Reliability Analysis in Smart Grid Networks Considering Distributed Energy Resources and Storage Devices

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***Abstract*—This paper analyses the reliability of Smart Grid (SG) networks by integrating Distributed Renewable Energy Resources (DRERs) and Storage Devices (SDs) into the power grid. In this paper, three types of power grid systems are analyzed: 1) conventional power grid 2) power grid with DRERs 3) power grid integrated with both DRERs and SDs. The performance evaluation is carried out based on the IEEE 9 bus system, where we employ one conventional power generator, solar and wind power generators as the DRERs, and one SD. The results demonstrate that the integration of DRERs and SDs into the power grid can provide more reliable power to customers while reducing greenhouse gas emissions and energy wastage.**

***Index Terms*—distributed energy resources, distribution networks, reliability, smart grid communication, storage devices.**

I. Introduction

A Smart Grid (SG) is a combination of the electricity grid with the Information and Communication Technologies (ICT), allowing two-way communication between utility companies and consumers [1]. The electric power industry has faced significant challenges, among them, reliability has emerged as a sensitive issue for both end-users and providers. Due to the increased deployment of renewable energy, Distributed Generation (DG) and energy storage, reliability assessment techniques are required when designing the future electric power system infrastructure.

Renewable Energy Sources (RESs) are able to reduce global warming and negative health impacts, stabilize energy costs and provide sustainable energy to customers [2]. DG is generation plants connected to the distribution network or metered infrastructure, which can also be considered to be a Distributed Energy Resource (DER) [3]. Renewable energy based DG offers commercial and operational benefits such as improved voltage regulation and reliability, reduced network losses and greenhouse gas emissions.

The utilization of energy storage within the power system sector can significantly enhance system reliability and minimize costs of transmission upgrades [4]. The integration of RESs into the electric power system is not a sufficient solution because of its stochastic nature, thus the integration of renewable energy based DGs with energy storage is a key factor in SG system reliability.

In this paper, we have striven to discuss the aspects of reliability in SGs based on the three types of power grid systems: conventional power grid, power grid with Distributed Renewable Energy Resources (DRERs) and power grid integrated with both DRERs and Storage Devices (SDs). DigSILENT software program is used to simulate and analyze electrical power systems. According to the results, more reliable and sustainable power can be supplied to end-users when the power grid is coupled with both DRERs and SDs.

The remaining paper is organized as follows. A general overview of the state of the art is presented in Section II. Section III elaborates on power grid systems, while a performance evaluation is discussed in Section IV. Finally, the paper contains concluding remarks in Section V.

II. Related Work

Reliability issues in SG communication networks have been capturing the interests of the research community for a while. Therefore, there exists a lot of relevant studies in this area. In this section, we review the existing works which take into account reliability analysis in SG.

The effect of SG applications in enhancing the reliability of distribution networks using Monte Carlo (MC) simulation method is studied in paper [5]. A MATLAB code is developed to examine this effectiveness based on the IEEE 34 test feeder, where the auto reclosers and the DG units are installed. DGs along with the installation of the auto reclosers will be appreciated during blackouts and major outages, leading to a reduction in reliability indices and the repair time by isolating the healthy parts of the system automatically.

DGs are well-recognized for their uncertainty owing to the dependency on RESs like sunlight, wind, and water flow [6]. Because of the uncertainty, a number of problems such as frequency offset and voltage fluctuation occur in the distribution system. To tackle these issues, the authors of [6] proposed a new method to assess the reliability of the distribution networks with DGs using an

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MC approach. Various DG models and switch devices, taking into account multiple accidents under certain islanding schemes were also discussed. Accordingly, the reliability improvements can be observed brought by DGs and islanding schemes, although further research of multiple accidents is needed. However, accurate frequency indices are unavailable due to the non-sequential MC method and every aspect cannot be covered in the practical use.

