2019 IEEE PES Innovative Smart Grid Technologies Asia

Microgrid Reliability Evaluation Using Distributed Energy Storage Systems

Mohammed A. Abdulgalil[1] and Muhammad Khalid[1,2], and Jaber Alshehri[1]
[1]*Electrical Engineering Department, King Fahd University of Petroleum & Minerals (KFUPM), Dhahran 31261, Saudi Arabia*
[2]*Researcher at K.A.CARE Energy Research & Innovation Center at Dhahran, Saudi Arabia*
atta@kfupm.edu.sa

***Abstract*—Reliability assessment of power systems is a very important factor to judge utilities and suppliers. Many suppliers lose millions of dollars because of the failure happening in their systems. Although these failures are out of control and cannot be avoided strictly, there are methods developed to enhance the reliability of power systems to minimize the number of failures and they work very efficiently. Integrating an energy storage system (ESS) with the power system is one of these methods to enhance the reliability. This paper presents the effects of integrating an ESS with a microgrid on the reliability evaluation and compares between the reliability indices of the microgrid without the ESS and with it. Also, dynamic programming is used to solve the unit commitment problem in both cases to calculate the production cost in both cases. The simulation results and numerical analysis depict the effectiveness of the proposed approach.**

***Index Terms*—Reliability assessment, microgrid, energy storage system.**

NOMENCLATURE

A	Availability of a component or system
U	Unavailability of a component or system
λ	Failure rate of a component or system
μ	Repair rate of a component or system
$MTTR$	Mean time to repair of a component or system
$MTTF$	Mean time to fail of a component or system
$MTBF$	Mean time between failures
N_i	Number of interrupted customers for each i event
N_T	Total number of customers served
λ_{LP}	Failure rate at the load point LP
r_i	Restoration time for each interruption event

I. INTRODUCTION

The importance of green energy and renewable energy sources increases to save the environment. When it comes to renewable energy sources, it is very important to talk about energy storage systems (ESS) and their applications in microgrids integrated with renewable energy. ESSs also have the ability to enhance the microgrid reliability and lower costs. In order to connect an ESS to a microgrid, the optimal size must be found. Many methods and techniques have been developed to find the optimal size of an ESS.

The number of microgrids coupled with renewable energy resources is increasing and the need to such systems in today's world is increasing as well due to the growing proportion of renewable energy. This need made researchers and engineers in the field of power systems seek for possible improvements to make these systems more efficient and economic. Energy storage systems (ESS) are integrated with systems coupled with renewable energy resources to overcome the challenges that might be faced in case of using renewable energy [1].

Power systems, including microgrids, are built for one goal and this goal is to supply customers with electrical energy. This energy must be available when it is needed, so, it must be available continuously. However, this is not possible and out of control for power engineers because of the failure probabilities of system components, but it is possible to enhance the availability of a system in case of increasing the investment cost [2]. In addition, one of the techniques to enhance the reliability of a microgrid is to integrate an ESS with it. In literature, many optimization techniques are used to size an ESS optimally for a specific microgrid such as mixed-integer linear programming (MILP) [3], dynamic programming (DP) [4], and particle swarm optimization (PSO) [5]. The optimal size of an ESS minimizes the total cost of investment and operation [6]. One of the reasons that makes an ESS reduces the total cost is that it charges in low-price periods and discharges in high-price periods. The investment cost of an ESS increases linearly with its capacity whereas the operation cost decreases exponentially as the capacity of the ESS decreases. The goal is to find the capacity at the minimum total cost. Fig. 1 shows how these costs vary with as the capacity of the ESS increases. Also, a larger ESS does not increase the profits necessarily and it costs more than the actual required cost [7].

