# Analysis the Impact of Renewable Energy Based-Wind Farms Installed with Electrical Power Generation System on Reliability Assessment

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**Abstract-** Regard to the vast growing technologies in the use of wind turbines and wind farms as a renewable energy source, many searches had been proved its good impact on electrical transmission systems performance regarding congestion, power losses, voltage stability, and voltage profiles. This paper aims to prove the positive effect of the connection of wind farms to power system from the view of reliability and evaluates all the states of different generation's probabilities for the power systems. The proposed method used both block diagrams and the Markov chain techniques to assess the whole generation system reliability, the generation buses reliabilities, the states of generation probabilities, the frequency and mean duration of generation failure states, and the capacities of generation's system that are in or out of service for each failure state. Also, it is assessed the system reliability, reliability indices, and analyzed the impact of forced outage rate for each wind turbine and the number of used wind turbines in each wind farm. MATLAB code is developed using Markov chain construction. The effectiveness of the proposed method is demonstrated through an updated version of IEEE_RTS_24_node with installed six wind farms (IEEE_UV_EPS_24_bus_6_WFs). Each wind farm has power capacity of 200 MW. The proposed methodology by using block diagram technique has been succeeded to reduce the number of system components from 434 to only 12 components and Markov's states from infinity number to 4096 states. On the other hand, this proposed system is feasible.

**Keywords-** Block diagrams; Electrical power system; Markov chain; Probability failure states; Reliability evaluation; Wind farms.

## 1. Introduction

Due to the fast technology creativity in renewable energy generation, the developments of new innovative products are becoming very complex to meet their system functions, performances, and components. Therefore, the system reliability assessment is playing an important role in academic research and practice to check the system security.

The analysis of the system's reliability evaluation of any electrical power system divided into three main partition zones. The first zone named generation system or hierarchical level I, in which the analysis for the generation part only of the electrical power system. The second zone named composite system or hierarchical level II, in which the analysis for the generation and transmission of the electrical power system. The third part named distribution system or hierarchical level III, in which the analysis for the generation, transmission, and distribution of the electrical power system. The assessment of system reliability used to determine the components' ability to achieve the best system performance. The main step in the reliability studies is the construction of mathematical or simulation models for the system and meta-heuristic. For these reasons, the newly proposed technique studied, analyzed, and assessed the reliability of the electrical power generation side of the electric power system with and without wind farms installation. The reliability system evaluation based on the failure and repair rates of wind farms and each unit of generators for each bus. The proposed technique designed the analytical system model which represented the electrical system by mathematical model and depended on block diagrams and Markov chain process as two main combined techniques. Markov technique based on system components' assessment predictive.

In the past few years, researchers concentrated on reliability evaluation of the electrical power system and transmission by using many techniques to achieve their aims. For example, Zhao et al. [1], proposed the power system reliability assessment of a power station and focused on finding the optimum value of wind turbine generators with multi-energy storage systems. The results show that the use of multi-energy storage systems with a wind turbine installed to the power system is good to ensure reliability. Al-Muhaini et al. [2], presented the evaluation of distribution system reliability indices which based on wind turbine taking the fluctuations of wind speed into account. The results show that, the system reliability is sensitive to the types of wind speed modeling technique and that the best optimal model is the auto-regressive moving average. Dezaki et al. [3], proposed 69_bus distribution system reliability indices assessment with six distributed generators technology scenarios and tried to reduce the evaluation computing time. The results show that, the use of hybrid DG technologies is the most effective solution to reduce the reliability assessment running time. Peyghami et al. [4], presented the power system reliability indices evaluation which is incorporated with the power electronic converters model. The results showed by studying the impact of power converters on the system reliability with different applications and different penetration levels of wind turbines that, the wind profile for all WTs are considered to be identical. Verma et al. [5], proposed the reliability evaluation of substations system 66/11 kV by the trapezoidal fuzzy technique based on fault tree analysis and minimal cut sets method. The results show the most critical events which affect the reliability system. The author's technique succeeded to assess the reliability of subsystems and expressed the real-life situation in a more flexible manner. Kadhem et al. [6], evaluated the reliability of three buses' electrical power systems by fault tree analysis, minimal cut sets, and tracing minimal paths techniques. Chen et al. [7], assessed the reliability indices of composite power systems with wind farms by using the Monte Carlo simulation technique and spearman's rank correlation coefficient. The authors used two kinds of wind farms and installed them in the IEEE RTS 79. The results show that, the impact of wind speed correlation on the capacity credit of wind farms is related to transmission congestion and wind farm's sitting. Zheng et al. [8], simulated the operation of generation units with installing wind turbines and energy storage systems to assess the reliability indices of the IEEE RTS system by considering random speed fluctuations of the wind. The results show that, the installing of wind turbines with energy storage improves the system reliability at peak load. Allahnoori et al. [9], considered the uncertainty in both generation side and load demand and evaluated the microgrid distribution system reliability's performance. The authors demonstrated their method of the distribution system by installing renewable energies. The results show that the microgrid's performances are affected by the nature of loads and generations. Chang et al. [10], presented the performance and the reliability assessment of part of China's southern power grid under cascading failures due to earthquakes and hypothetical terrorist attacks. The authors used the Matrix Based System Reliability (MBSR) method which based on OPA and CASCADE models. The results show the evaluation of blackout's risk by cascading failures and improve the power system's resilience with disturbances. Kadhem et al. [11], used the Monte Carlo simulation technique to study the effect of duration and frequency of failure of wind turbine generators on the wind energy conversion system. Singh et al. [12], proposed a reliability evaluation for some hybrid systems involving conventional and alternating energy sources by using the Monte Carlo simulation technique. Billinton et al. [13], used the Monte Carlo simulation method to evaluate the reliability of the bulk electric system with the installation of wind energy conversion systems which had been connected to a weak point in the transmission system. Billinton et al. [14], presented analytical models for wind energy conversion systems which can be used with the Monte Carlo simulation technique or analytical reliability assessment method. Billinton et al. [15], proposed the reliability assessment for composite generation and transmission of electric power system with wind energy conversion system by using the Monte Carlo simulation technique. Ling-jun et al. [16], presented a fuzzy analytic hierarchy process evaluation method to assess the grid system with the connection of wind farms. Karki et al. [19], used the Monte Carlo simulation method to evaluate the electrical power system with wind turbine generators taking into account the wind speed as a parameter in the simulation model.