The implementation of three smart solutions altogether, such as a dynamic network restoration scheme, integration of wind generation and installation of a composite system, consisting of a wind turbine and an on-site storage system can enhance the distribution network reliability significantly [7]. In [8], reliability assessment of the power system was studied considering wind turbine generator with battery energy storage system installed on a wind farm. Reliability evaluation models and methods were also proposed using an MC simulation. The paper [9] studied power system reliability impact of the deployment of energy storage with DRERs, considering an intelligent operation strategy which improves reliability.

A number of relevant studies, such as [5], [10], and [11] have assessed the reliability of distribution networks with DGs, however, they have not considered the integration of energy storage systems into the power grid. In this paper, not only the presence of DG but also energy storage systems are taken into account to enhance the power system reliability significantly.

III. Power Grid Systems

In this section, we present an overview of the SG with its role globally, opportunities and challenges. Thereafter, we introduce three types of power grid systems: 1) conventional power grid 2) power grid integrated with DRERs and 3) power grid integrated with both DRERs and SDs.

A. *The Role of Smart Grids Globally*

A smart grid is a future of power grid, which is able to tackle many issues of today's power grid system. It is an enhancement of the traditional power grid by integrating digital communication technologies for providing efficient, secure, reliable and sustainable delivery of electricity, while exchanging information between suppliers and users of the electric power.

Many countries are constantly striving to develop energy policies to reduce carbon emission and ensure a steady supply. A comprehensive survey of the current and potential development of SG, the strategic plans and cost-benefit analysis for the SG in Taiwan and Great Britain was presented in [12] and [13] respectively. Although most of the developing countries are currently investigating potentials of research and SG utilization, applications of SG in such countries are still lagging behind in comparison with developed nations. The development progress for SG in developing countries like China, India, and Brazil was investigated by M. Fadaeenejad *et al*. [14] and found that these countries are frontier in this technology among developing nations. In paper [15], benefits and deployment issues of SG technology for a sustainable future and the ongoing major research programs in Europe, the USA and Australia in terms of the current scenario, substantial research, planning, and development work were introduced. Further developments, research works as well as policy support from the government in the field of SG are needed when designing the future modern grid.

B. *Conventional Power Grid*

In the conventional power grid, generators should produce more power than what end-users require, causing a depletion of fossil-fuel reserves because of the ever-increasing demand on energy use. In addition, the system is environmentally extravagant, unfit, as well as outdated to deal with increasing demand. Owing to its one-way communication and inflexibility, traditional power infrastructure cannot support the development of technologies that would make it more sustainable. The conventional power grid focuses on the generation, transmission, distribution, and control of the electricity with electromechanical structure, centralized generation, fewer sensors, manual recovery and checks. However, consumers demand more resilient, flexible, reliable and safe power supply, causing a transition from conventional to the modern grid, which transforms the current electrical grid into an intelligent network by information technology [16].

C. *Power Grid with Distributed Renewable Energy Resources*

DERs, also known as DGs or dispersed power, are small-scale units of local generation connected to the grid at distribution level, which can comprise renewable and non-renewable generation, storage components, inverters, electric vehicles, controllable loads, smart meters, data services and other energy management technologies as depicted in Fig. 1.

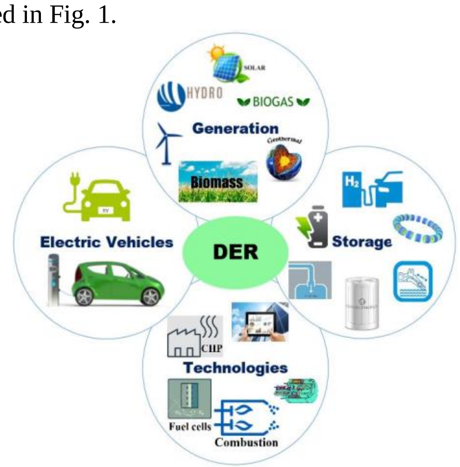

Fig. 1. Distributed energy resources.