The reliability of a power system means the availability of electrical energy at an economic cost [2]. So, minimizing the total cost contributes directly in optimizing the reliability. The authors in [7] presented a way to optimally size an ESS using MILP with reliability constraints to guarantee high reliability indices. Moreover, the authors in [8] used a near-optimal method for locating an ESS in a power system. Optimal locating of an ESS contributes in reducing power losses in transmission lines and enhancing the efficiency of the system. In addition, the authors in [9] presented a way to size an ESS for electric vehicles which are becoming a promising alternative to current vehicles which depend on the internal combustion in their engines. An ESS enhances the reliability of a system in terms of production costs and reliability indices. ESS provides the flexibility of generation in systems having renewable energy sources since these systems could have mismatches between the output power and demand. This happens because of some errors such as forecasting errors in predicting the wind speed [10]. Fig. 2 shows how the battery energy storage system (BESS) contributes to provide the demand with electrical energy, such as load peak shaving when the generation does not overcome the peak [11]. This paper contributes to the literature through studying the effects and and impacts of integrating an ESS to a microgrid on its reliability indices. The reliability indices increase and thus the reliability enhances, and this paper analyzes this enhancement through detailed calculations.

Micrrogrids appeared as a solution for what is called integrating distributed energy resources since the use of renewable energy sources increased [12]. As the penetration of distributed generation (DG) units is increasing, microgrids containing several symmetrically organized DG units have been proposed as a concept [13]. The diagram in Fig. 3 shows the components of microgrids such as electric vehicles and energy storage systems [14].

In this paper, a microgrid is studied in two cases: (1) a microgrid without an ESS, (2) a microgrid with an ESS. The production costs and reliability indices of the two cases are compared with each other to see the effect of integrating an ESS with a microgrid. The reliability indices calculated are Average System Availability Index (ASAI), Average System Unavailability Index (ASUI), System Average Interruption Frequency Index (SAIFI), System Average Interruption Duration Index (SAIDI), and Customer Average Interruption Duration Index (CAIDI). The units of all reliability indices in this paper are hours per year. In this paper, the ESS is considered as a generation unit that does not have a limit and always discharges. In addition, the ESS is not optimally sized. The main objective of this paper, studying the effect of integrating an ESS with a microgrid, is not presented in literature. This paper focuses on the effects of integrating an ESS on the operation cost and reliability indices.

The remainder of the paper is organized as follows. The proposed methodology is described in Section II. Section III presents the simulation results followed by a conclusion in Section IV.

II. Proposed Methodology

.

The objective of this research is to study the effect of integrating an ESS with a microgrid. To reach this objective, a microgrid that has three generation units is studied and the unit commitment is performed using dynamic programming (DP) [15] to calculate the output power of each unit during a typical day to supply the demand and to calculate the total production cost during that day. Then, the reliability indices are calculated. The MATLAB code presented in [16] has been used to perform the unit commitment and calculate the total production cost in both cases. After that, an ESS is integrated

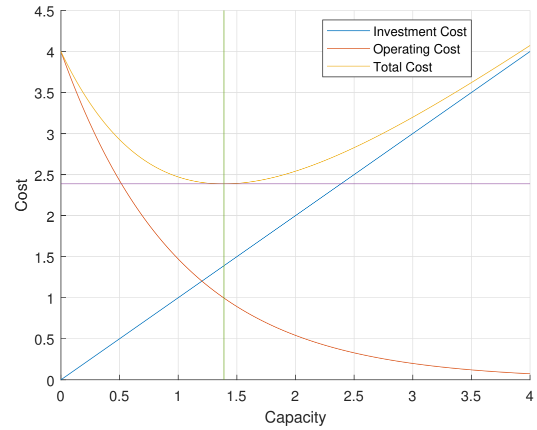

Fig. 1: Total cost Vs. ESS capacity.

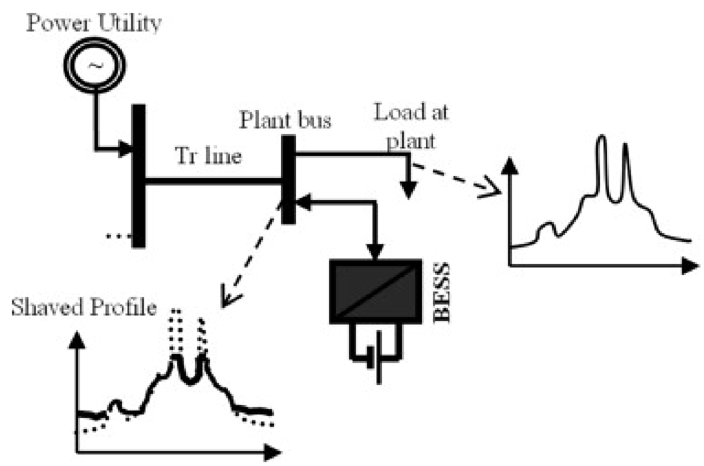

Fig. 2: Load peak shaving by BESS.

with the microgrid and all previous calculations are performed again.

