A Reliability Study of Renewable Energy Resources and their Integration with Utility Grids

Samy M. Ghania
University of Jeddah
Saudi Arabia, Jeddah
sghania@uj.edu.sa

Khaled Mahmoud
University of Jeddah
Saudi Arabia, Jeddah
mrmahmoud@uj.edu.sa

Anas M. Hashmi
University of Jeddah
Saudi Arabia, Jeddah
ahashmi@uj.edu.sa

Received: 18 May 2022 | Revised: 9 June 2022 and 5 July 2022 | Accepted: 12 July 2022

Abstract-Reliability analysis is considered an impressive approach for investigating the planning and design processes of industrial and commercial electrical power distribution systems. Reliability analysis is mainly concerned with the analysis of devices and systems whose individual components are prone to failure risk. The demand for renewable energy resources that work in parallel or replace traditional energy resources is significantly increasing. The current research presents the reliability analysis of the IEEE 40-bus system integrated with large-scale PV and wind systems. Reliability parameters evaluation of power distribution systems will be performed using the zone branch methodology to divide the power system layout into several sections (protected zones). The compensating capacitors will be addressed to clarify their impacts on the system reliability indices. The 40-bus system, known as the IEEE Standard 493-1997, integrated with large-scale PV and wind is simulated using ETAP software. The simulation results reveal that the integration of renewable energy resources with the utility grids can improve the reliability indices. These simulation results are consistent with similar works found in literature and some standards in the field of reliability analysis. The integration of power distribution systems with renewable energy resources improves the reliability indices of the distribution grids.

Keywords-reliability analysis; zone branch methodology; renewable energy resources; high penetration level; impact of compensating capacitors

I. INTRODUCTION

The depletion of fossil fuels, their replacement by renewable energy resources, and the global impact on the environment are the main reasons to implement reliable energy resources. The reliability analysis of the power distribution systems integrated with large-scale renewable energy resources is a critical issue. For the last two decades, the PV/solar and wind energy resources have become the main solution to the rapidly increasing energy demand [1]. Therefore, the reliability analysis of renewable energy resources is receiving more concern from utility engineers and researchers. Reliability analysis approach is used to determine the impact of distribution network components based on their types (overhead lines, cable, transformers, substation, renewable energy resources, etc.) on the system reliability [2, 3]. Many researches can be found about the reliability of energy generation systems connected with renewable energy resources [4, 5]. Several approaches have been attempted to enhance the renewable energy integration process. Distributed Generation (DG) and its integration have been investigated to dispatch bidirectional flows [6, 7]. The reliability of any system can be simply defined as the probability that a system can perform its intended function for a specified interval under specified conditions [8-10]. The reliability analysis of electrical power distribution systems integrated with renewable energy resources is performed using mathematical model approaches [11, 12]. These approaches aim to control the consequence of failures and to identify the frequency and their causes. Reliability computation mathematical models of the electrical power distribution systems should be developed to include the relationships between different sub systems [13, 14]. There are many approaches that can be implemented to study the reliability of the power distribution systems integrated with renewable energy resources [15, 16]. Various approaches such as the optimal location of protective and switching equipment, proper monitoring and maintenance, the use of distributed generation units, electrical energy storage, network automation and smart grid concepts, and preventive and reliability-based maintenance and repairs have been reported [17, 18]. One of the simplest and most practical approaches of reliability studies is sensitivity analysis by which the critical component of the system can be identified [15, 19]. The demand of increased reliability and optimum economic performance of utility grids integrated with renewable energy resources has become very important. Recently, concern have been given to the substantial growth in utilizing distributed energy resources. The more the electrical power distribution systems become larger and

Corresponding author: Samy M. Ghania

interconnected with renewable energy resources, the more complex computational approaches are needed [20, 21]. These approaches should be able to assess the impacts of unreliable protective equipment and protection–coordination schemes on individual load point reliability indices within a given system configuration. One of these approaches is the zone branch methodology that overcomes many limitations and can be applied to a large electrical power distribution system [22, 23]. The main advantage of the zone branch methodology is that it can readily identify faulty protection schemes involving all the components of large electrical power distribution systems and can evaluate load point reliability indices.

The current research presents a full simulation of the 40-bus system known as the IEEE Std. 399-1997 system integrated with large-scale PV and wind systems with capacity up to 3GW. Simulations were performed to introduce the reliability concepts and indices of electrical distribution systems integrated with renewable energy resources for the two modes (ON and OFF of the grid) of the system. The reliability evaluation of power distribution systems was performed using the zone branch methodology in which the distribution system is divided into several sections (protected zones). The obtained results will be compared with similar works found in literature and some standards in the field of reliability analysis [24, 25].

The current research could be used by utility engineers that want to estimate the impact of the integrating renewable energy resources on system reliability. Moreover, it could be a very powerful planning tool for load scheduling and forecasting in order to meet the increasing demand of electrical energy.

II. RELIABILITY INDICES AND ZONE BRANCH METHODOLOGY

A. Reliability Main Concepts and Indices

Electrical power distribution systems are made up of components or subsystems. Each component has its own expected failure rate which is defined as the number of expected failures per unit in a given time interval [26, 27]. The failure rate is evaluated as $\lambda\left(\frac{f}{yr}\right)$:

$$\lambda = \frac{Number\ of\ failures}{Total\ operating\ time\ of\ the\ unit} \quad (1)$$

As the reliability function is actually a failure density function, the average time for a failure to occur and is known as the Mean Time To Failure (MTTF) which is given as [28]:

$$MTTF = \int_0^\infty e^{-\lambda t}dt = \frac{1}{\lambda} \quad (2)$$

The repair time is the time taken to change the unit state from the off state to the on state and it is denoted as MTTR. The failure rate is reciprocal of MTTF and similarly, the repair rate (r) is equal to the reciprocal of repair time. The percentage of time that the system is functioning is called availability (A), meanwhile its outage of services is the unavailability ($\bar{A}$) of the system:

$$A = \frac{total\ hours\ of\ on\ time\ in\ 1\ year}{8760} = \frac{MTTF}{MTTF+MTTR} \quad (3)$$

$$\bar{A} = \frac{\text{total hours of off time in 1 year}}{8760} = \frac{MTTR}{MTTF+MTTR} \quad (4)$$