DRERs create the vast amounts of benefits for customers, such as avoided costs and network investments, enhanced power quality and resilience, reduced carbon emissions while potentially improving the grid as a whole simultaneously [17]. Although the participation of RESs in DG has made DG more complex, it has created a path for SG. This complexity includes the high variability of output owing to the stochastic nature of RESs, which can impose a negative impact on the power grid.

D. Power Grid Integrated with Both Distributed Renewable Energy Resources and Storage Devices

Energy production is changing in the world due to the ever-increasing energy demand with the greenhouse gasses reduction goal, requiring the introduction of RESs on a large scale. However, the behavior of renewable sources is often intermittent as well as unpredictable, and the only solution to this problem is an energy storage. The energy storage is a dominant factor in the integration of RESs, playing an important role in raising the energy production efficiency and maintaining a reliable and robust modern electricity system [18]. It can reduce power fluctuations and improve the electric system flexibility, reliability and stability. For these reasons, energy storage systems are considered to be crucial for the future development of energy production. A huge variety of energy storage systems [19] were used in electric power systems such as chemical, electrochemical, mechanical, electrical and thermal as illustrated in Fig. 1.

IV. Performance Evalution

The performance evaluation conducted based on the IEEE 9 bus system is illustrated in Fig. 2. In this system, the deployment includes one conventional power generator, solar and wind power generators as the DRERs, and one SD.

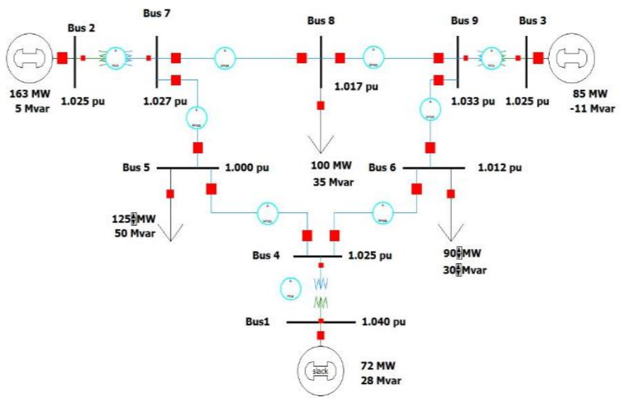

Fig. 2. IEEE 9 bus system.

The system reliability indices can be calculated with the three basic load point indices such as failure rate $\lambda_s = \sum \lambda_i$, repair duration $r_s = \sum \lambda_i r_i / \sum \lambda_i$ and annual outage duration $U_s = \sum \lambda_s r_s$ (unavailability). Among the system reliability indices, System Average Interruption Duration Index (SAIDI) and System Average Interruption Frequency Index (SAIFI) are the most commonly used indices to measure the system reliability as given in the following equations:

$$\text{SAIFI}=\frac{\sum \lambda_i N_i}{\sum N_i} \tag{1}$$

$$\text{SAIDI}=\frac{\sum U_i N_i}{\sum N_i} \tag{2}$$

where λ_i is the failure rate, N_i is the total number of customers at load point i, and U_i is the annual outage duration at load point i.

The indices of Customer Average Interruption Duration Index (CAIDI) and Average System Availability Index (ASAI) are also one of the most evaluated indices since they can be represented in relation to SAIDI and/or SAIFI as follows:

$$\text{CAIDI}=\frac{\text{SAIDI}}{\text{SAIFI}} \tag{3}$$

$$\text{ASAI}=1-\frac{\text{SAIDI}}{8760} \tag{4}$$

The IEEE 9 bus system includes 9 buses, 3 generators, 3 transformers and 3 loads as presented in Fig. 2. Assume that the system includes 300, 250, and 150 customers at load points A (Bus 5), B (Bus 6), and C (Bus 8) respectively, a total of 700 end-users on the system. The load parameters of the IEEE 9 bus system are given in Table I. The active power in medium voltage (MV) of the IEEE 9 bus system is provided in Fig. 3.