This paper presents the reliability assessment for hierarchical level I (HL- I ) of the IEEE_UV_EPS_24 bus_6_WFs system includes 6 wind farms installed to the IEEE_EPS_24 bus. Each wind farm has 67 wind turbines. The electrical power capacity for each wind turbine is equal to 3 MW. The main contribution of this paper is as follows:

- The assessment of the whole generation system reliability
- The generation buses availability and unavailability

- The states of generation probabilities
- The frequency and mean duration of generation failure states
- The capacities of generation's system that are in or out of service for each failure state.

In addition, it studied the analyses of the impact of forced outage rate (FOR) for each wind turbine and also the effect of changing the number of used wind turbines in each wind farm.

The proposed technique and tested case are performed by Lenovo laptop with processor Intel ®core™, i3-4030u, CPU@ 1.90 GHz., and Ram memory are equal to 4.00 GB. All programs executed by MATLAB, R2015a with the time taken about 285.226 sec.

The paper is organized as follows. Section 2 describes the system failure rate. Section 3 represents the problem formulation, while section 4 describes the analytical Markov technique based on the transition between probability states. Section 5 represents the case study, the failure frequency, the mean duration, the generation capacity in or out of service with failure probabilities, the reliability for each generation bus, and the impact of FOR of the wind turbine on the system reliability. Section 6 describes the results and discussions. Finally, section 7 is the conclusions.

## 2. Failure rate

The component's reliability depends on the failure frequency which is expressed by Mean Time To Failures (MTTF). The MTTF is the average expected time between failures of a component and can be calculated by the failure rate inverse (1/λ). The prediction of reliability is based on the failure rate which is defined as the predicted number of times to fail a component in a determined period of time [18]. Figure 1, shows the bath tub curve for component's life time.

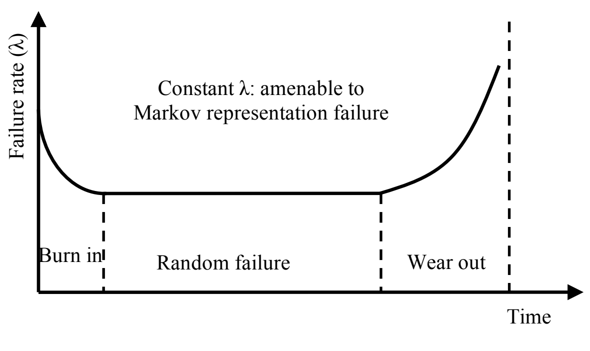


**Fig.1:** Bath tub curve for component's life time

Another important expression is the meantime to repair (MTTR) which is defined as the total time that spends for repairing the component divided by the total repair numbers. The MTTR can be calculated by the repair rate inverse (1/μ). Fig.1 shows the relation between time life for wind turbines and the failure rate for different values of deterioration phase β [18].

Figure 1 shows the three parts of bath-tub curve which are,

- Early failures, this is the first part and in which β is less than 1
- Constant failure rate, this is the second part in which β is equal to 1.
- Deterioration failures, this is the third part in which β is more than 1.

The FOR is calculated as shown in the following equation [19].

$$FOR=\lambda/(\lambda+\mu) \quad (1)$$

The relation failure rate with operating time is calculated as in the following equations [20].

$$\lambda(t)= (\beta/\Theta)(t/ \Theta)( \beta-1) \quad (2)$$

$$= \rho\ (t/ \Theta\ )(\beta-1) \quad (3)$$

$$\rho = 1/( \Theta\beta) \quad (4)$$

Where: Θ is the scale parameter and Θ>0 for time (t) ≥0.

## 3. Problem Formulation

### 3.1. Block Diagram

The block diagram technique used to evaluate the system components' reliability and assess the total reliability for a group of components connected together in series or parallel connection [21]. By representing the failure rates for the system's components in a graphical representation model and dividing the system into groups in series or parallel connection, the total failure rate for this system can be calculated.

### 3.2. Series and Parallel connections

The system consists of an interconnected group of exponential functions which represents the components' failure rate. The block diagram for a group consists of n components in series is shown in Fig.2 is calculated by the following equations [22-24].

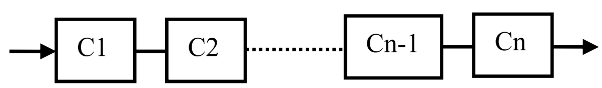


**Fig.2:** Block diagram for a group consists of n components in series

$$R(t) = e^{-\lambda t} \quad (5)$$

$$R_{total} = \prod_{i=1}^{n} R_i \qquad \text{For } i= 1, \ldots\ldots, n \quad (6)$$

$$\lambda_{total} = \sum_{i=1}^{n} \lambda i \qquad \text{For} \quad i= 1,\ldots\ldots, n \qquad (7)$$

Where: $R_{total}$ is the total reliability of the system components; $\lambda_{total}$ is the total failure rate of system components; λi is the failure rate for component i.

The Block diagram consists n components connected in parallel is shown in Fig.3 which, is calculated by (9) [22-24].

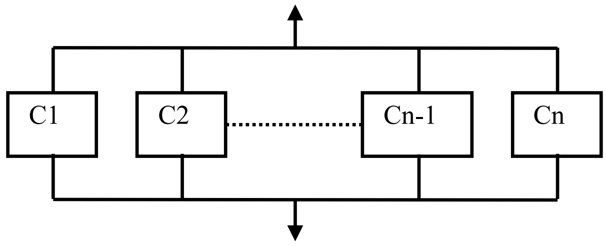


**Fig.3.** Block diagram consists n components connected in parallel

$$R_{total} = 1 - [\,(1-R_1)(1-R_2)\ldots..(1-R_n)] \qquad (8)$$

$$\frac{1}{\lambda total} = [\,\frac{1}{\lambda 1} + \frac{1}{\lambda 2} + \ldots.. + \frac{1}{\lambda n}\,] - [\,\frac{1}{\lambda 1+\lambda 2} + \frac{1}{\lambda 1+\lambda 3} + \ldots.. + \frac{1}{\lambda 1+\lambda n}\,] + [\,\frac{1}{\lambda 1+\lambda 2+\lambda 3} + \frac{1}{\lambda 1+\lambda 2+\lambda 4} + \ldots.. + \frac{1}{\lambda 1+\ldots+\lambda n}\,] - \ldots\ldots\ldots.. + [\,(-1)^{n+1}\,(\frac{1}{\sum_{1}^{n} \lambda n})\,] \qquad (9)$$

The analytical Markov technique presents representation for all the states of the system's probabilities by the transition between states [25]. To determine the states of the system's probabilities, the analytical Markov technique starts by establishing a transition matrix that depends on Markov's zero and one matrix and represents all transitions between the states either transition between each component's failure mode or repair mode.

