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Evaluation of the generation and protection capabilities of a grid-connected microgrid

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Abstract. Microgrids have been recognized for benefits to the electrical system such as improved reliability and reduced transmission costs and pollutant emissions. The study of microgrids makes it necessary to know and quantify the performance of technical aspects and identify characteristics to improve their performance. The paper proposes to evaluate the performance of generation and protection of a microgrid connected to the grid based on a procedure that includes the definition of indicators, the use of Power Factory software to obtain results and the weighting of indicators based on the DEMATEL technique. The laboratory microgrid studied is located at the Universidad Industrial de Santander and has three 1.5 kW photovoltaic systems and meets demands of 5 and 10 kWh/day. The results show that its generation and protection capacities have a high performance.

Keywords. Generation, microgrid, performance, protection.

1. Introduction

In recent years, the participation of renewable energy sources has increased to improve the energy reliability of the electric grid and contribute to environmental protection. The integration of energy resources makes the electric system more complex and dynamic, allows the participation of users, and gives way to the emergence of more advanced electric grids such as microgrids [1], [2].

A microgrid is a system composed of a group of distributed loads and energy resources that can operate as a controllable unit and be connected or not to the grid; the first type allows operating either in islanded or grid-connected mode [3]. Microgrids increase supply reliability, system controllability by the grid operator, savings in energy transmission and distribution, and reduce pollutant emissions [4].

The growing interest in microgrids makes it necessary to understand their operation and determine their performance to know their characteristics and detect their strengths and weaknesses. This examination makes it possible to identify the aspects that should be maintained and those that should be improved [5], [6].

Performance evaluation implies knowing the level of compliance with the objectives of a system concerning a reference value, given by regulations or according to the expectations of the designers. The evaluation considers metrics that facilitate the interpretation of the performance and allow to know the status of a component or the whole system [7],[8].

Some studies have used indicators to determine the best configuration (design stage) or to know its performance (operation stage). For example, Zhao *et al*. [9] carry out a performance analysis considering technical, economic, and environmental aspects, such as energy supplied, pollutant emissions, and energy savings. Likewise, Uddin *et al*. [8] use indicators to determine the level of utilization of the microgrid, the energy supplied, and the costs associated with the operation. Based on the results, they present recommendations to improve technical performance and financial viability. Pinceti *et al*. [10] present indicators to be used in the design of microgrids, which make it possible to compare different solutions and determine the most appropriate one based on technical and economic analysis of the results.

The performance of a microgrid can be discriminated into diverse capacities such as generation, operation, protection, and control, among others, which facilitates a more detailed analysis of the microgrid. Likewise, the metrics used to evaluate the performance of microgrids can be grouped into the capabilities [3],[6].

This paper presents the evaluation of generation and protection capacities based on the application of metrics (indicators) identified in the literature. In addition, the DEMATEL technique is used to assign weights to each indicator, which allows for establishing a valuation by capacity. Thus, the procedure allows quantifying the performance of a specific aspect of the microgrid and considers the level of importance of each metric in a certain capacity.

The generation study includes the variation of the power supply due to irradiance, while the protection analysis considers single-phase and three-phase faults at various points of the microgrid.

The results are obtained using Power Factory software (PF4R v2021). This tool facilitates the analysis of electrical systems, allowing to obtain load flows, fault analysis and stability analysis, among others. It is used in the analysis of generation, transmission, distribution, industrial systems and distributed generation [11], [12].

The paper is structured as follows: Section 2 presents the methodology, Section 3 describes the analysis of the results and, finally, Section 4 lists the conclusions obtained from the study.

2. Methodology

The paper presents the assessment of the generation and protection capabilities of the microgrid shown in Figure 1. The power generation analysis comprises two scenarios, namely: high irradiance and low irradiance. The protection includes the study of the microgrid in the presence of single-phase faults and three-phase faults.

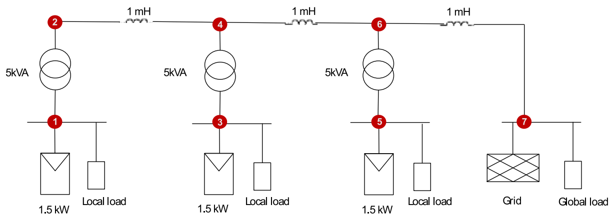

Figure 1. One-line diagram of the microgrid.

The case study, the metrics for capability assessment, the DEMATEL technique, and the procedure for capability assessment are presented below.

A. Case study

The study considers a grid-connected laboratory microgrid consisting of three 1.5 kW PV systems to satisfy a local demand of 5 kWh/day and a global load of 10 kWh/day. The microgrid is located at the Guatiguará campus of the Universidad Industrial de Santander in the municipality of Piedecuesta Santander, Colombia (6.98°N, 73.07°W). Figure 2 presents the load profiles.

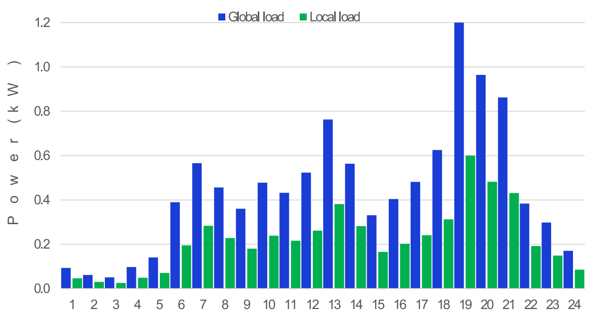

Figure 2. Load profiles.