Table I. Load Parameters of IEEE 9 Bus System

Bus	Nominal active power (MV)	Nominal reactive power (MVar)
Load 5	125	50
Load 6	90	30
Load 8	100	35

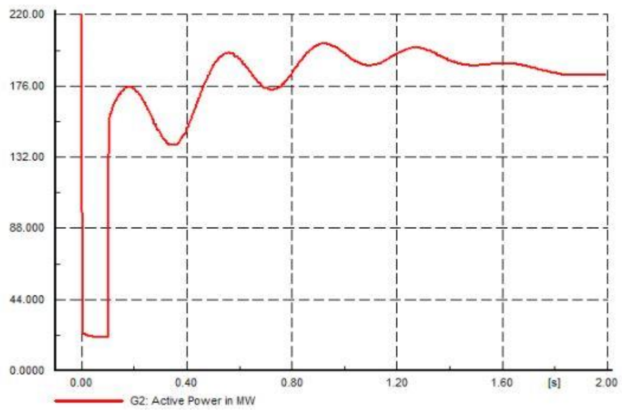

Fig. 3. Active power in MV of IEEE 9 bus system.

Table II. Reliability Indices for Case 1

Load points	A	B	C
λ (failures/yr)	1.95	1.7	1.45
r (hr/failure)	2.01	2.73	3.48
U (hr/yr)	3.91	4.64	5.05
Annual customer interruptions = 1227.5 Customer interruption duration = 3095 SAIFI = 1.75 interruptions/system customer/yr SAIDI = 4.42 hr/system customer/yr CAIDI = 2.52 hr/customer interrupted ASAI = 0.999495			

As noted earlier, the basic predictive indices, such as the average load point repair/outage duration, the average load point failure rate, and the average annual load point outage duration are used to predict the reliability of a distribution system. SAIFI, SAIDI, CAIDI, and ASAI reliability indices were calculated using the basic predictive load point indices for the conventional power grid with the aid of DigSILENT software program, as provided in Table II (Case 1).

The integration of a number of DRERs into the power grid system by the electrical utility companies can enhance the reliability of their network. The solar and wind power generator systems were adopted in this research study owing to their economic, environmental and technical benefits. Solar power is the conversion of energy from sunlight into electricity, using photovoltaic, concentrating solar power and concentrating photovoltaic technologies. It does not produce any pollution and has extremely low operating and maintaining costs [20]. Wind power, being cost-effective and available everywhere with zero emissions, is a great alternative to burning fossil fuel. The integration of the DRERs into the conventional distribution system improved the values of the reliability indices as illustrated in Table III (Case 2). In case 2, the values of the distribution system reliability indices, such as SAIFI, SAIDI, CAIDI, and ASAI were enhanced by 23.4%, 51.6%, 36.5%, and 0.026% respectively, compared to case 1.

TABLE III. RELIABILITY INDICES FOR CASE 2

Load points	A	B	C
λ (failures/yr)	1.75	1.5	1.25
r (hr/failure)	1.25	1.63	1.24
U (hr/yr)	2.19	2.44	1.55
Annual customer interruptions = 935.5 Customer interruption duration = 1499.5 SAIFI = 1.34 interruptions/system customer/yr SAIDI =2.14 hr/system customer/yr CAIDI = 1.60 hr/customer interrupted ASAI = 0.999755			

The output of solar power and wind power changes with time as a consequence of the intermittent nature of RESs. This is a strong incentive to ensure that a part of the electric power generated from these systems be stored in a battery storage system. By doing so, power outage time can be reduced and the efficiency of the electrical power system can be considerably increased. The output power of the solar system depends upon the solar irradiance and operating temperature, whereas the output power of the wind system [21] depends on the characteristics, such as the wind speed and regime, air density, turbine's size and performance amongst others. An SD was therefore employed in this study in order to reduce the uncertainty associated with the RESs, resulting in reliability improvements. The implementation of both DRERs and SD produced reliability improvements in terms of SAIDI, SAIFI, CAIDI, and ASAI when compared with case 2. This can be seen from Table IV (Case 3).