The availability of a unit is expressed as a probability. This probability implies the time that a unit will be available or ON during it, so the unavailability is calculated as:

$$U = 1 - A \tag{1}$$

The availability is calculated from MTTR and MTTF:

$$A = \frac{MTTF}{MTBF} \quad and \quad U = \frac{MTTR}{MTBF} \tag{2}$$

Where MTBF is calculated as:

$$MTBF = MTTF + MTTR \tag{3}$$

Also, we can use the failure and repair rates to calculate the A and U since:

$$\lambda = \frac{1}{MTTF} \quad and \quad \mu = \frac{1}{MTTR} \tag{4}$$

These equations give:

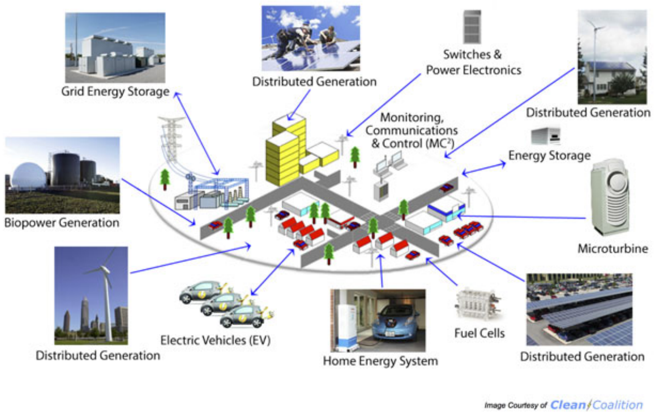

Fig. 3: The components of a microgrid.

$$A = \frac{\mu}{\lambda + \mu} \quad and \quad U = \frac{\lambda}{\lambda + \mu} \tag{5}$$

The units, distributed generators and ESS, are connected in parallel in the case study below. The following equations are used to evaluate the reliability of a two-parallel-unit system. In systems having more than two units, the equations can be derived in the same way. For components connected in parallel in a system, the equivalent unavailability is equal to the sum of all individual unavailabilities as:

$$U_{sys} = U_1 U_2 \tag{6}$$

So, the equivalent availability is calculated as:

$$A_{sys} = 1 - U_{sys} \tag{7}$$

In more details:

$$A_{sys} = 1 - U_1 U_2 \tag{8}$$

$$A_{sys} = 1 - \frac{MTTR_1}{MTTF_1 + MTTR_1} \cdot \frac{MTTR_2}{MTTF_2 + MTTR_2} \tag{9}$$

Using the failure and repair rates, we get:

$$U_{sys} = \frac{\lambda_1 \lambda_2}{(\lambda_1 + \mu_1)(\lambda_2 + \mu_2)} \tag{10}$$

$$A_{sys} = 1 - \frac{\lambda_1 \lambda_2}{(\lambda_1 + \mu_1)(\lambda_2 + \mu_2)} \tag{11}$$

To calculate the total repair and failure rates:

$$\mu_{sys} = \mu_1 + \mu_2 \tag{12}$$

$$U_{sys} = \frac{\lambda_1 \lambda_2}{(\lambda_1 + \mu_1)(\lambda_2 + \mu_2)} \tag{13}$$

$$\frac{\lambda_{sys}}{\lambda_{sys} + \mu_{sys}} = \frac{\lambda_1 \lambda_2}{(\lambda_1 + \mu_1)(\lambda_2 + \mu_2)} \tag{14}$$

TABLE I: Characteristics of Generation Units

Unit No.	Fuel Cost ($/MBTU)	Startup Cost ($)	Min. Capacity (MW)
1	2	350	4
2	2	400	10
3	2	1100	10
Unit No.	**Max. Capacity (MW)**	**Min. Up Time (h)**	**Min. Down Time (h)**
1	10	4	2
2	40	5	3
3	40	5	4

$$\lambda_{sys} = \frac{\mu_{sys} \lambda_1 \lambda_2}{\mu_1 \mu_2 + \lambda_1 \mu_2 + \lambda_2 \mu_1} \tag{15}$$

