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Optimum Renewable Generation Capacities in a Microgrid Using Generation Adequacy Study

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Abstract—Microgrids, as small power systems, may be comprised of different types of loads and distributed generation. As the integration of renewable power generation increases, the total available generation capacity of the system will be more derated due to the effect of equipment failures and the intermittent nature of these resources. Therefore, it is critical to determine optimum renewable generation capacities and provide enough reserve margin to meet the target reliability of the microgrid. In this paper, we first model a microgrid, including conventional and renewable distributed generation and the loads. Second, we determine the renewable generation capacity required to meet growth in demand at a certain level of grid reliability through a generation adequacy study. Adequacy of the microgrid is evaluated using parameters such as loss of load probability (LOLP) and expected energy not served (EENS). Third, the impact of different conditions, such as wind speed diversity (captured by correlating the wind power output), a combination of wind and solar power, and load diversity, on generation adequacy is studied through sensitivity analyses. Finally, the optimum renewable generation capacities are determined such that the total cost of generation and unserved power is minimized. The optimization process is based on the particle swarm optimization (PSO) method which uses Monte Carlo (MC) simulation for generation adequacy studies in each iteration.

Index Terms—generation adequacy, microgrid, Monte Carlo simulation, optimum generation capacity, particle swarm optimization, renewable generation.

I. INTRODUCTION

A microgrid may be perceived as a small power system which integrates enough distributed generation capacity to be able to operate as a standalone system. In other words, microgrids can satisfy their own loads in case of a contingency and in isolation from the distribution system [1].

There are a number of generation technologies that may be used in a typical microgrid, such as a diesel engine, microturbine, photovoltaic (PV) system, and wind power generation [2]. They may generally be categorized into conventional and renewable generation systems. Recently, increasing concerns about climate change, improved

manufacturing technology, and cost reduction have been the major drivers toward integration of wind and PV power generation systems as distributed energy resources (DER).

The reliability of a microgrid in terms of generation adequacy depends on a variety of factors, such as system configuration, generation system capacity and characteristics, and load types [3]. The capability of a microgrid to operate in both connected and isolated mode provides an opportunity to minimize the interrupted duration of the loads and thereby improve system reliability [4]. In fact, reliability of a microgrid is improved by including multiple generation assets as power suppliers of the system loads [5]. On the other hand, the integration of intermittent renewable generation may adversely affect the reliability of a microgrid. Wind and PV power generation systems do not have power following capability and, therefore, are not considered dispatchable [3]. As a result, higher capacities of intermittent generation would be required to provide the same level of reserve margin and reliability fulfilled by conventional generation.

Different aspects of microgrids have been addressed in the literature. A number of these research studies have focused on the operation and control of the microgrid in island and grid-connected modes [6, 7]. A study of microgrid generation adequacy indicates that with a certain total generation capacity, a higher number of DER units results in higher system reliability [3]. Fang et al. determined the impact of wind generation on the generation adequacy of a microgrid [8]. However, their study does not include other types of renewable generation and load diversity. In addition, the authors have not studied the optimum renewable generation capacities of their case study. The research papers addressing the optimum capacities of DER have usually focused on microgrid loss minimization or cost minimization of system operation and maintenance [9, 10] and have not included the failure rates of the generation system and the costs associated with the unserved power. The authors in [11] calculate the optimum swept area of wind generation and the area of PV panels in order to minimize the cost, using generation adequacy studies. The cost of unsupplied energy and demand sector diversity have not been included in this study.

In this paper, we provide a detailed analysis on the microgrid generation expansion using wind and PV generation systems considering system reliability. The dynamic behavior of intermittent generation and loads is included in the study as well. First, wind generation capacities required to satisfy the target reliability of a system are determined with different load growth projections using Monte Carlo (MC) simulation. The adequacy of the system is evaluated using indices, such as loss of load probability (LOLP) and expected energy not supplied (EENS). Next, the effects of wind speed correlations and combination of both wind and PV generation systems on the microgrid reliability are determined. Finally, the optimum capacities of wind and PV systems are calculated in order to minimize the total cost of generation and unserved energy for different types of load sectors, subject to a certain reliability target. Particle swarm optimization (PSO) is employed on top of the MC simulation to calculate the optimum capacities. In the following section, the study approach and system modeling are described, and then, the simulation results are provided.

II. MODELING

Figure 1 shows the schematic of the microgrid used for the generation adequacy study. The main components modeled are the distributed generation and the loads. It is assumed in this model that the microgrid is disconnected from the main utility grid and works as an isolated power system in a remote area.