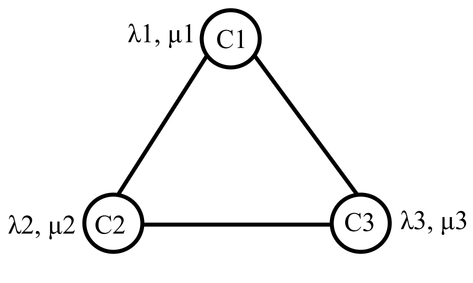


**Fig.4:** Three generation components system

Figure 4 shows an three generation components system which has three generator components C1, C2, and C3. Each component has failure and repair rates λ1, µ1, λ2, µ2, λ3, and µ3, respectively. As Markov technique, the number of cases is equal to 2n cases and n is equal to the number of components [25]. In an electrical power system the component's failure and repair are represented by up and down states, respectively. The up-state is characterized by 0 and the down-state is characterized by 1.

The dimensions of zero one matrix are equal to i and j, where, i equals to number of components and j equals to $2^i$.

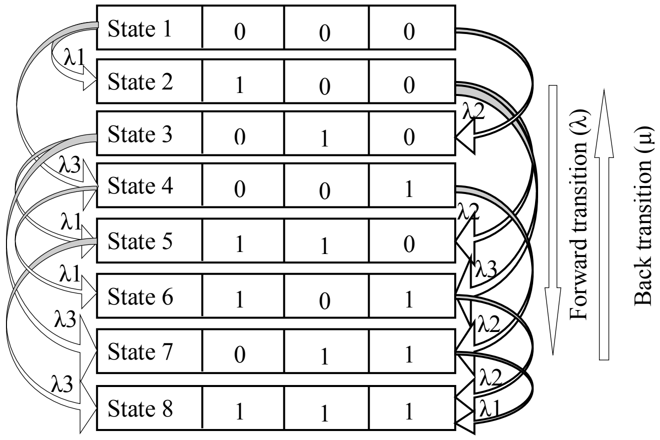


**Fig.5:** The transition diagram between states

Figure 5 shows the transition diagram between states. The forward transition represents the transition from 0 to 1 and represents the change from operation mode to failure mode. The back transition represents the transition from 1 to 0 and represents the change from failure mode to operation mode. State 1 represents the on case for all components of whole system and has three transitions by λ1, λ2, and λ3 and each transition case can back to the previous state by µ1, µ2, and µ3, respectively. States 2, 3, and 5 have two transitions by λ2, λ3, λ1, λ3, λ1, and λ2, respectively. Each transition case from them can back to previous states by µ2, µ3, µ1, µ3, µ1, and µ2, respectively. States 4, 6, and 7 have one transition by λ3, λ2, and λ1, respectively. Each transition case from them can back to previous states by µ3, µ2, and µ1, respectively. State 8 represents the off case for all components and hasn't any transition except back to previous states by µ1, µ2, µ3. This last state represents the blackout of the system. The transition from state 1 to state 2, 3, and 4 occur by fail of components 1, 2, and 3, respectively. The transition from state 2 to state 5 and 6 occur by fail of components 2 and 3, respectively. The transition from state 3 to state 7 occur by fail of components 3. The transition from state 4 to state 8 occurred by fail of components 1 and 2.

Constructing the transition matrix by entering the failure and repair rates to represent the change between probabilities of states. It is noticed from the transition matrix in (11) that, the part found upper of the diagonal represents the transition of failure mode between states, the part found under the diagonal represents the transition of repair mode between states. The diagonal part represents Markov's assumption. Each element in the diagonal part is equal to minus the sum of its row's elements as Markov assumption [26].

$$[Pr] \times [T] = [0] \qquad (10)$$

Where: Pr is the states of system's probabilities, T is the transition matrix [26].

$$[Pr] \times \begin{bmatrix} -(\lambda1+\lambda2+\lambda3) & \lambda1 & \lambda2 & 0 & \lambda3 & 0 & 0 & 0 \\ \mu1 & -(\mu1+\lambda2+\lambda3) & 0 & \lambda2 & 0 & \lambda3 & 0 & 0 \\ \mu2 & 0 & -(\mu2+\lambda1+\lambda3) & \lambda1 & 0 & 0 & \lambda3 & 0 \\ 0 & \mu2 & \mu1 & -(\mu2+\mu1+\lambda3) & 0 & 0 & 0 & \lambda3 \\ \mu3 & 0 & 0 & 0 & -(\mu3+\lambda1+\lambda2) & \lambda1 & \lambda2 & 0 \\ 0 & \mu3 & 0 & 0 & \mu1 & -(\mu3+\mu1+\lambda2) & 0 & \lambda2 \\ 0 & 0 & \mu3 & 0 & \mu2 & 0 & -(\mu3+\mu2+\lambda1) & \lambda1 \\ 0 & 0 & 0 & \mu3 & 0 & \mu2 & \mu1 & -(\mu3+\mu2+\mu1) \end{bmatrix} = [0] \quad (11)$$

Take the transpose of matrices, equation (11) changed to the form in (12).

$$[Pr]^{-1} \times [Pr] = [0] \quad (12)$$

Another assumption on Markov technique is that, the sum of all states of system's probabilities is equal to one as shown in the following equations [25-28].

$$Pr1 + Pr2 + Pr3 + Pr4 + Pr5 + Pr6 + Pr7 + Pr8 = 1 \quad (13)$$

$$\begin{bmatrix} 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 \\ \lambda1 & -(\mu1+\lambda2+\lambda3) & 0 & \mu2 & 0 & \mu3 & 0 & 0 \\ \lambda2 & 0 & -(\mu2+\lambda1+\lambda3) & \mu1 & 0 & 0 & \mu3 & 0 \\ 0 & \lambda2 & \lambda1 & -(\mu2+\mu1+\lambda3) & 0 & 0 & 0 & \mu3 \\ \lambda3 & 0 & 0 & 0 & -(\mu3+\lambda1+\lambda2) & \mu1 & \mu2 & 0 \\ 0 & \lambda3 & 0 & 0 & \lambda1 & -(\mu3+\mu1+\lambda2) & 0 & \mu2 \\ 0 & 0 & 0 & 0 & \lambda1 & 0 & -(\mu3+\mu2+\lambda1) & \mu1 \\ 0 & 0 & 0 & \lambda3 & 0 & \lambda2 & \lambda1 & -(\mu3+\mu2+\mu1) \end{bmatrix} \times [Pr] = \begin{bmatrix} 1 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \end{bmatrix} \quad (14)$$

States of system's probabilities can be gotten by solving the Markov (14).