For systems that can be treated as a single component with a constant failure rate λ and repair rate μ the availability is:

$$A = \frac{MTTF}{MTTF+MTTR} = \frac{\frac{1}{\lambda}}{\frac{1}{\lambda}+\frac{1}{\mu}} = \frac{\mu}{\lambda+\mu} \quad (5)$$

Based on the functionality sequence point of view, the electrical power distribution systems are connected in series, in parallel, or in combinations. Each component in a series system has its own failure rate and reliability. The probability of all the components functioning is simply the product of the probabilities of individual components functioning. Consequently, if the components have exponential failure probabilities with corresponding failure rates, $\lambda_1, \lambda_2 \ldots\ldots\ldots \lambda_n$, then the system reliability and the MTTF can be presented as:

$$R_{system}(t) = R_1(t)\ X\ R_2(t)\ X \ldots\ldots\ldots..XR_n(t) \quad (6)$$

$$R_{system} = e^{-\lambda_1 t}\ X\ e^{-\lambda_2 t}X \ldots e^{-\lambda_n t} = e^{-\lambda t} \quad (7)$$

$$MTTF_{system} = \frac{1}{\lambda} \quad (8)$$

For the parallel systems, if the $Q(t)$ is the probability of failure in a given period, which is considered as the unreliability, then:

$$Q(t)_{system} = Q_1(t)X\ Q_2(t)X \ldots XQ_n(t) \quad (9)$$

If all the components have the same $Q(t)$, then the system reliability $R(t)$ can be presented as:

$$Q(t)_{system} = Q^n(t) \quad (10)$$

$$R(t)_{system} = 1 - Q(t)_{system} \quad (11)$$

$$R(t)_{system} = 1 - \left[(1-e^{-\lambda_1 t})X(1-e^{-2t})X \ldots (1-e^{-\lambda_n t})\right] \quad (12)$$

If all the components have the same λ, then the system reliability and MTTF can be expressed as:

$$R(t)_{system} = 1 - \left[1-e^{-\lambda t}\right]^n \quad (13)$$

$$MTTF = \frac{1}{\lambda} + \frac{1}{2\lambda} + \frac{1}{3\lambda} + \cdots + \frac{1}{n\lambda} \quad (14)$$

Reliability evaluation of the electric power distribution systems depends on two basic parameters: load point indices and system reliability indices. The load point indices include the load point failure rate, the average outage time, and the average annual unavailability or outage. Load point indices are very important from the customer's viewpoint. System reliability indices are important for system performance. The system reliability indices can be divided into two categories: interruption indices and energy-oriented indices [29, 31]. Interruption indices are used to evaluate the average number of sustained interruptions noticed by a customer for long-term sustained interruptions. Based on the IEEE Standard 1366-2012, the four main interruption indices used are:

- System Average Interruption Frequency Index (SAIFI)
- System Average Interruption Duration Index (SAIDI)
- Customer Average Interruption Duration Index (CAIDI)
- Customer Total Average Interruption Duration Index (CTAIDI)

SAIFI indicates the average number of interruptions happened to a customer within one year. It is given by:

$$SAIFI = \frac{\sum N_i}{N_T} \quad (15)$$

where N_i is the total number of customers interrupted and N_T is the total number of customers served.

SAIDI is the most used index to evaluate the system performance through calculating the sustained interruption of each customer in service area during a determined period (minutes or hours) per year and it can be obtained by the following expression [21, 23]:

$$SAIDI = \frac{\sum r_i * N_i}{N_T} \quad (16)$$

where r_i is the restoration time for each interruption event.

CAIDI gives the average outage duration that any customer may have exposed. It can be calculated as:

$$CAIDI = \frac{\sum r_i * N_i}{N_i} \quad (17)$$

CTAIDI represents the average time the customer spents during interruptions. The value of this index is calculated as:

$$CTAIDI = \frac{\sum r_i * N_i}{C_N} \quad (18)$$

where C_N is the number of customers interrupted.

The Average Service Availability Index (ASAI) is the ratio of the total hours that the service is available during a determined period (usually monthly or yearly) to the total hours of customer demand [24, 26].

$$ASAI = 1 - \left(\frac{\sum r_i * N_i}{T * N_T}\right) \quad (20)$$

where T is the time under study.

Energy-oriented indices are very important in evaluating the load in distribution networks. The most important indices are the average load, the Expected Energy Not Supplied (EENS) index, and the Average Energy Not Supplied (AENS) index. EENS index is used to calculate the total energy generated but not supplied by the system and is calculated by:

$$EENS = \sum L_{a(i)} * U_i \quad (21)$$

where $L_{a(i)}$ is the average connected load at point i and U_i represents the average annual outage time at the load point i. AENS index represents the average value of the energy not supplied by the system corresponding to the total number of customers that are served.

$$AENS = \sum_i^n \frac{L_{a(i)} * U_i}{N_i} \quad (22)$$

LOEE is used to determine the total expected energy losses (KWh) when the load demand is not satisfied from the generation system [27].

$$LOEE = \sum_{i=1}^n e_i \,(EP_i < LED_i) \quad (23)$$

where EP_i is the generated total energy, LED_i is the total load demand, and e_i is the unsupported load demand.