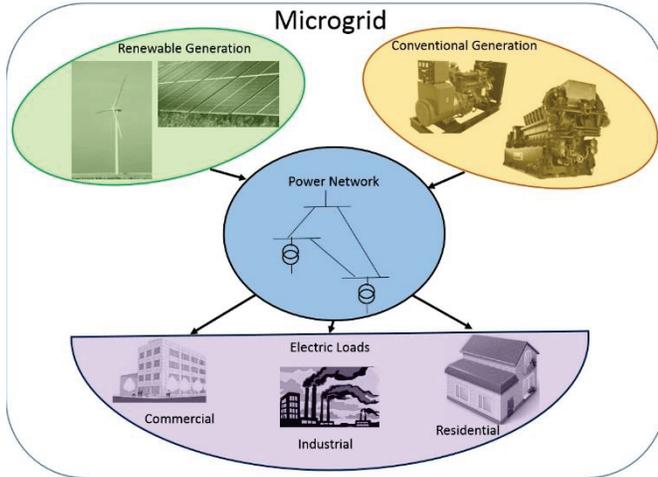


Figure 1. Schematic of the microgrid model for generation adequacy study.

A. Distributed Generation Model

There are generally two generation categories included in this study: 1) the conventional generators which can follow the load and 2) renewable generators whose output depends on the stochastic nature of the renewable resource. Each conventional and renewable generator is considered using a two-state (success; failure) operational model.

The two types of renewable generation in this paper are PV and wind generation whose output power is modeled using hourly time series data. Figures 2 and 3 show the average power generated from a typical PV system and a wind turbine for duration of a day, respectively [12, 13].

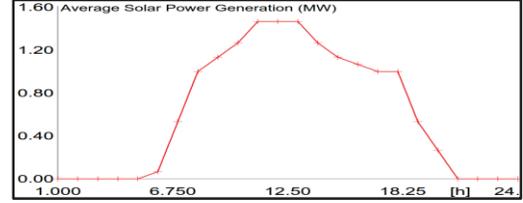


Figure 2. Average output power of a PV generation system.

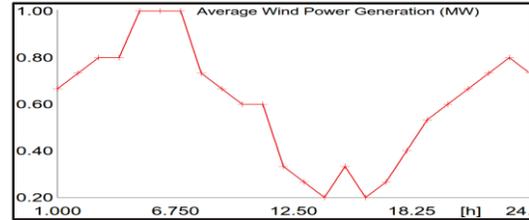


Figure 3. Average output power of a wind generation system.

B. Load Model

Three types of customer sectors are modeled using their hourly load profiles: residential, commercial, and industrial, as shown by Figures 4, 5, and 6, respectively [14].

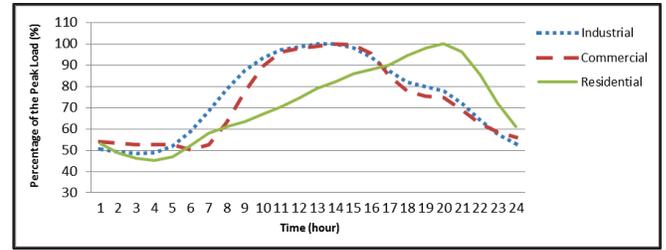


Figure 4. Load curves of different customer sectors.

III. STUDY APPROACH

A. Generation Adequacy

The generation adequacy of the microgrid is studied using MC simulation. At each iteration (hour) of the simulation, the operation states for all of the generation units are obtained. Then, the output power of the renewable generators and demand of the loads are determined by sampling their corresponding curves for that iteration. The reliability indices, LOLP and EENS, and their 90% confidence interval are calculated using the hourly sample values of load and generation for the desired number of iterations.

$$DNS(i) = \sum_{k=1}^{N_L} P_L(k, i) + P_{Loss} - \sum_{m=1}^{N_G} P_G(m, i) \quad (1)$$

$$EDNS = \frac{\sum_{i=1}^N DNS(i)}{N} \quad (2)$$

$$EENS = EDNS \times T \quad (3)$$

$$LOLP = \frac{\sum_{i=1}^N N_{DNS}(i)}{N} \times 100 \quad (4)$$

where:

$$\begin{cases} N_{DNS}(i) = 1 & DNS(i) \geq 0 \\ N_{DNS}(i) = 0 & DNS(i) < 0 \end{cases} \quad (5)$$

In these equations, $P_L(k, i)$ and $P_G(m, i)$ are demand of load point k and output power of generator unit m for iteration i , respectively. N_L and N_G are the number of load points and generator units. DNS and P_{Loss} denote the demand not served and the total power loss of the microgrid, respectively. N represents the total number of iterations, and T is the duration of the *EENS* calculation, which is one year in this study.