The probability state Pr8 represents the completely black out of system and unacceptable state. The system's availability and reliability are calculated by the following equations [18, 29].

$$Availability = Pr1 + Pr2 + Pr3 + Pr4 + Pr5 + Pr6 + Pr7 \quad (15)$$

$$Unavailability = \sum All\ probability - Pr1 \quad (16)$$

The failure frequency of states ($FFS_i$) can be calculated by the following equations [30-31].

$$FFS_i = RDS_i \times Pr_i \quad (17)$$

Where: $RDS_i$ is the rate of departure of i state.

The mean duration of states ($MDS_i$) can be calculated by the following equation [30].

$$MDS_i = 1 / RDS_i \quad (18)$$

The loss of load probability (LOLP) definition is the probability of the system load exceeding available generation capacity in the day and can be calculated as the following equation [22].

$$LOLP = \sum_{i=1}^{n} P_i t_i \quad (19)$$

Where: $t_i$ is the duration of loss of capacity in percent.

The loss of load expectation (LOLE) definition is the probability that aggregates will not be able to cover the necessary power consumption and can be calculated as the following equation [22].

$$LOLE = \sum_{i=1}^{n} P_i (t_i - t_{(i-1)}) \quad (20)$$

## 4. Case Study

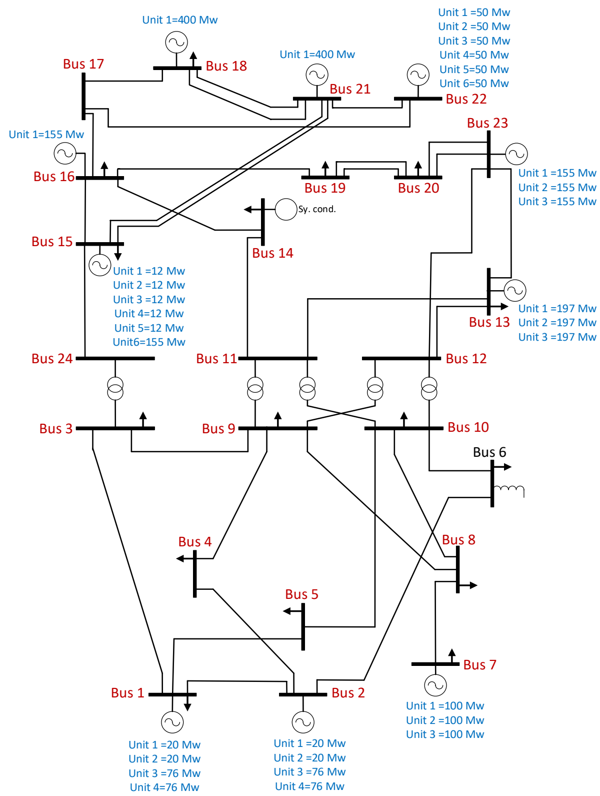


**Fig.6:** Updated single line diagram of IEEE_UV_EPS_24 bus _6 WFs system and its generation unit data

Figure 6 shows updated single line diagram of IEEE electrical power system RTS_24_node (IEEE_UV_EPS_24 bus _6 WFs) system and its generation unit data which installed six wind farms. IEEE_EPS_24_bus has 24 buses, 5 electrical power transformers, 9 cable lines, 29 overhead lines, and 10 generators connected to 10 buses; each generator contains some generation units as shown in Table 1 [33-34]. The six wind farms in the IEEE_UV_EPS_24 bus_6 WFs system have been connected to buses 3, 5, 7, 16, 21, and 23. Buses 3 and 5 had been operated as load buses in the old version and had been transformed into generation buses by wind farms connection. The number of generation units has been increased in buses 7, 16, 21, and 23 by wind farms connection in parallel with the old generation's units [32, 35].

Table 2 illustrated the failure and repair rates for each generation unit which connected to the buses and all data collected from [34]. Also, the table illustrated the failure and repair rates for each wind turbine in the wind farms with different FORs and all data collected from [35].

**Table 1:** Location and power capacity of wind farms and generation unit [33-34].

| Bus No. | 1 | 2 | 3 | 5 | 7 | 13 | 15 | 16 | 18 | 21 | 22 | 23 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Wind farm capacity (MW) | - | - | 200 | 200 | 200 | - | - | 200 | - | 200 | - | 200 |
| Unit Capacity (MW) | 20 | 20 | - | - | 100 | 197 | 12 | 155 | 400 | 400 | 50 | 155 |
| | 20 | 20 | - | - | 100 | 197 | 12 | - | - | - | 50 | 155 |
| | 76 | 76 | - | - | 100 | 197 | 12 | - | - | - | 50 | 350 |
| | 76 | 76 | - | - | - | - | 12 | - | - | - | 50 | - |
| | - | - | - | - | - | - | 12 | - | - | - | 50 | - |
| | - | - | - | - | - | - | 155 | - | - | - | 50 | - |
| Total capacity | 192 | 192 | 200 | 200 | 500 | 591 | 215 | 355 | 400 | 600 | 300 | 860 |

Each used wind farm has power capacity equal to 200 MW [35], the proposed method assumed each wind farm contains 67 wind turbines and each wind turbine has 3 MW. All wind turbines in each wind farm connected together in parallel. By applying the block diagram theory on this connection, the proposed technique calculated the failure and repair rates for wind farms as explained in (9) as shown in Table 3. The failure and repair rates for each wind farm are shown in Table 3 with different FORs. It is noticed from Tables (2, 3) that, the failure rate for wind farm is less than the value of wind turbine and the repaire rate is more than the value of wind turbine because the wind turbines connected in parallel. The flow chart for the proposed technique has been shown in Fig.7. The presented method divides into seven steps.