B. Zone Branch Methodology

To evaluate the protection–coordination and reliability characteristics of the electrical power distribution systems, it is essential to divide the electrical power distribution system into protective zones. Any protective zone is a part of the power system and can isolate or detach itself automatically or manually from the remaining power system if a fault occurs in any of its links. These protective zones are connected in series or in parallel and each zone is formed by a group of branches. The symbol $\lambda(i,j)$ represents the failure rate of zone i within the branch j. Each zone branch has an isolating device labeled $S(i,j)$ and these isolating devices can be manual or automatic switches, fuses, reclosers, or a relay breaker combination. Each isolating device has a probability $q(i,j)$ it will not recognize and isolate any permanent faults of the equipment within its zone The failure rate $\lambda(i,j)$ of any zone i and branch j is the sum of all the equipment failure rates whose failure will result in the operation of the isolating device of zone i and branch j only. The total failure rate $\lambda_T(i,j)$ (f/yr) and the annual downtime $\lambda_r(i,j)$ for any zone i and branch j can be calculated as:

$$\lambda_T(i,j) = \lambda_s + \sum RIA(z,k) \; x \; FZB(k)^T \quad (24)$$

$$\lambda_r(i,j) = \lambda_s \; x \; rs \sum RIA(z,k) \; x \;\; FZB(k)^T \; x \; R(z,k) \quad (25)$$

where λ_s is the failure rate of utility supply or plant supply, rs is the restoration duration of utility supply, z the zone branch number, k the total number of zone branches in system, $R(z,k)$ the repair or switching time of each zone branch, $FZB(k)$ is the failed zone branch array that contains the failure rate of each zone branch k, and $RIA(z,k)$ is the recognition and isolation array coefficients. Figure 1 presents a simple schematic of the zone branch and the main indices used in the sectionalization process.

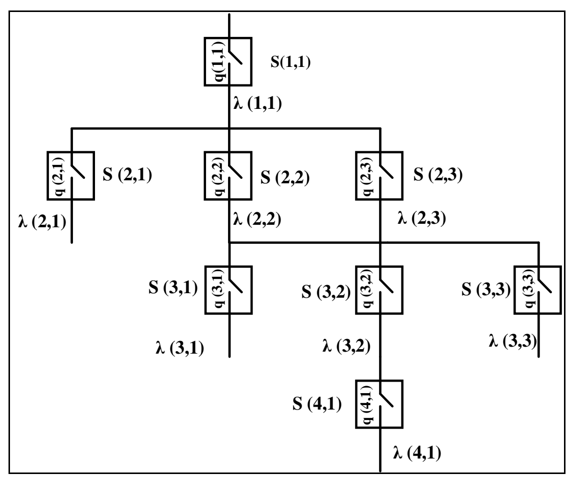

Fig. 1. Simple schematic of a branch zone with main parameters.

III. SIMULATED SYSTEM CONFIGURATION

In this section, the grid system, along with two large-scale renewable energy sources (PV and wind), is simulated using the ETAP software package. ETAP is an analytical engineering software package for simulation, design, monitoring, control, operator training, optimizing, and automating power systems. ETAP can be used to design, analyze, and exchange the system data into many different simulating software packages like PSCAD to perform electromagnetic transient analysis, such as switching transients, insulation coordination, lightning surges, resonance, etc. The ETAP interface is a powerful tool needed to be more user-friendly rather than other simulating software packages. ETAP has impressive capabilities to simulate unlimited number of buses. The selected grid is the 40-bus system, also known as the IEEE Standard 493-1997 [25], which consists of loads, capacitor banks, transmission lines, and generators. This grid is a 13.8KV (RMS line-line) transmission system. Zone branch methodology can be applied in many different scenarios by sectionalizing the electrical power system single line diagram. These scenarios are based on the system configurations. Table I shows the main reliability data of the grid and the simulated solar and wind farms. The Table is truncated to fit and comply with the restrictions and limitations of the paper size and more data can be obtained from the Standard. The reliability values given in Table I are the design reliability parameters for each piece of equipment and instrument. These values are implemented as the base values for each element in the utility grid.

TABLE I. MAIN RELIABILITY DATA OF THE SIMULATED SYSTEM

Main characteristics of the transformers			
Trans. No.	**Rating (MVA)**	**λ (Failure/year)**	**Replace time (h/year)**
T1	15	0.0153	192
T2	15	0.0153	192
…..	……	……..	…….
T13	3.5	0.0059	79.3
T14	1.5	0.0059	79.3
Main characteristics of the motors/generators			
Motor. No.	**Rating (MVA)**	**λ (Failure/year)**	**Replace time (h/year)**
M1	0.7	0.0824	42.5
M2	0.5	0.0109	18.3
…..	…	….	….
M20	1.5	0.0714	75.1
M21	1.75	0.0404	76.0
G	10	0.00536	478.0
Main characteristics of the switchgear bus and bus ducts			
Bus bar. No.	**Rating (MVA)**	**λ (Failure/year)**	**Replace time (h/year)**
1	-	0.0034	26.8
2	-	0.0034	26.8
…	-	….	….
39	-	0.001048	11.5
40	-	0.003601	109.8
Main characteristics of each PV and Wind system			
Equip.	**Rating (MVA)**	**λ (Failure/year)**	**Replace time (h/year)**
PV systems	1500	1.254	5
Wind turbine	1500	0.02	50

In the current research, 5 different case studies will be implemented, as shown in Figure 2. The simplified schematic diagram of the simulated systems connected with the PV and wind systems can be seen in [26]. The PV system consists of 5 sub-farms, 300MW each. Meanwhile, the wind system consists of 5 sub-farms, also 300MW each. Each PV and wind farm will be connected to the main utility bus labelled by bus number 40 as shown in Figure 3. The PV/wind systems are connected to the main supply bus No.40 because of the large scale of the PV and wind systems. The bus No. 40 is the utility bus and the proposed PV and wind system will phase out completely the utility supply. Also, based on the limitations of the IEEE 40 bus configuration for power capacity and total load flow, the renewable energy systems are connected to bus No. 40. The connected PV and wind farms with different capacities of 300, 600, 900, 1200, and 1500MW respectively are based on the proposed scale by the Electric holding company of Egypt for two different projects [30, 31]. As the bus No. 40 is the main utility bus, the renewable energy resources will be connected to this bus to work in parallel with the utility grid or phasing out the grid supply. Different scenarios for patching of the renewable sources will be simulated to calculate the impacts of connecting different renewable energy resources on the reliability indices.

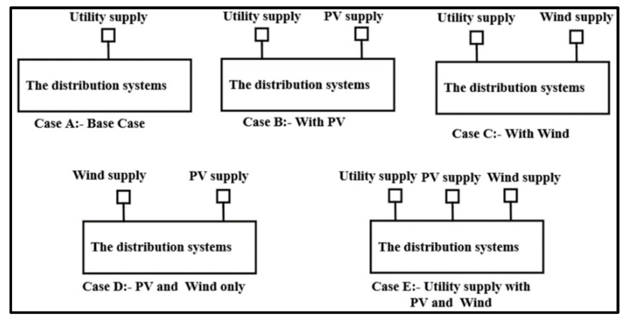

Fig. 2. Simple schematic of the different case studies.