B. Renewable Generation Capacity Optimization

In a microgrid consisting of conventional distributed generation, the goal is to determine the total optimum capacities of the wind and PV generation to supply the system's expected load growth, such that the total cost of renewable generation and unserved power is minimal. In fact, there is a trade-off between the cost of higher reserve margin in a microgrid due to higher generation capacity and the cost of unsupplied demand. Therefore, the objective function is defined by (6).

$$F = N_W \cdot Cap_W \cdot C_W + N_{PV} \cdot Cap_{PV} \cdot C_{PV} + C_{DNS} \cdot EDNS \quad (6)$$

Subject to:

$$\begin{cases} Cap_W + Cap_{PV} \geq \Delta P \\ LOLP < p \end{cases} \quad (7)$$

where Cap_W and N_W are the unit capacity and the number of wind generation systems; and Cap_{PV} and N_{PV} represent similar parameters for the PV system, respectively. C_W and C_{PV} are the levelized costs of wind and PV generation per Megawatt of capacity, respectively. C_{DNS} is the cost of the customer sector for the demand not supplied. ΔP denotes the expected peak load growth of the microgrid, and p is the target loss of load probability of the system.

The optimization process uses the PSO method as follows:

- 1- Obtain the generation and load profiles, expected load growth, components' failure data, and the costs of renewable generation and demand not served.
- 2- Start PSO with the initial values for the wind generation and PV capacities.
- 3- Perform the generation adequacy study using MC simulation, and calculate the objective function F based on the equations provided.
- 4- Update the best renewable generation capacities in the PSO algorithm based on the minimum objective function.
- 5- If the PSO stop criterion is not met, go to Step 3, otherwise provide the results of the optimized renewable generation capacities.

IV. BASE CASE STUDY

The microgrid of the base case scenario consists of residential loads and conventional generation. The peak load is 34.72 MW, and it follows the curve presented by Figure 4. There are a total of 7 gas and diesel distributed generation units supplying the load. It is assumed that the generator units

may fail with a probability of 1%. The input data and the results are shown in Table I.

TABLE I. INFORMATION ON THE BASE CASE

Input Data	System Peak Load (MW)	34.72	
	P_{Loss} (%)	3	
	Number of Conventional Generators	Gas	2
		Diesel	5
	Capacity of Conventional Generation (MW/unit)	Gas	12
Diesel		3	
90% CI for the Reliability Indices	$LOLP$ (%)	[0.86, 0.96]	
	$EENS$ (MWh/Year)	[377, 429]	

The results are calculated using MC simulation with Power Factory software and a total of 100,000 iterations. Figure 5 shows the $LOLP$ and its upper and lower 90% confidence limits with increasing number of MC iterations.

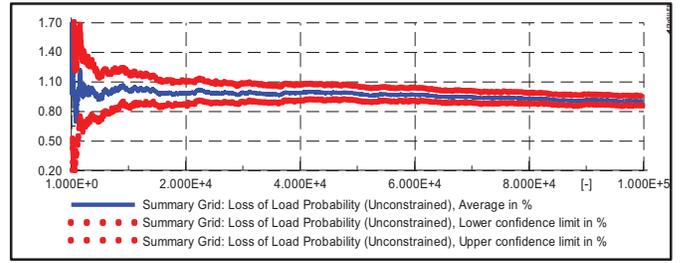


Figure 5. Calculation of $LOLP$ with increasing iterations of Monte Carlo simulation (base case).

Another method of determining the $LOLP$ is based on the reserve generation. Figure 6 shows the probability distribution of total reserve generation. The negative values of the reserve indicates the loss of load. Therefore, the intersection of this curve with the $Y=0$ axis can determine $LOLP$ which is nearly 0.9% in this case.

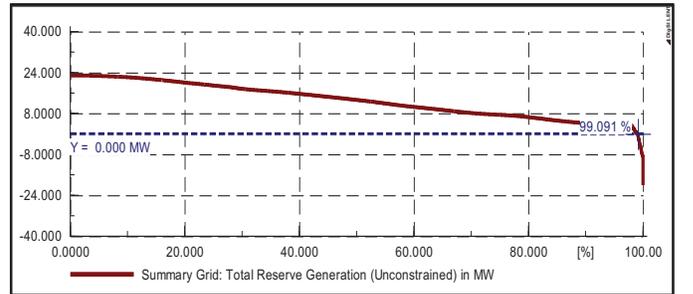


Figure 6. Probability distribution of the reserve generation (base case).