- The first step is titled the system's data reading step, in which all information for system's data are collected like number of generation units, the capacity for each generation bus, FOR, failure rate, and repair rate for each unit.

- The second step is titled block diagram construction. In this step the number of systems' components reduced from infinite number to 12 components by applying Block diagram theory.

**Table 2:** Failure and repair rate for generation unit and wind turbine [33, 35].

| Generation unit | Capacity (MW) | FOR | λ | μ |
|---|---|---|---|---|
| Unit 1 | 12 | 0.02 | $0.34e^{-3}$ | 0.0166 |
| Unit 2 | 20 | 0.1 | $0.222e^{-2}$ | 0.02 |
| Unit 3 | 50 | 0.01 | $0.505e^{-3}$ | 0.05 |
| Unit 4 | 76 | 0.02 | $0.51e^{-3}$ | 0.025 |
| Unit 5 | 100 | 0.04 | $0.833e^{-3}$ | 0.02 |
| Unit 6 | 155 | 0.04 | $0.104e^{-2}$ | 0.025 |
| Unit 7 | 197 | 0.05 | $0.105e^{-2}$ | 0.02 |
| Unit 8 | 350 | 0.08 | $0.87e^{-3}$ | 0.01 |
| Unit 9 | 400 | 0.12 | $0.909e^{-3}$ | 0.00667 |
| Wind turbine | 3 | 0.04 | 2.43333 | 0.00667 |
| | | 0.08 | 2.72050 | 0.003571 |
| | | 0.12 | 3.61983 | 0.00303 |

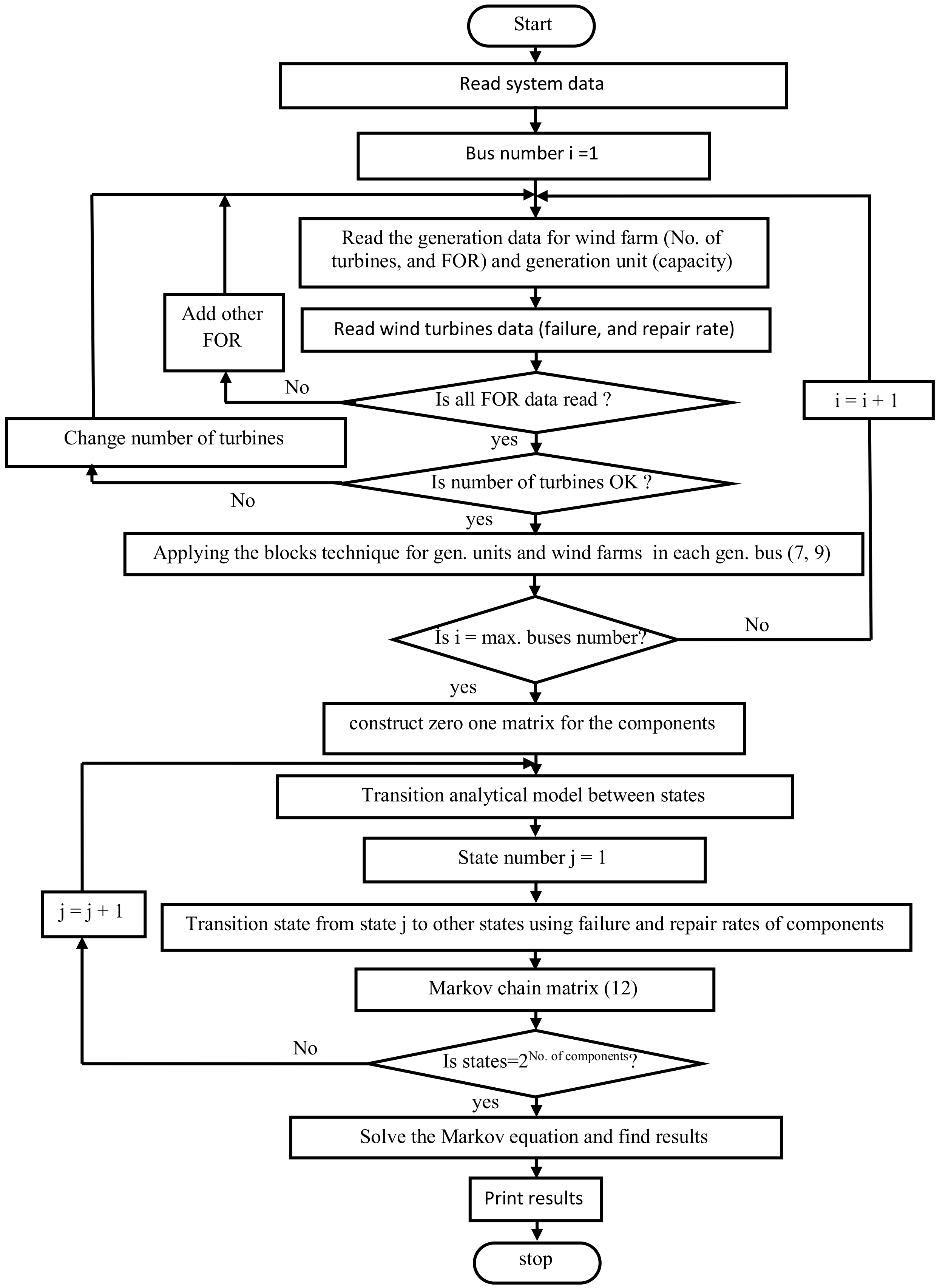


**Fig.7:** Flow chart of proposed technique

- The third step is zero one matrix construction, the dimension of the matrix is 12 columns and 4096 rows. This matrix represents the changes in probabilities' state from 0 to 1.
- The fourth step is Markov chain construction. The matrix represents the transition between probability states by changing the failure and repair rates. This matrix has dimensions 4096 column and 4096 rows.
- The fifth step is Markov equations solution and the discussion of the results.
- The sixth step is FOR effective. Changing the FOR to collect the results and analyze the effect of FOR on the system reliability.
- The seventh step is the assessing of the system reliability indices and analyze the results.