Which yields to:

$$\lambda_{sys} = \frac{(\mu_1 + \mu_2) \lambda_1 \lambda_2}{\mu_1 \mu_2 + \lambda_1 \mu_2 + \lambda_2 \mu_1} \tag{16}$$

The equivalent MTTF and MTTR are calculated simply as:

$$MTTF_{sys} = \frac{1}{\lambda_{sys}} \quad and \quad MTTR_{sys} = \frac{1}{\mu_{sys}} \tag{17}$$

The reliability indices are calculated as:

$$SAIDI = \frac{Total\ duration\ of\ all\ interruptions}{Total\ number\ of\ customers\ connected} \tag{18}$$

$$SAIDI = \frac{\sum_{i=1}^{n} r_i N_i}{N_T} \tag{19}$$

$$SAIFI = \frac{Total\ number\ of\ all\ interruptions}{Total\ number\ of\ customers\ connected} \tag{20}$$

$$SAIFI = \frac{\sum_{i=1}^{n} N_i}{N_T} = \frac{\sum_{i=1}^{n} \lambda_{LP} N_{LP}}{N_T} \tag{21}$$

$$CAIDI = \frac{Total\ duration\ of\ all\ interruptions}{Total\ number\ of\ all\ interruptions} \tag{22}$$

$$CAIDI = \frac{\sum_{i=1}^{n} r_i N_i}{N_T} = \frac{SAIDI}{SAIFI} \tag{23}$$

TABLE II: MTTF and MTTR of Generation Units and ESS in a Year

Unit No.	MTTF (h)	MTTR (h)
1	400	25
2	1100	35
3	1350	40
ESS	150	15

TABLE III: Load Profile of the Typical Day

Hour	1	2	3	4	5	6	7	8
Demand	53.7	50.5	48.1	47.3	47.3	48.1	59.3	68.9
Hour	9	10	11	12	13	14	15	16
Demand	76.2	77.0	77.0	76.2	76.2	76.2	74.6	75.4
Hour	17	18	19	20	21	22	23	24
Demand	79.4	80.2	80.2	77.0	73.0	66.5	58.5	50.5

III. Simulation Results and Discussions

A. Case Study

In this section, a microgrid with three generation units is studied to calculate the generation cost and reliability indices. Then, an ESS is added to the microgrid and the same cost and indices are calculated again to see how these values are compared with the previous ones. Table 1 shows the characteristics of the generation units in the microgrid and Table 2 shows the mean time to fail (MTTF) and mean time to repair (MTTR) of the three generation units and ESS. The demand is the demand of the first day in the IEEE Reliability Test System (RTS) in [17] and [18] and all calculations are based on this day. This day has been considered as a typical day in this research. The RTS was developed and modified by IEEE and it is an enhanced test system given in a report by IEEE to be used in bulk power system reliability evaluation studies [18]. The demand of the typical day is shown in Table III in megawatts (MW).

All generation units and ESS are assumed to be connected in parallel to supply one load point where all customers are connected to it. The techniques mentioned in [19] and [20] have been used to calculate the reliability indices. The characteristics of the components are given in Tables I and II.

B. Results and Analysis

The unit commitment has been performed to calculate the output power of each generation unit at each hour and calculate the total production cost in both cases. Fig. 4 shows the generation units work to supply the demand in Case-1 and Fig. 5 shows how these units and the ESS work to supply the same demand in Case-2.

Integrating an ESS with the microgrid reduces the production cost by 28.67% during that typical day. The reliability indices are enhanced significantly. Although the ESS used in