V. SENSITIVITY ANALYSES

The adequacy of the microgrid is studied with different load growth projections. It is assumed that growth in demand is intended to be supplied only by renewable power, such as wind and PV generation. It is recommended that the intermittent generations without storage do not comprise more

than certain percentage of the microgrid generation capacity due to probable frequency and voltage control issues [3]. In this study, the dynamic behavior of renewable generation integration is not included.

The impact of renewable resource correlations and wind to PV generation capacity ratio are studied in this section. The capacity factors of wind and PV generation are typically around 30% and 25%, respectively [15]. Therefore, the unit capacities of the renewable generation systems in this study are selected to be $Cap_W = 1MW$ and $Cap_{PV} = 1.25MW$ so that their output generated powers become comparable.

A. Sensitivity to Load Growth

In this study, the load increment is supplied solely by the wind generation. Figure 7 shows the LOLP and EENS of the microgrid with 10 MW peak load growth. According to the results, 50 MW of wind generation capacity is required to reach to LOLP of less than 1% where the EENS is approximately 400MWh per year.

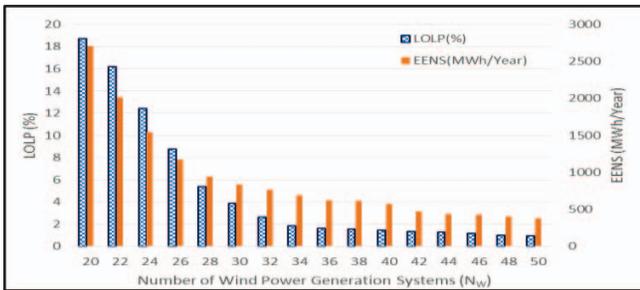


Figure 7. Reliability of microgrid with 10MW load growth supplied by wind generation.

Figure 8 depicts the LOLP results with different values of peak load growth. It is observed that with higher system load increment, the percentage of the required capacity to meet that demand rises for the same level of reliability (400% with 4 MW of peak load growth vs. 500% with 10 MW, for $p = 1\%$). This is due to the fact that higher contribution of wind generation escalates the generation uncertainty in the microgrid.

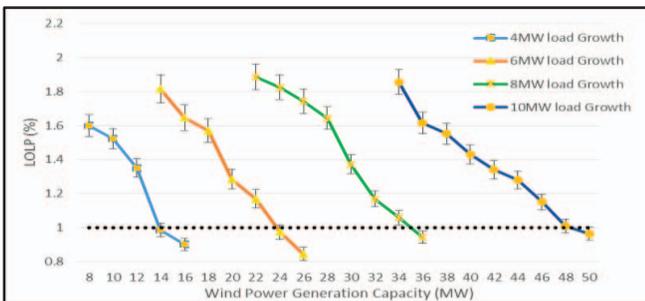


Figure 8. LOLP of microgrid with different load growth projections supplied by wind power generation.

B. Sensitivity to Wind Power Correlation

It is known that a higher diversity of wind resources reduces the output power variations [16]. The wind speed correlation decreases at the sites located further apart in a microgrid [17]. In order to evaluate the system adequacy

impact, two wind speed correlation values of 1 and 0.5 are considered in this section. The wind speeds are generated from their base case values with a resampling approach. Using this method, the data of a wind speed profile for the duration of interest are bootstrapped, using MATLAB software, to create different series of wind speeds that have various correlations with the original wind speed data.

Figure 9 shows that with lower wind speed correlation, an up to 30% less wind generation capacity may be able to supply a 10 MW load growth with the same level of reliability. The difference is more noticeable in higher desirable reliability.

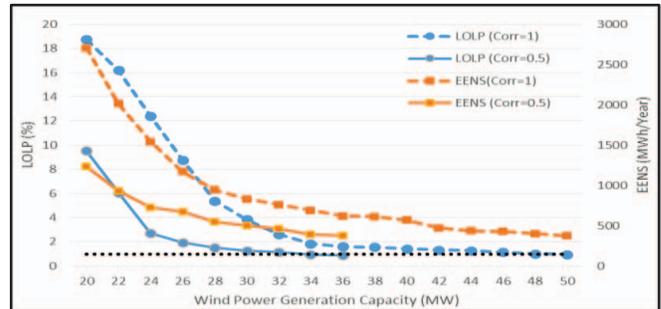


Figure 9. Reliability of microgrid with 10MW load growth with different wind speed correlations.