Table 3: Failure and repair rate for wind farm and its FOR

| Forced outage rat (FOR) | Failure rate (λ) | Repair rate (μ) |
|---|---|---|
| 0.04 | 0.05218 | 0.44689 |
| 0.08 | 0.058333 | 0.239257 |
| 0.12 | 0.07762 | 0.20301 |

## 5. Results

### *5.1. The first issue*

The first issue studied the impact of wind farms which installed on the IEEE_UV_EPS_24 bus _6 WFs system in case of FOR of wind turbine equal to 0.04. It's found by applying the proposed technique that, the failure probabilities' states are shown in Figs. (8, 9, 10, 11). The failure probabilities' states from 2 to 1026 are shown in Fig.8, the failure probabilities' states from 1026 to state 1666 are shown in Fig.9, the failure probabilities' states from 1666 to state 2386 are shown in Fig.10, and the failure probabilities' states from 2386 to state 4096 are shown in Fig.11. It noticed from the previous figures that, the maximum and minimum failure probabilities' values are equal to 0.86567 at state No.1 and $6.55e^{-41}$ at state No. 3840. All generators are in operation mode in case of maximum failure's probability. All generators are in failure mode except that connected at bus 18 in case of minimum failure's probability.

Figure 12 shows the generation's buses availability and unavailability. It noticed from the figure that, the maximum and minimum availability of generation's bus are equal to approximately 1 at generation's bus 15 and 0.877906387 at generation's bus 16, respectively, and maximum and minimum generation's bus unavailability are equal to 0.122094 at generation's bus 16 and $1.03834e^{-11}$ at generation's bus 1, respectively.


**Fig.8:** The failure probability values from state 2 to state 1026

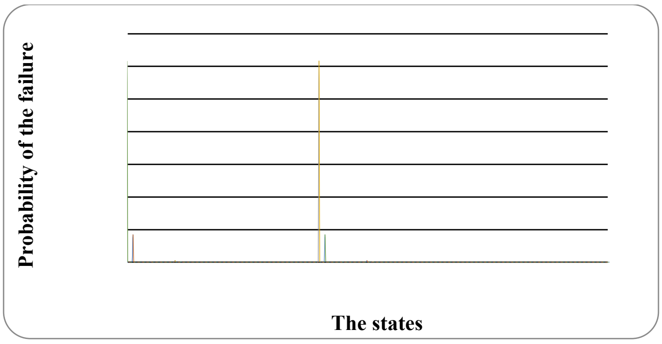


**Fig.9:** The failure probability values from state 1026 to state 1666

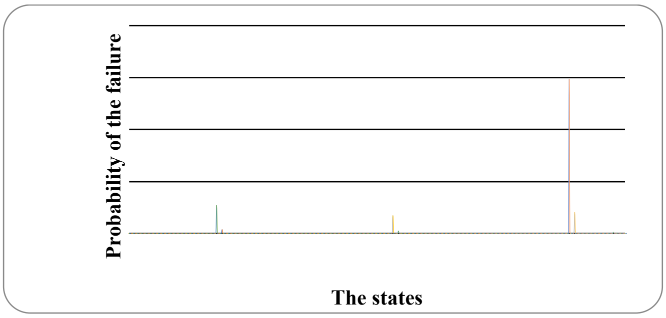


**Fig.10:** The failure probability values from state 1666 to state 2386


**Fig.11:** The failure probability values from state 2386 to state 4096

The last failure's probability state is the unacceptable state and equal to $1.02e^{-40}$ at state 4096. In the unacceptable state, all generation's buses are in failure mode and the system is completely blackout.

Figure 13 shows the probability of generation power states which remained in operation for each probability state. Fig.14 shows the probability of generation power states out of operation for each probability state. The first probability state has complete generation's power equal to 4605 MW and no generation's failure. The last probability state hasn't a generation's power and all of the generation's buses are in failure operation.

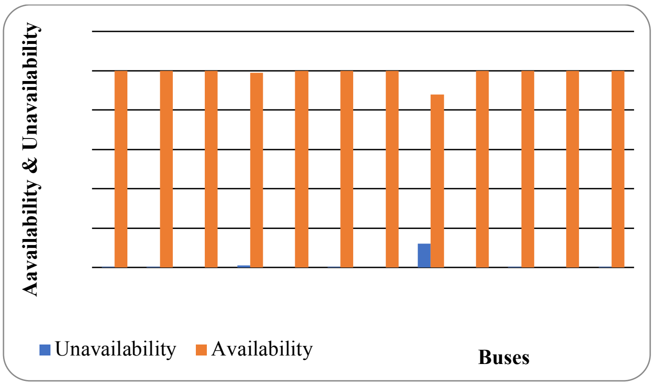


**Fig.12:** Generation's buses availability and unavailability

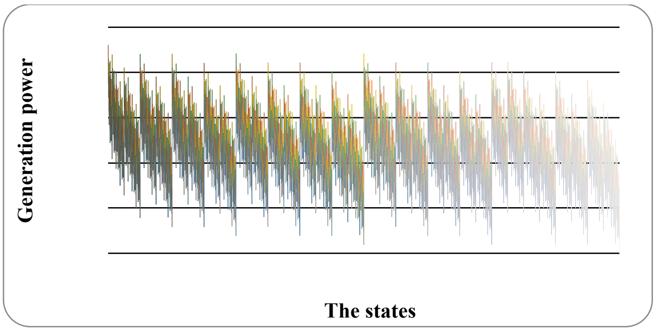


**Fig.13:** Probability of generation power states which remained in operation for each probability state.

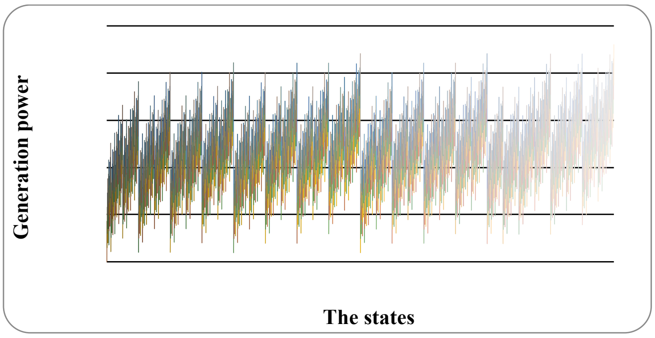


**Fig.14:** Probability of generation power states out of operation for each probability state.

The inferred probability failure frequencies shown in Figs. (15, 16, 17, 18). The failure frequencies from state 2 to state 1026 are shown in Fig.15, the failure frequencies from state 1026 to state 1666 are shown in Fig.16, the failure frequencies from state 1666 to state 2386 are shown in Fig.17, and the failure frequencies from state 2386 to state 4096 are shown in Fig.18, Maximum and minimum failure frequencies are equal to 0.094602 and $604156e^{-38}$ at state 3840, respectively. The corresponding max. and min. mean duration of state to state are equal to 9.150645 and 0.001021.