TABLE IV. RELIABILITY INDICES FOR CASE 3

Load points	A	B	C
λ (failures/yr)	1.40	1.12	0.90
r (hr/failure)	1.14	1.83	2.17
U (hr/yr)	1.60	2.05	1.95
Annual customer interruptions = 835 Customer interruption duration = 1285 SAIFI = 1.19 interruptions/system customer/yr SAIDI =1.84 hr/system customer/yr CAIDI = 1.54 hr/customer interrupted ASAI = 0.999790			

When the SD was integrated, SAIDI and SAIFI reliability indices decreased considerably, leading to a noticeable enhancement in the system reliability and sustainable power supply as well as smoothing of the curve of conventional power generation. Fig. 4 depicts the reliability assessment of the power grid system for all three cases. SAIFI, SAIDI, CAIDI, and ASAI reliability indices are highlighted. The installation of DRERs and SDs into the conventional power grid improved SAIFI by approximately 32%, a change from 1.75 to 1.19 hours/year. SAIDI experienced a great reduction from 4.42 to 1.84 occurrence/year, accounting for almost 58.4% improvement. Moreover, a 38.9% improvement was noticed in CAIDI with only a slight increase in ASAI from 99.9495% to 99.979%.

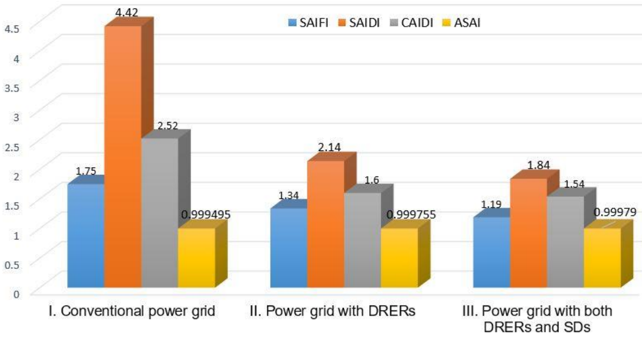

Fig. 4. Reliability assessment of the power grid systems.

V. CONCLUSION

This paper has assessed the reliability of SG networks considering DRERs and SDs. We have discussed three types of power grid systems such as a conventional power grid, power grid coupled with DRERs and power grid with both DRERs and SDs. The performance evaluation has been carried out based on the IEEE 9 bus system using DigSILENT software program. According to the results, more reliable and inexhaustible power can be provided to consumers by integrating DRERs and SDs into the power grid, resulting in reducing greenhouse gas emissions and energy wastage. As a future work, the performance evaluation will be conducted on a large-scale by integrating more DRERs and SDs to analyze the reliability of power systems.

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REFERENCES

[1] S. S. Reka and T. Dragicevic, “Future effectual role of energy delivery: A comprehensive review of internet of things and smart grid,” *Renewable and Sustainable Energy Reviews*, vol. 91, pp. 90–108, 2018.

[2] A. Pfeifer, V. Dobravec, L. Pavlinek, G. Krajai, and N. Dui, “Integration of renewable energy and demand response technologies in interconnected energy systems,” *Energy*, vol. 161, pp. 447–455, 2018.

[3] L. Mehigan, J. Deane, B. Gallachir, and V. Bertsch, "A review of therole of Distributed Generation (DG) in future electricity systems," *Energy*, vol. 163, pp. 822–836, 2018.

[4] F. Mohamad and J. Teh, "Impacts of energy storage system on power system reliability: A systematic review," *Energies*, vol. 11, no. 7, p. 1749, 2018.