C. Sensitivity to Wind/PV Generation Capacity Ratio

A hybrid generation capacity, equally from wind and PV resources, is used to supply a 10 MW load growth. Figure 10 shows the total generations units required to meet certain microgrid reliability target. Comparison of this figure with Figure 7 indicates that the reliability of the microgrid is higher with the same total number of generation units in the current case. Here, the impact of resource diversity reduces the total required generation capacity by almost 10% with $p = 1\%$.

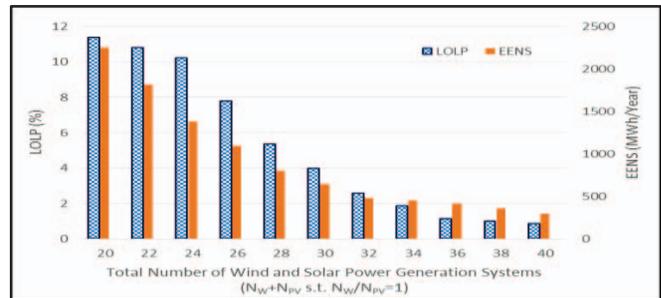


Figure 10. Reliability of microgrid with 10MW load growth supplied equally by wind and solar generation.

Different combinations of wind to PV capacity ratios may alter the adequacy of the system. Table II shows the total hybrid wind and PV capacity required to supply a certain load growth affected by the ratio of wind to PV number of units. According to the load curve and its correlation with a renewable generation, a specific wind/PV ratio can result in lower required total renewable generation capacity with a certain desired reliability level.

TABLE II. RENEWABLE GENERATION CAPACITY REQUIRED TO SUPPLY 4MW AND 10MW OF LOAD GROWTH ($p = 1\%$)

ΔP (MW)	Wind/PV Ratio	Wind Generation Capacity (MW)	PV system Capacity (MW)	Total Renewable Generation Capacity (MW)
4	$N_W/N_{PV} = 0.5$	6	15	21
	$N_W/N_{PV} = 1$	8	10	18
	$N_W/N_{PV} = 2$	12	7.5	19.5
10	$N_W/N_{PV} = 0.5$	16	40	56
	$N_W/N_{PV} = 1$	20	25	45
	$N_W/N_{PV} = 2$	28	17.5	45.5

VI. OPTIMUM RENEWABLE GENERATION CAPACITIES

The goal is to determine the optimum capacities of wind and PV generation in a microgrid with different load growth projections, various load sectors, and specific reliability levels. The objective function is defined by (6). The cost of damage to the customers could be different for different customer sectors [18]. In this study, it is assumed that C_{DNS} is 1, 10, and 20 \$/kW for residential, commercial and industrial customers, and the leveled generation costs, C_{PV} and C_W , are 30, and 25 \$/MW of capacity per hour, respectively [19]. According to the results provided in Table III, different combinations of wind and PV capacities become optimum with various load sectors. While higher wind generation capacity is chosen by the optimization process for residential customers, the optimum hybrid generation capacity for commercial and industrial customers includes higher PV capacities.

TABLE III. OPTIMUM RENEWABLE GENERATION CAPACITIES TO SUPPLY 4MW AND 10MW OF LOAD GROWTH

	ΔP (MW)	p	Wind Generation Capacity (MW)	PV system Capacity (MW)	EENS (MWh/year)
Residential	4	1%	10	5	420
		0.1%	36	15	13
	10	1%	26	12.5	411
		0.1%	54	22.5	9
Commercial	4	1%	2	10	360
		0.1%	4	25	15
	10	1%	2	25	306
		0.1%	14	35	14
Industrial	4	1%	2	15	228
		0.1%	6	25	10
	10	1%	4	30	158
		0.1%	14	37.5	11

VII. CONCLUSIONS

The optimum hybrid capacities of wind and PV generation were determined for different load sectors and reliability target values in a microgrid. MC simulation and PSO were used for generation adequacy and optimization studies, respectively. Higher correlation between the average PV generation and industrial/commercial load curves, causes higher contribution of PV system in the optimum hybrid generation capacity compared with the case of the residential loads. In addition, the impact of generation diversity and various load growth on

system adequacy were analyzed using sensitivity analyses. According to the results, as the load increases by 10-20%, nearly 3-5 times this demand growth should be added as renewable generation capacity in order to maintain the reliability level of the microgrid. It is recommended that the dynamic behavior of renewable generation integration be added to the future studies.

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