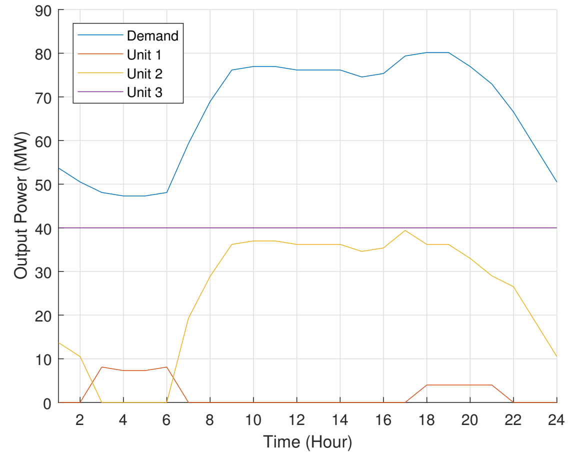

Fig. 4: Unit commitment of Case-1

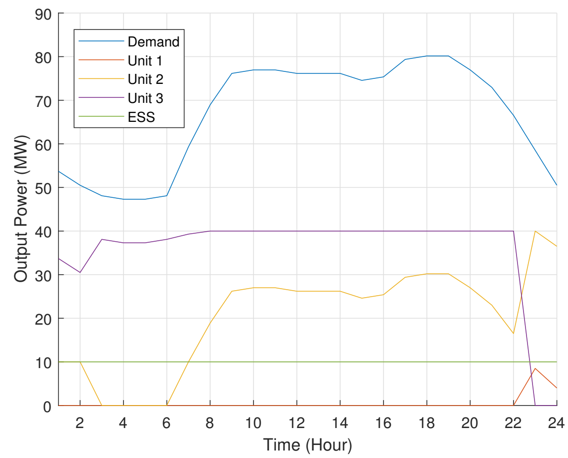

Fig. 5: Unit commitment of Case-2

this paper is not optimally sized, the effect of integrating it is significant. Table IV shows the results of both cases and how they differ between the two cases.

Microgrid reliability has been evaluated in order to investigate the effects of connecting the ESS on the reliability. Table IV shows some reliability indices in addition to the production cost before and after integrating the ESS. As shown in this table, the availability of the microgrid improves. The reliability indices related to load points enhance with noticeable differences. Also, SAIFI and SAIDI are found to be within the proposed limits.

IV. Conclusion

In this paper, the production cost and reliability indices have been calculated in two cases to see the effects of integrating an ESS with a microgrid. The ESS enhances the reliability in terms of reliability-indices and economic cost. Moreover, the reliability enhancement is more if the ESS is optimally sized. A larger ESS than the optimal one does not enhance the reliability because its investment cost is too large and the

TABLE IV: Comparison between the Two Cases

Term	Case-1	Case-2	Enhancement
Prod. Cost ($)	2157.8	1539.2	-28.668088%
ASAI	9.999478E-01	9.999953E-01	0.004746%
ASUI	5.219975E-05	4.745432E-06	-90.909091%
SAIFI	1.722759E-10	5.705448E-13	-99.668819%
SAIDI	1.722759E-08	6.561265E-11	-99.619142%
CAIDI	1.000000E+02	1.150000E+02	15.000000%

extra size is not needed. The strategy is quite general and can be extended for reliability analysis particularly for larger penetration of intermittent energy resources like wind and solar into the electricity grid. This work will be enhanced in future research, e.g., the ESS will not be considered as a generation unit like in the discharging case considered in this research. Also, the ESS will be optimally sized to minimize the cost and optimize the reliability. In addition, the demand will be considered for one year to expand the horizon.

Acknowledgment

The authors would like to acknowledge the support provided by the Deanship of Research (DSR) at King Fahd University of Petroleum & Minerals (KFUPM) for funding this work through project No. RG171009. In addition, Dr. Muhammad Khalid would like to acknowledge the funding support provided by the King Abdullah City for Atomic and Renewable Energy (K.A. CARE).

References

[1] Y. Zheng, J. Zhao, Y. Song, F. Luo, K. Meng, J. Qiu, and D. J. Hill, "Optimal operation of battery energy storage system considering distribution system uncertainty," *IEEE Transactions on Sustainable Energy*, vol. PP, no. 99, pp. 1–1, 2017.

[2] R. Billinton and R. N. Allan, "Power-system reliability in perspective," *Electronics and Power*, vol. 30, no. 3, pp. 231–236, 1984.

[3] S. Chen, H. B. Gooi, and M. Wang, "Sizing of energy storage for microgrids," *IEEE Transactions on Smart Grid*, vol. 3, no. 1, pp. 142–151, 2012.

[4] T. A. Nguyen, M. L. Crow, and A. C. Elmore, "Optimal sizing of a vanadium redox battery system for microgrid systems," *IEEE Transactions on Sustainable Energy*, vol. 6, no. 3, pp. 729–737, 2015.