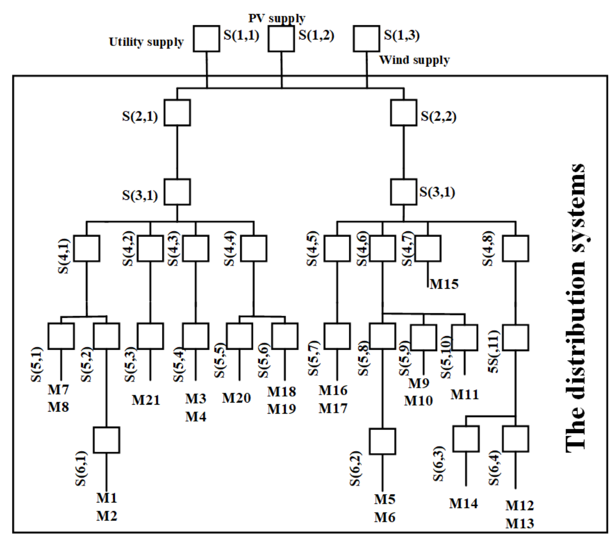

Fig. 3. The main zones for the grid model connecting PV and wind systems.

Figure 3 presents the main zones of the simulated model with connections with PV and wind systems. Different scenarios for patching of the renewable sources will be tackled. The main target is to investigate the different impacts on the reliability indices over the different cases of connecting PV and wind systems to the grid. Figure 4 presents a simple flowchart for the proposed simulated systems. Figure 5 presents a screenshot of the simulated IEEE 40 bus system with PV /Wind farms using the ETAP software.

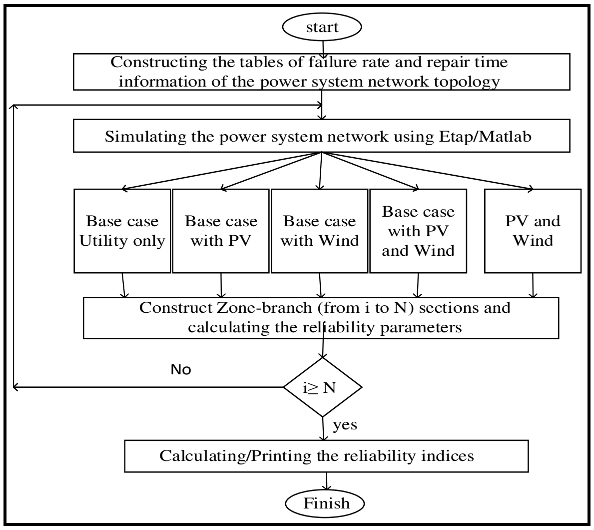

Fig. 4. Flowchart of the proposed approach.

IV. SIMULATION RESULTS

The IEEE 40 bus power distribution system was simulated to investigate the reliability indices for different case studies. Therefore, each case study was performed to show the impact of connecting PV and wind renewable energy resources to the utility grid on the different reliability indices. The zone branch methodology was used to sectionalize the different protective zones in the simulated system. These protective zones are used to calculate the reliability parameters for all the pieces of equipment included in the zone. The main target is to calculate the failure rate of each zone. For the new added zones of PV and wind systems, the zone failure/repair rates can be calculated by (24) and (25). Considering all the components inside the PV system and the circuit breaker, transformer, and busbar systems, the failure rate is: $\lambda_T(1,2) = \lambda(PV + Trans. + 2C.B + busbar) = 1.254 + 0.0153 + 2 * 0.012 + 0.03 = 1.3233$f/yr and the replace time is 76.56h/f. Similarly, while considering all the components inside the wind system and the circuit breaker, transformer, and busbar systems $\lambda_T(1,3) = 0.09$f/yr and the replace time is 18.91h/f. Based on the different zones shown in Figure 3, Table II tabulates the main reliability data of the different zones for the base-case and the different case studies. The renewable energy resources are added as Zone (1,2) and Zone (1,3) for PV and wind respectively. The failure rates of these two added zones are calculated and added with double-cell borders in Table II. Table III tabulates the different reliability indices for the different case studies while connecting the PV and wind systems with maximum capacity of 1500MW. It can be observed from Table III that when connecting PV and wind systems, the reliability indices are improved, and consequently, the performance of the electrical power distribution systems is improved. This improvement will be reflected to the energy continuity at the customer's side. Moreover, focus will be given to the 3 most important indices (EENS, AENS and LOEE) while demonstrating the impacts of the compensating capacitors connected as shown in Figure 5. The main configuration of the network topology is mentioned in [25]. The main voltage stability indices (reactive and active power, Voltage, and power factor) are used to pre-identify the location/size of the capacitor. Initially the optimal location depends on the network topology, configurations, loading, etc. In order to overcome this issue, the load flow study is performed using ETAP to determine the main voltage stability indices at each bus. Bus No. 3 is considered the main loading bus and based on the results of the load flow, it is found to have the worst voltage stability indices. So, this bus is connected to the compensating capacitors. The values of 4MVAr and 8MVAr of the compensating capacitors are proposed after trials to maintain the main targeted voltage stability indices (voltage not less than 98% and power factor not less than 0.9).

