants is equal to 100 units, the generation system reliability is equal to 0.73331. At the number of PV plants is equal to 200 units, the generation system reliability is equal to 0.74084. it can conclude from the results that the generation system reliability increased by increasing the number of PV system capacity.
4) When used two, three, or four PV systems with a total power capacity of 300 MW, the power capacity is divided between two, three, and four buses, respectively. The generation system reliability assessed by the proposed technique and found equal to 0.7521, 0.75035, and 0.755958, respectively. The system reliability increased by distributing the PV power capacity on buses compared to that obtained by the first model.
5) The optimum system reliabilities are 0.7577, 0.7562, and 0.7559 when applied the MAACPSO optimization algorithm on the second, third, and fourth model, respectively. This optimum system reliability increased by 2.28 %, 2.07 %, and 2.033 % compared to that obtained by the first model.
6) The proposed technique succeeded in constructing the optimum generation system reliability for IEEE_EPS_24_bus with installed two PV systems.

The installed PV systems are 51 MW and 249 MW installed on bus 4 and 9, respectively. In this optimum model, the LOLP and LOLE were reduced by 8.5 % and 26.33 %, respectively, about the primary system.

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