[5] T. Kerdphol, Y. Qudaih, and Y. Mitani, "Battery energy storage system size optimization in microgrid using particle swarm optimization," in *Innovative Smart Grid Technologies Conference Europe (ISGT-Europe), 2014 IEEE PES*. IEEE, 2014, pp. 1–6.

[6] S. Bahramirad, W. Reder, and A. Khodaei, "Reliability-constrained optimal sizing of energy storage system in a microgrid," *IEEE Transactions on Smart Grid*, vol. 3, no. 4, pp. 2056–2062, 2012.

[7] ——, "Reliability-constrained optimal sizing of energy storage system in a microgrid," *IEEE Transactions on Smart Grid*, vol. 3, no. 4, pp. 2056–2062, 2012.

[8] H. Pandžić, Y. Wang, T. Qiu, Y. Dvorkin, and D. S. Kirschen, "Near-optimal method for siting and sizing of distributed storage in a transmission network," *IEEE Transactions on Power Systems*, vol. 30, no. 5, pp. 2288–2300, 2015.

[9] Z. Song, J. Li, X. Han, L. Xu, L. Lu, M. Ouyang, and H. Hofmann, "Multi-objective optimization of a semi-active battery/supercapacitor energy storage system for electric vehicles," *Applied Energy*, vol. 135, pp. 212–224, 2014.

[10] K. Bruninx and E. Delarue, "Improved energy storage system & unit commitment scheduling," in *2017 IEEE PowerTech, Manchester*. IEEE, 2017, pp. 1–6.

[11] M. Y. Suberu, M. W. Mustafa, and N. Bashir, "Energy storage systems for renewable energy power sector integration and mitigation of intermittency," *Renewable and Sustainable Energy Reviews*, vol. 35, no. Supplement C, pp. 499 – 514, 2014. [Online]. Available: http://www.sciencedirect.com/science/article/pii/S1364032114002366

[12] N. L. Diaz, T. Dragičević, J. C. Vasquez, and J. M. Guerrero, "Intelligent distributed generation and storage units for dc microgrids - a new concept on cooperative control without communications beyond droop control," *IEEE Transactions on Smart Grid*, vol. 5, no. 5, pp. 2476–2485, Sept 2014.

[13] X. Wu and C. Shen, "Distributed optimal control for stability enhancement of microgrids with multiple distributed generators," *IEEE Transactions on Power Systems*, vol. 32, no. 5, pp. 4045–4059, Sept 2017.

[14] "Ny prize." [Online]. Available: https://www.nyserda.ny.gov/All-Programs/Programs/NY-Prize/Resources-for-applicants/Microgrids-101

[15] H. Kanchev, B. Francois, and V. Lazarov, "Unit commitment by dynamic programming for microgrid operational planning optimization and emission reduction," in *2011 International Aegean Conference on Electrical Machines and Power Electronics and 2011 Electromotion Joint Conference (ACEMP)*. IEEE, 2011, pp. 502–507.

[16] W. L. Snyder, H. D. Powell, and J. C. Rayburn, "Dynamic programming approach to unit commitment," *IEEE Transactions on Power Systems*, vol. 2, no. 2, pp. 339–348, 1987.

[17] R. T. Force, "Ieee reliability test system," *IEEE Trans. on PAS*, vol. 98, no. 6, pp. 2047–2054, 1979.

[18] C. Grigg, P. Wong, P. Albrecht, R. Allan, M. Bhavaraju, R. Billinton, Q. Chen, C. Fong, S. Haddad, S. Kuruganty *et al.*, "The ieee reliability test system-1996. a report prepared by the reliability test system task force of the application of probability methods subcommittee," *IEEE Transactions on Power Systems*, vol. 14, no. 3, pp. 1010–1020, 1999.

[19] R. Billinton and S. Jonnavithula, "A test system for teaching overall power system reliability assessment," *IEEE Transactions on Power Systems*, vol. 11, no. 4, pp. 1670–1676, 1996.

[20] R. Allen and R. Billinton, "Power system reliability and its assessment: Part 3 distribution systems and reliability costs," *Power Engineering Journal*, vol. 7, no. 4, pp. 185–192, 1993.