TABLE II. FAILURE RATE AND DURATION OF DIFFERENT ZONE BRANCHES

Case A: Base case (utility only)			
Zone	**λ (failure/year)**	**Interruption (h/year)**	**Replace time (h/failure)**
(1,1)	1.0583	2.16133	2.04226
(2,1)	0.0223	3.32788	149.232
---	--------	---------	---------
(6,3)	0.1032	8.120	75.339
(6,4)	0.1032	4.2711	41.3869
Case B (utility with PV)			
Zone	**λ (failure/year)**	**Interruption (h/year)**	**Replace time (h/failure)**
(1,1)	1.0583	2.16133	2.04226
(1,2)	1.3233	2.752	76.56
(2,1)	0.0223	3.32788	149.232
---	--------	---------	---------
(6,3)	0.1032	8.120	75.339
(6,4)	0.1032	4.2711	41.3869
Case C (utility with Wind)			
Zone	**λ (failure/year)**	**Interruption (h/year)**	**Replace time (h/failure)**
(1,1)	1.0583	2.16133	2.04226
(1,3)	0.09	2.3	18.91
(2,1)	0.0223	3.32788	149.232
---	--------	---------	---------
(6,3)	0.1032	8.120	75.339
(6,4)	0.1032	4.2711	41.3869
Case D (utility with PV and Wind)			
Zone	**λ (failure/year)**	**Interruption (h/year)**	**Replace time (h/failure)**
(1,1)	1.0583	2.16133	2.04226
(1,2)	1.3233	2.752	76.56
(1,3)	0.09	2.3	18.91
(2,1)	0.0223	3.32788	149.232
---	--------	---------	---------
(6,3)	0.1032	8.120	75.339
(6,4)	0.1032	4.2711	41.3869
Case E (PV and Wind without the utility)			
Zone	**λ (failure/year)**	**Interruption (h/year)**	**Replace time (h/failure)**
(1,2)	1.3233	2.752	76.56
(1,3)	0.09	2.3	18.91
(2,1)	0.0223	3.32788	149.232
---	--------	---------	---------
(6,3)	0.1032	8.120	75.339
(6,4)	0.1032	4.2711	41.3869

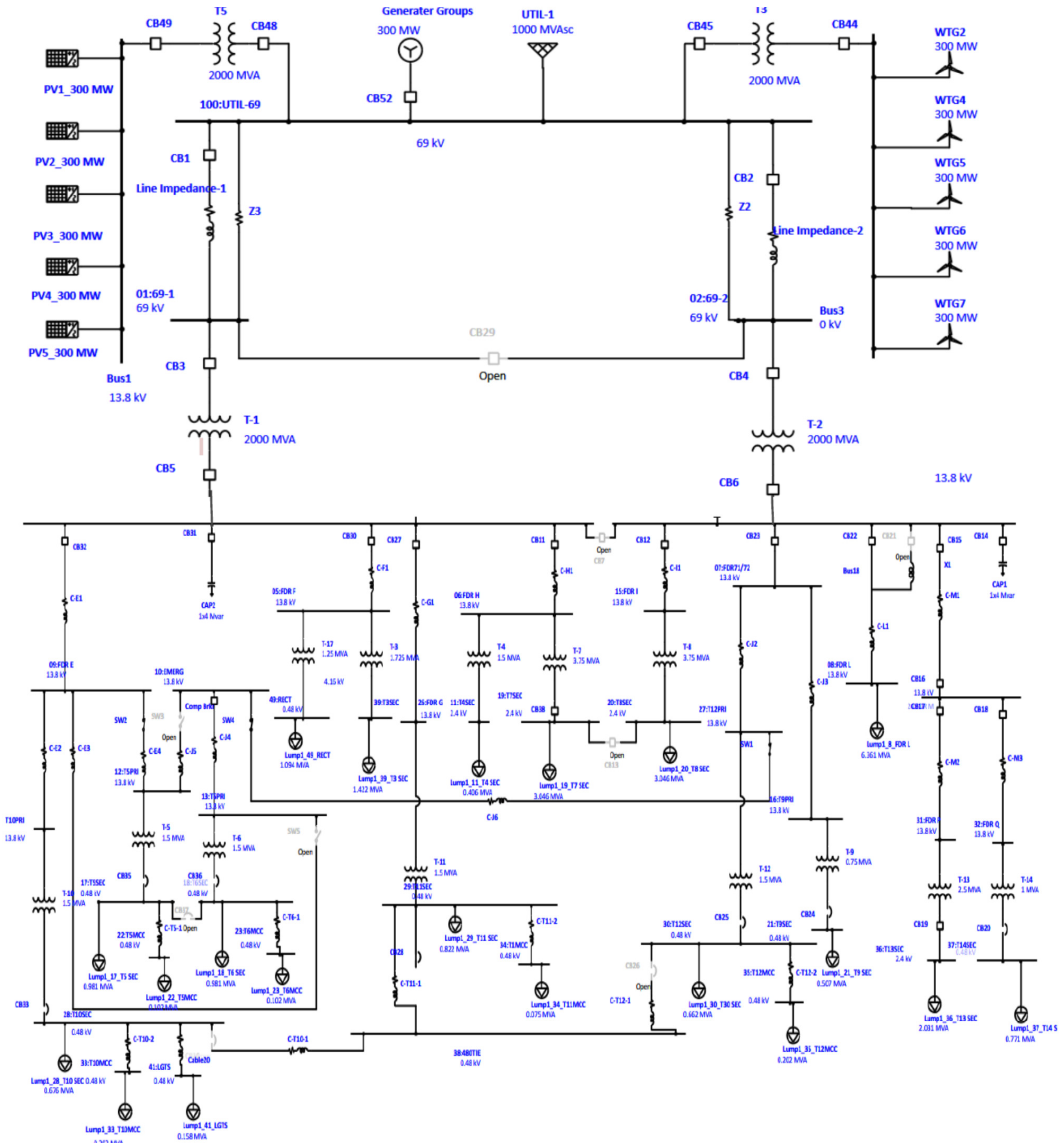

Fig. 5. Screenshot of the simulated IEEE 40 bus system with PV and wind farms.

TABLE III. SYSTEM PERFORMANCE RELIABILITY INDICES

Indices	Case A	Case B	Case C	Case E	Case D
SAIFI	0.1335	0.1348	0.1348	0.1361	0.1373
SAIDI	9.9537	9.9923	9.9923	10.0309	10.069
CAIDI	74.569	74.144	74.144	73.727	73.317
ASAI	0.9989	0.9989	0.9989	0.9989	0.9989
ASUI	0.00114	0.0011	0.0011	0.00115	0.0011
EENS	176.322	177.54	177.54	178.753	179.96
AENS	8.3963	8.4542	8.4542	8.512	8.5699
LOEE	294.21	296.15	296.52	297.13	300.75

The two capacitor banks of 4MVAr are considered for the different case studies to show the improvement for reliability indices. Figure 6 presents the impact of using 8MVAr capacitors on the total energy generated but not supplied by the system (EENS) for the different case studies. It can be noted that the EENS is improved by about 3%.