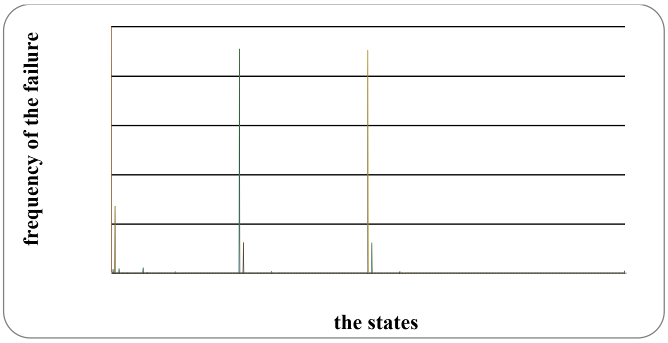


**Fig.15:** Failure frequency from state 2 to 1026.

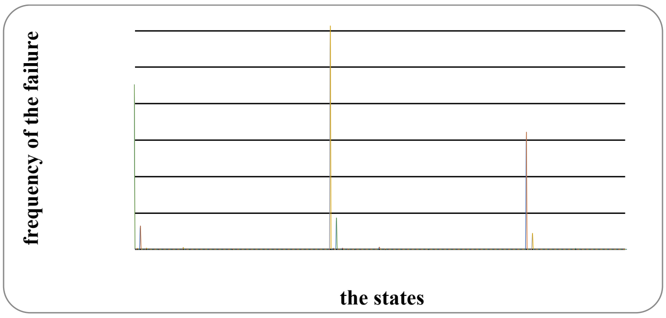


**Fig.16:** Failure frequency from state 1026 to 1666.

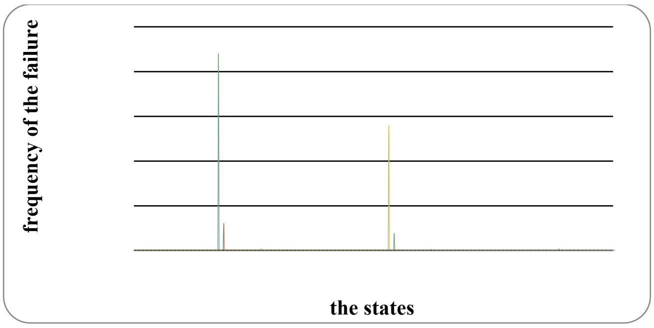


**Fig.17:** Failure frequency from state 1666 to 2386.

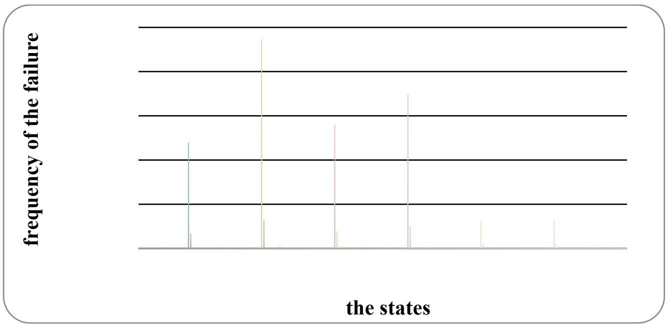


**Fig.18:** Failure frequency from state 2386 to 4096.

**Table 4:** The calculated system reliability indices.

| | |
|---|---|
| Average frequency duration [36] | 0.21885769 |
| Total interruption duration | 244.787734 |
| Average interruption duration [36] | 0.05971919 |
| System failure rate | $3.21e^{-05}$ |
| System reliability | 0.7552 |
| System unavailability | $1.91e^{-06}$ |
| LOLP [22] | 0.9198 |
| LOLE [22] | 1.115 |

The proposed technique calculated the reliability indices for the whole system which are shown in table 4. It is noticed from the table that, the whole system failure rate during a year is equal to $3.21e^{-05}$. The whole generation system reliability is equal to 0.7551934. The loss of load probability (LOLP) is equal to 0.9198. The loss of load expectation (LOLE) is equal to 1.115.

*5.2. The second issue*

The second issue studied the impact of FOR at each wind turbine in the wind farm on the failure probability, system reliability, probability frequency, mean duration, and reliability of each generation's bus. The study is demonstrated through the IEEE_UV_EPS_24 bus _6 WFs system. The same wind turbines and wind farms are used in this study. Three values of FOR and its related failure and repair rates are used as tabulated in Tables (2, 3).

The first value of FOR of each wind turbine is equal to 0.04 and its related failure and repair rates are equal to 2.43333 and 0.00667, respectively. The second value of FOR of each wind turbine is equal to 0.08 and its related failure and repair rates are equal to 2.72050 and 0.003571, respectively. The third value of FOR of each wind turbine is equal to 0.12 and its related failure and repair rates are equal to 3.61983 and 0.00303, respectively.

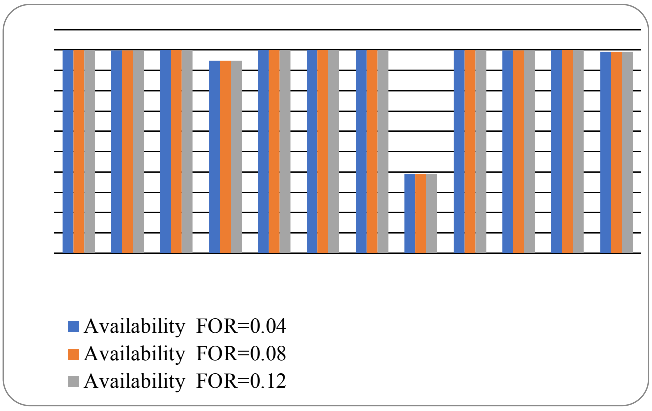


**Fig.19:** The gen. buses availability with different FOR

By applying the block diagram theory on wind turbines connection, the proposed technique can calculate the failure and repair rates for wind farms as explained in (9). The failure and repair rates for each wind farm are shown in Table 3 with different FOR's values.