[5] T. Aljohani and M. Beshir, "Matlab code to assess the reliability of the smart power distribution system using monte carlo simulation," *Journal of Power and Energy Engineering*, vol. 5, no. 1, pp. 30–44, 2017.

[6] X. Zhang, Z. Bie, and G. Li, "Reliability assessment of distribution networks with distributed generations using monte carlo method," in *Proc. Energy Procedia, the Proc. of Int. Conf. on Smart Grid and Clean Energy Technologies*, 2011, vol. 12, pp. 278–286.

[7] H. Guo, V. Levi, and M. Buhari, "Reliability assessment of smart distribution networks," in *Proc. IEEE Innovative Smart Grid Technologies-Asia (ISGT ASIA)*, Nov. 2015, pp. 1–6.

[8] U. Oh, J. Choi, and H. H. Kim, "Reliability contribution function considering wind turbine generators and battery energy storage system in power system," *IFAC-PapersOnLine*, vol. 49, no. 27, pp. 301–306, 2016.

[9] Y. Xu and C. Singh, "Power system reliability impact of energy storage integration with intelligent operation strategy," *IEEE Trans. on Smart Grid*, vol. 5, no. 2, pp. 1129–1137, March 2014.

[10] S. Conti and S. Rizzo, "An algorithm for reliability assessment of distribution systems in presence of distributed generators," *Int. Journal on Electrical Engineering and Informatics*, vol. 7, no. 9, pp. 502–516, 2015.

[11] A. Escalera, B. Hayes, and M. Prodanovic, "Reliability assessment of active distribution networks considering distributed energy resources and operational limits," in *Proc. CIRED Workshop 2016*, June 2016, p. 14.

[12] A. H. Lee, H. H. Chen, and J. Chen, "Building smart grid to power the next century in Taiwan," *Renewable and Sustainable Energy Reviews*, vol. 68, pp. 126–135, 2017.

[13] N. Jenkins, C. Long, and J. Wu, "An overview of the smart grid in Great Britain," *Engineering*, vol. 1, no. 4, pp. 413–421, 2015.

[14] M. Fadaeenejad, A. Saberian, M. Fadaee, M. Radzi, H. Hizam, and M. AbKadir, "The present and future of smart power grid in developing countries," *Renewable and Sustainable Energy Reviews*, vol. 29, pp. 828–834, 2014.

[15] G. Shafiullah, A. Oo, A. Ali, and P. Wolfs, "Smart grid for a sustainable future," *Smart Grid and Renewable Energy*, vol. 4, no. 1, p. 12, 2013.

[16] M. L. Tuballa and M. L. Abundo, "A review of the development of smart grid technologies," *Renewable and Sustainable Energy Reviews*, vol. 59, pp. 710–725, 2016.

[17] S. Kakran and S. Chanana, "Smart operations of smart grids integrated with distributed generation: A review," *Renewable and Sustainable Energy Reviews*, vol. 81, pp. 524–535, 2018.

[18] R. Amirante, E. Cassone, E. Distaso, and P. Tamburrano, "Overview on recent developments in energy storage: Mechanical, electrochemical and hydrogen technologies," *Energy Conversion and Management*, vol. 132, pp. 372–387, 2017.

[19] A. K. Rohit, K. P. Devi, and S. Rangnekar, "An overview of energy storage and its importance in Indian renewable energy sector: Part I technologies and comparison," *Journal of Energy Storage*, vol. 13, pp. 10–23, 2017.

[20] A. Shahsavari and M. Akbari, "Potential of solar energy in developing countries for reducing energy-related emissions," *Renewable and Sustainable Energy Reviews*, vol. 90, pp. 275–291, 2018.

[21] G. Ren, J. Liu, J. Wan, Y. Guo, and D. Yu, "Overview of wind power intermittency: Impacts, measurements, and mitigation solutions," *Applied Energy*, vol. 204, pp. 47–65, 2017.

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