Table III shows that some reliability indices increase and others decrease with more penetration of PV and wind. The increasing/decreasing level depends on the system configuration and the index definition. For example, the CAIDI is decreased and this decrease is considered as an improvement based on its meaning and the system's performance is consistent with [35]. Figure 7 presents the impact of using 8MVAr capacitors on the AENS for the different case studies. It can be noted that the AENS improved when using the PV and Wind systems by about 7%. Figure 8 presents the impact of using 8MVAr capacitors on LOEE for the different case studies. It can be noted that, LOEE is improved by using the PV and Wind systems by about 8%.

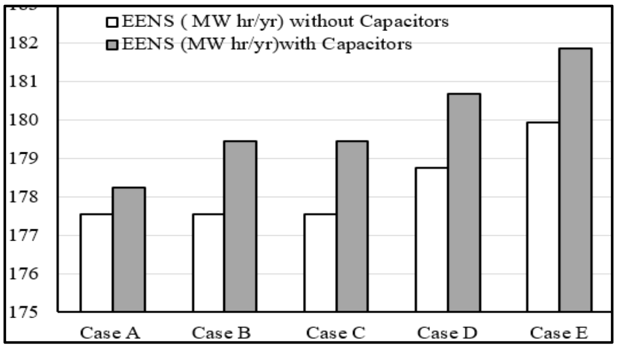

Fig. 6. Impact of the compensating capacitor on the EENS for different case studies.

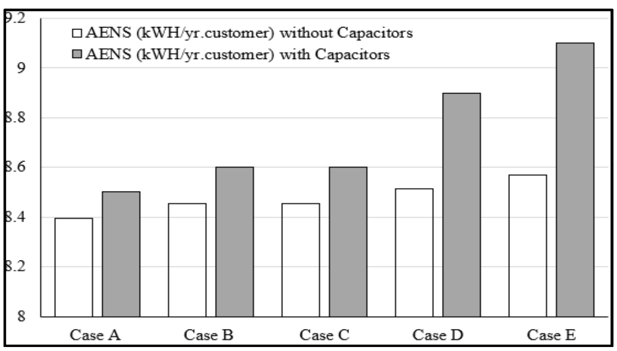

Fig. 7. Impact of the compensating capacitor on AENS for different case studies.

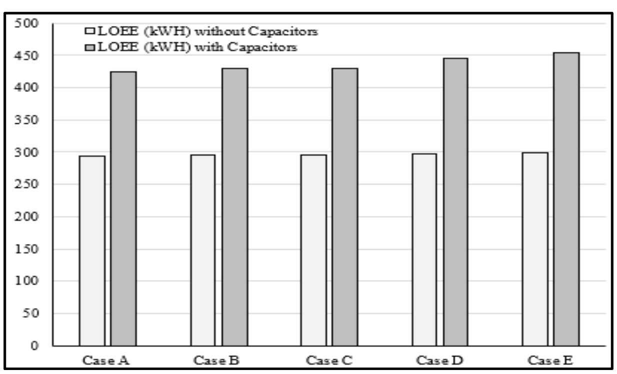

Fig. 8. Impact of the compensating capacitor on the LOEE for different case studies.

To verify and validate the obtained simulated results of the proposed model, they will be compared with the results of similar models found in literature. The reliability and its indices sensitivity analysis has been conducted for IEEE 94 – bus and IEEE 69– bus with two different techniques [32, 34]. The Fault Index Matrix (FIM) technique was implemented in [33], and Gaussian distribution and fuzzy technique was used in [34]. EENS and SAIDI reliability indices are shown in Table IV for the proposed model and the two studied cases of the literature [33, 34]. The simulated results of the proposed method show reasonable consistency with the two other techniques with minor differences. The differences are less than 10% and mainly come due two the differences in the configuration and the loading conditions.

TABLE IV. SYSTEM PERFORMANCE RELIABILITY INDICES

Reliability indices	Proposed model	FIM [33]	FUZZY [34]
SAIDI	10.0309	11.2	11.5
EENS	178.753	181.1	187.8

V. CONCLUSIONS

The different reliability indices of the electric power distribution system of IEEE 40 bus integrated with large-scale PV and wind renewable energy source systems are elaborated with the use of the ETAP software. The integration process is simulated for the IEEE 40 bus grid with two renewable energy sources consisting of 5 sub-farms of 300MW each. The total capacities of PV and wind systems are 1500MW each. The power distribution system of IEEE 40 bus is sectionalized using the zone branch methodology that divides the power system network into several sections (protected zones) in order to calculate the different reliability parameters for the different zones including the new connected PV and wind systems. The reliability indices were evaluated for different case study scenarios.

The impact of penetrating PV and wind systems on the reliability indices is demonstrated in this study. Furthermore, the impact of connecting the compensating capacitor banks of 2×4Mvar on the most important reliability indices (EENS, AENS, and LOEE) has been investigated. The reliability indices can be improved by about 8% for integrating PV and wind systems. According to the obtained results, the integration of PV and wind systems into the electric power distribution systems improves their reliability indices. The obtained results have very good consistency and compliance with other research studies and with the standards related to the renewable energy sources. This research can be a pre-design powerful tool for system designers and utility engineers to avoid any maloperation or power discontinuity problems.

ACKNOWLEDGEMENT

This work was funded by the University of Jeddah, Jeddah, Saudi Arabia, under grant No. (UJ-21-DR-72). The authors, thank the University of Jeddah for the technical and financial support.

REFERENCES

[1] O. US EPA, "Energy Resources for State, Local, and Tribal Governments," Jun. 19, 2017. https://www.epa.gov/statelocalenergy.