Figure 19 shows The gen. buses availability with different FOR and compares between the calculated availability of each generation's bus with different FOR's values. It is noticed from the figure that, the maximum and minimum availability of generation's bus at the generation's bus 15 and 16, respectively in all values of FOR.

Figure 20 shows the system reliability with different FOR and compares between the calculated whole system's reliability with different FOR's values. It is noticed from the figure that, the best system's reliability value when the FOR's value is equal to 0.12. These obtained results due to the changing values of MTTF and MTTR of each FOR's value. The MTTF values are equal to 3600, 3220, and 2420 hours and the MTTR are equal to 150, 280, and 330 hours when FOR's values are equal to 0.04, 0.08, and 0.12, respectively [35].

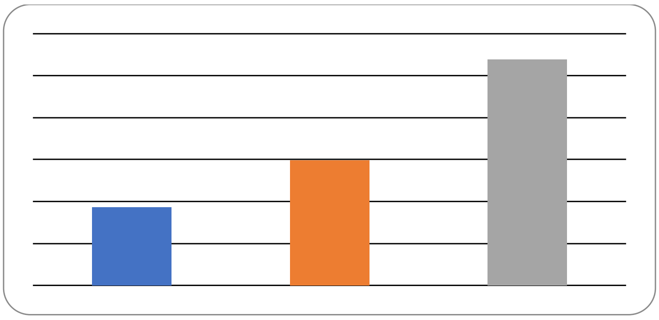

**Fig.20:** The system reliability with different FOR

Table 5 illustrates the whole system reliability without wind farms and with wind farms, 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 generation's bus availability.

At FOR equals to 0.04, the results are discussed in the previous section. At FOR equal to 0.08, the whole generation system's reliability assessed and equal to 0.75525, the maximum and minimum of the frequency of failure probabilities are determined and equal to 0.0288 and $9.8687e^{-16}$, respectively, the mean duration corresponding to maximum and minimum of the frequency of failure probabilities are determined and equal to 10.52268 and 0.682425, respectively, the maximum and minimum failure probabilities are calculated and equal to 0.216473 and $7.52956e^{-16}$, respectively, and the maximum and minimum of generation's bus availability are assessed and equal to approximetly to 1 and 0.8779, respectively.

At FOR equal to 0.12, the whole generation system's reliability assessed and equal to 0.7553692, the maximum and minimum of the frequency of failure probabilities are determined and equal to 0.0341212 and $1.339e^{-15}$, respectively, the mean duration corresponding to maximum and minimum of the frequency of failure probabilities are determined and equal to 8.7476612 and 0.7923033, respectively, the maximum and minimum failure probabilities are calculated and equal to 0.1987661 and $1.385e^{-15}$, respectively, and the maximum and minimum of generation's bus availability are assessed and equal to approximetly 1 and 0.8779054, respectively.

**Table 5:** Reliabilities, states frequency, mean duration, and probabilities for various FOR.

| Reliability without wind farms | | 0.7315888 | | | |
|---|---|---|---|---|---|
| Different FOR | | 0.04 | 0.08 | 0.12 | - |
| System reliability | | 0.755193392 | 0.755249362 | 0.7553692 | - |
| Frequency | Max. | 0.094601972 | 0.028812137 | 0.0341212 | at state 1 |
| | Min. | $6.41562e^{-38}$ | $9.8687e^{-16}$ | $1.339e^{-15}$ | at state 3840 |
| Corresponding mean duration | Max. | 9.150644824 | 10.52268112 | 8.7476612 | - |
| | Min. | 0.001021444 | 0.682424983 | 0.7923033 | - |
| Failure probability | Max. | 0.865669045 | 0.216472886 | 0.1987661 | at state 1 |
| | Min. | $6.55319e^{-41}$ | $7.52956e^{-16}$ | $1.385e^{-15}$ | at state 3840 |
| The availability of generation' buses | Max. | 1 | 1 | 1 | at bus 15 |
| | Min. | 0.877906387 | 0.8779061 | 0.8779054 | at bus 16 |

## 6. Conclusions

The proposed method focused on the probability analysis and reliability assessment for the generation system's part with installed 6 wind farms. Each wind farm has 67 connected wind turbines in parallel. Each wind turbine has 3 MW and connected on the buses of the IEEE_UV_EPS_24 bus _6 WFs. The analyzed system has 32 generation units and 402 wind turbines so the total system components are 434 components and the total Markov's states are $2^{434}$. In this case, Markov's states represent the infinity number. The proposed methodology by using the block diagram technique has been succeeded to reduce the number of system components from 434 to only 12 components and Markov's states from infinity number to 4096 states. The effectiveness of the proposed method appears on assessing the whole generation system's reliability, maximum and minimum of failure probabilities' frequency, mean duration corresponding to maximum and minimum of failure probabilities' frequency, maximum and minimum failure probabilities, maximum and minimum of the generation's buses availability, and generation system reliability indices assessment. In addition, there are some meaningful conclusions about the reliability assessment of the system with wind farms to be pointed out, as follows

- The impact of installed wind farms on the system, the whole generation system's reliability assessed and found equal to 0.7316 without any installed wind farms. When connected wind farms, the whole generation system's reliability assessed and increased to 0.7552 by an approximated percentage equal to 3.226 %. It can be concluded from the results that; wind farms have a positive effect on the generation system's reliability of electrical power systems. The installing of winds farm to power system has also a major positive effect on the voltage profiles of buses, the system stability, avoiding current congestion, and reduce the power losses of the system [37-40].

- At FOR equal to 0.04, The whole system failure rate during a year is calculated and equal to $3.21e^{-05}$. The whole generation system reliability is assessed and equal to 0.7552. The loss of load probability (LOLP) is evaluated and equal to 0.92. The loss of load expectation (LOLE) is assessed and equal to 1.115.

- The impact of FOR, At FOR equal to 0.08 and 0.12, the whole generation system's reliabilities assessed and increased to 0.75525 and 0.7554, respectively. It is concluded from that point, the whole electrical power system generation reliability can be increased by improving the failure and repair rates of wind turbines.

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