[2] S. S. Refaat, H. Abu-Rub, M. Trabelsi, and A. Mohamed, "Reliability evaluation of smart grid system with large penetration of distributed energy resources," in *International Conference on Industrial*

Technology, Lyon, France, Feb. 2018, pp. 1279–1284, https://doi.org/10.1109/ICIT.2018.8352362.

[3] V. Vivek and C. P. Das, "Reliability Analysis using Renewable Energy Sources," *International Journal of Mechanical and Industrial Engineering*, vol. 1, no. 1, pp. 47–50, Jul. 2011, https://doi.org/10.47893/IJMIE.2011.1011.

[4] A. M. Huseynov and O. B. Azadkhanov, "Development of intellectual information-measuring system for Azerbaijan power system regime reliability control," in *Modern Electric Power Systems*, Wroclaw, Poland, Sep. 2019, pp. 1–3, https://doi.org/10.1109/MEPS46793.2019.9394977.

[5] L. Anan, "Application of MATLAB Software in Reliability Verification Test of Success or Failure Product," in *International Conference on Computer Systems, Electronics and Control*, Dalian, China, Dec. 2017, pp. 1191–1193, https://doi.org/10.1109/ICCSEC.2017.8447042.

[6] Y.-W. Chen and J. M. Chang, "EMaaS: Cloud-Based Energy Management Service for Distributed Renewable Energy Integration," *IEEE Transactions on Smart Grid*, vol. 6, no. 6, pp. 2816–2824, Aug. 2015, https://doi.org/10.1109/TSG.2015.2446980.

[7] R. A. Walling, R. Saint, R. C. Dugan, J. Burke, and L. A. Kojovic, "Summary of Distributed Resources Impact on Power Delivery Systems," *IEEE Transactions on Power Delivery*, vol. 23, no. 3, pp. 1636–1644, Jul. 2008, https://doi.org/10.1109/TPWRD.2007.909115.

[8] P.-C. Chen *et al.*, "Analysis of Voltage Profile Problems Due to the Penetration of Distributed Generation in Low-Voltage Secondary Distribution Networks," *IEEE Transactions on Power Delivery*, vol. 27, no. 4, pp. 2020–2028, Jul. 2012, https://doi.org/10.1109/TPWRD.2012.2209684.

[9] A. K. Verma, S. Ajit, and D. R. Karanki, *Reliability and Safety Engineering*. New York, NY, USA: Springer International Publishing, 2010.

[10] M. Rausand and A. Hoyland, *System Reliability Theory: Models, Statistical Methods, and Applications*, 2nd edition. Hoboken, NJ, USA: John Wiley & Sons, 2003.

[11] M. Xie, Y.-S. Dai, and K.-L. Poh, *Computing System Reliability: Models and Analysis*. New York, NY, USA: Kluwer Academic Publishers, 2004.

[12] E. A. Elsayed, *Reliability Engineering*, 2nd edition. Hoboken, NJ, USA: Wiley, 2012.

[13] J. Sun, V. Palade, X.-J. Wu, W. Fang, and Z. Wang, "Solving the Power Economic Dispatch Problem With Generator Constraints by Random Drift Particle Swarm Optimization," *IEEE Transactions on Industrial Informatics*, vol. 10, no. 1, pp. 222–232, Oct. 2014, https://doi.org/10.1109/TII.2013.2267392.

[14] A. Golshanfard and H. Hashemi-Dezaki, "Sensitivity Analysis of Distribution System Reliability for Identifying the Critical Elements," in *27th Iranian Conference on Electrical Engineering*, Yazd, Iran, Dec. 2019, pp. 522–526, https://doi.org/10.1109/IranianCEE.2019.8786589.

[15] M. Lwin, J. Guo, N. Dimitrov, and S. Santoso, "Protective Device and Switch Allocation for Reliability Optimization With Distributed Generators," *IEEE Transactions on Sustainable Energy*, vol. 10, no. 1, pp. 449–458, Jan. 2019, https://doi.org/10.1109/TSTE.2018.2850805.

[16] H. Hashemi-Dezaki, H. Askarian-Abyaneh, A. Shams-Ansari, M. DehghaniSanij, and M. A. Hejazi, "Direct cyber-power interdependencies-based reliability evaluation of smart grids including wind/solar/diesel distributed generations and plug-in hybrid electrical vehicles," *International Journal of Electrical Power & Energy Systems*, vol. 93, pp. 1–14, Dec. 2017, https://doi.org/10.1016/j.ijepes.2017.05.018.

[17] M. Abdelghany and S. Tahar, "Cause-Consequence Diagram Reliability Analysis Using Formal Techniques With Application to Electrical Power Networks," *IEEE Access*, vol. 9, pp. 23929–23943, 2021, https://doi.org/10.1109/ACCESS.2021.3051968.

[18] H. H. Dezaki, H. A. Abyaneh, Y. Kabiri, H. Nafisi, K. Mazlumi, and H. A. Fakhrabadi, "Optimized protective devices allocation in electric power distribution systems based on the current conditions of the devices," in *International Conference on Power and Energy*, Kuala Lumpur, Malaysia, Nov. 2010, pp. 577–582, https://doi.org/10.1109/PECON.2010.5697648.

[19] K. Pereira, B. R. Pereira, J. Contreras, and J. R. S. Mantovani, "A Multiobjective Optimization Technique to Develop Protection Systems of Distribution Networks With Distributed Generation," *IEEE Transactions on Power Systems*, vol. 33, no. 6, pp. 7064–7075, Aug. 2018, https://doi.org/10.1109/TPWRS.2018.2842648.

[20] Z. Guo, H. Wang, Y. Wang, G. Liu, and Y. Li, "An improved algorithm for power system reliability sensitivity analysis," in *5th International Conference on Electric Utility Deregulation and Restructuring and Power Technologies*, Changsha, China, Nov. 2015, pp. 6–11, https://doi.org/10.1109/DRPT.2015.7432200.

[21] D. J. Smith, *Reliability, Maintainability and Risk: Practical Methods for Engineers including Reliability Centred Maintenance and Safety-Related Systems*, 8th ed. Butterworth-Heinemann, 2011.

[22] R. N. Allan and R. Billinton, *Reliability Evaluation of Power Systems*, 2nd ed. New York, NY, USA: Springer, 2013.

[23] G. Bhatt and S. Affljulla, "Analysis of large scale PV penetration impact on IEEE 39-Bus power system," in *58th International Scientific Conference on Power and Electrical Engineering of Riga Technical University*, Riga, Latvia, Oct. 2017, pp. 1–6, https://doi.org/10.1109/RTUCON.2017.8124840.

[24] Y. Xu and C. Singh, "Power System Reliability Impact of Energy Storage Integration With Intelligent Operation Strategy," *IEEE Transactions on Smart Grid*, vol. 5, no. 2, pp. 1129–1137, Mar. 2014, https://doi.org/10.1109/TSG.2013.2278482.

[25] "IEEE SA - IEEE 493-1997," *IEEE Standards Association*. https://standards.ieee.org/ieee/493/726.

[26] A. Chowdhury and D. Koval, *Power Distribution System Reliability: Practical Methods and Applications*. Hoboken, NJ, USA: John Wiley & Sons, 2011.

[27] B. Kekezoglu, O. Arikan, A. Erduman, E. Isen, A. Durusu, and A. Bozkurt, "Reliability analysis of hybrid energy systems: Case study of Davutpasa Campus," in *Eurocon*, Zagreb, Croatia, Jul. 2013, pp. 1141–1144, https://doi.org/10.1109/EUROCON.2013.6625124.

[28] S. S. Kar and L. B. Roy, "Probabilistic Based Reliability Slope Stability Analysis Using FOSM, FORM, and MCS," *Engineering, Technology & Applied Science Research*, vol. 12, no. 2, pp. 8236–8240, Apr. 2022, https://doi.org/10.48084/etasr.4689.

[29] B. M. Alshammari, "Probabilistic Evaluation of a Power System's Reliability and Quality Measures," *Engineering, Technology & Applied Science Research*, vol. 10, no. 2, pp. 5570–5575, Apr. 2020, https://doi.org/10.48084/etasr.3441.

[30] S. M. Ghania and A. M. Hashmi, "Transient Overvoltages Simulation Due to the Integration Process of Large Wind and Photovoltaic Farms With Utility Grids," *IEEE Access*, vol. 9, pp. 43262–43270, 2021, https://doi.org/10.1109/ACCESS.2021.3065874.

[31] *Egypt Energy Policy Laws and Regulations Handbook: Volume 1 Strategic Information and Developments*. Washington DC, USA-Egypt: International Buisiness Publications, 2015.

[32] M. Boukhalfa, A. Benaissa, M. R. Bengourina, A. Khoudiri, and M. Boudiaf, "Performance Enhancement of the DPC Control Based on a VGPI Controller Applied to a Grid Connected PV System," *Engineering, Technology & Applied Science Research*, vol. 12, no. 2, pp. 8253–8258, Apr. 2022, https://doi.org/10.48084/etasr.4697.

[33] T. Zhang, C. Wang, F. Luo, P. Li, and L. Yao, "Analytical Calculation Method of Reliability Sensitivity Indexes for Distribution Systems Based on Fault Incidence Matrix," *Journal of Modern Power Systems and Clean Energy*, vol. 8, no. 2, pp. 325–333, Mar. 2020, https://doi.org/10.35833/MPCE.2018.000750.

[34] I. Akhtar, M. Jameel, A. Altamimi, and S. Kirmani, "An Innovative Reliability Oriented Approach for Restructured Power System Considering the Impact of Integrating Electric Vehicles and Renewable Energy Resources," *IEEE Access*, vol. 10, pp. 52358–52376, 2022, https://doi.org/10.1109/ACCESS.2022.3174365.

[35] M. Z. Kamaruzaman, N. I. A. Wahab, and M. N. M. Nasir, "Reliability Assessment of Power System with Renewable Source using ETAP," in *International Conference on System Modeling & Advancement in Research Trends*, Moradabad, India, Nov. 2018, pp. 236–242, https://doi.org/10.1109/SYSMART.2018.8746980.

AUTHOR PROFILES

Samy M. Ghania was born in Egypt, in 1971. He received the B.Sc., M.Sc., and Ph.D. degrees in electrical engineering from the Faculty of Engineering, Benha University, Cairo, Egypt, in 1995, 2001, and 2005 respectively. In July 2006, he joined the University of Waterloo, Waterloo, ON, Canada, as a Postdoctoral Fellow. He is currently working as a Professor of electrical engineering at the University of Jeddah, Saudi Arabia. He has published several papers in international journals and conferences in electrical machines, drives, interference, and electromagnetic simulation, and effects on the human body. He has carried several projects on electrical machine control using micro-controllers, DSP, programmable logic control, and renewable energy resources. His areas of interest include modeling and simulation of electrical machines, drives for electrical vehicles, and its control systems.

Khaled R. M. Mahmoud, is a Professor in the Mechanical and Materials Engineering Department, College of Engineering, University of Jeddah, Saudi Arabia. He received his Ph.D. degree from the Heinz Nixdorf Institute, University of Paderborn, Paderborn, Germany in 2005. He has pioneered research in vehicle dynamics and vehicle braking systems and has published more than 35 research articles. He has reviewed several research papers in ISI journals, in fields such as Energy Conversion and Management and Vehicle dynamics. His current research is on the dynamics of hybrid vehicle systems and internal combustion engines fueled by alternative fuels.

Anas M. Hashmi was born in Saudi Arabia. He received the B.Eng. degree in electrical and electronic engineering with mathematics, the M.Sc. degree in electronic and ultrasonic instrumentation, and the Ph.D. degree in electrical and electronics engineering from the University of Nottingham, U.K. in 2011, 2012, and 2017 respectively. He was with the Optics and Photonics Group, University of Nottingham. Since 2014, he has been working with the University of Jeddah, Saudi Arabia and he is promoted as the Head of Electrical and Electronic Engineering Department. He is currently an Assistant Professor at the University of Jeddah. He has published 8 scientific articles. His research interests include the development of inexpensive differential ultrasonic calorimeter for accurate measurement of heat loss in machinery. He received the Best Paper Award at the 2016 IEEE International Conference for Students on Applied Engineering (ICSAE'2016).