Table I lists the characteristics of the microgrid components, which are considered to validate that the system operates within the admissible ranges.

Table I. component characteristics.

Component	Nominal value	Operating condition
Photovoltaic system	1.5 kW	110 V
Transformer 3φ	5 kVA	110 V, 15 A
Conductors	1 mH, 0.1 Ω	110 V, 32 A

B. Evaluation metrics

Generation is the ability to reliably meet demand. The metrics used to evaluate generation indicate the amount of energy that the system can supply, the relationship between energy production and installed capacity, and whether the electrical variables remain in a correct range in the face of variations in the energy supplied [13],[14]. Table II lists indicators applicable to generation capacity.

Protection is the ability of the system to resist and mitigate disturbances. It considers four conditions: sensitivity to detect faults, selectivity to identify the zone to be isolated, reliability to make the protection components act correctly and timely, and adaptability to modify the system configuration in fault events [15], [16].

The most widely used metric in fault analysis is the fault current, its application consists of simulating a disturbance and validating whether the fault currents remain within the allowed thresholds [17]–[19]. The currents of the protections in each branch of the studied microgrid are presented in Table III.

Table III. Currents assigned to the protections.

Branch (B_{ij})	Rated current (A)	Breaking capacity (kA)
B_{12}	20	25
B_{24}	40	25
B_{34}	20	25
B_{46}	40	25
B_{56}	20	25
B_{67}	40	25

B_{ij}: Branch connecting node i to node j.

C. Technical DEMATEL

DEMATEL (*Decision Making Trial and Evaluation Laboratory*) is a multi-criteria method that describes the relationships between the components of a system based on the perceptions of a group of experts on a specific subject. This technique considers the incidence of each indicator in the system and the relationship between them, in order to discriminate their level of importance [20],[21].

DEMATEL consists of five steps. First, the definition of the influence between indicators using a scale from 0 to 4, where 0 indicates no influence and 4 indicates that there is a direct influence. Second, the construction of a matrix (X) relating the influence between indicators obtained in Step 1. Third, normalization of the relationship matrix (X) with the maximum value of the sum of the rows. Fourth, the calculation of the indirect influence matrix (T) from Eq. (1), where I is the identity matrix.

$$T = X * (I - X)^{-1} \quad (1)$$

Table II. Indicators applicable to generation capacity.

Ref.	Year	Indicator	Formula	Description	Criteria
[22]	2019	Current (I_{rms})	Determination by simulation or measurement	Current in several branches of the system	Less than rated current of the component
[22]	2019	Voltage (V_{rms})	Determination by simulation or measurement	System node voltage	0.9 V < Vn < 1.1 V
[22]	2019	Loading	Determination by simulation or measurement	Percentage of overload of a component	Less than 110% of nominal component capacity
[9] [23]	2021 2020	Renewable fraction (RF)	$R_f = \frac{E_{ren}}{E_{tot}}$ (%)	Ratio of energy supplied by renewable sources to total energy consumption	Greater than 50%. System objective
[24]	2022	Capacity factor (CF)	$CF = \frac{\sum_{t=1}^{8760} P^G(t)}{8760 P^S}$	Presents the relationship between energy produced and installed capacity	Greater than 20% System objective
[8]	2019	Load factor (LF)	$LF = \frac{P_m}{P_p}$	Measures the efficiency of system utilization	Greater than 60% System objective

E_{ren}: energy supplied by renewable sources, E_{tot}: total energy demanded, P^G: energy generated by the source, P^s: installed power, P_L: Peak demand, ER: Renewable energy, P_m: average power, P_p: peak power, Vn: rated voltage.

And fifth, the determination of the weight of each indicator (W_i) from Eq. (2), where D_i is the sum of the rows of the direct influence matrix, R_i is the sum of the columns for the indicator i, and N is the total number of rows or columns of the matrix.

$$W_i = \frac{D_i + R_i}{\sum_{i=1}^{N}(D_i + R_i)} \quad (2)$$

D. Evaluation of capabilities

The evaluation provides a value between 0.0 and 1.0 for each capability in a period. The evaluation procedure comprises four steps as shown in Figure 3.

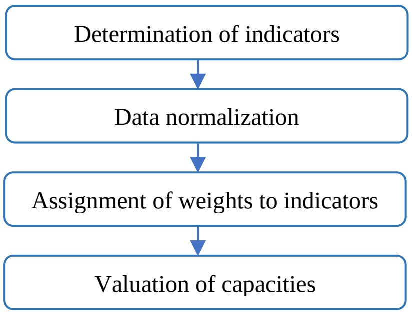

Figure 3. Procedure to evaluate capabilities.

First, the determination of the indicators by simulating the microgrid in Power Factory; second, the normalization of the data from reference values established by standard or defined in the system objectives; third, assigning weights to the indicators using the DEMATEL technique; and fourth, weighted valuation according to weights and normalized indicators. Capacity performance can be assessed according to the scale shown in Table IV.

Table IV. Performance evaluation scale

Scale of measurement	Range
High	$0.76 \leq C \leq 1.0$
Medium	$0.50 \leq C \leq 0.75$
Low	$0.0 < C \leq 0.49$
Null	$C = 0.0$

3. Results analysis

A. Analysis of generation capacity

Figure 4 shows the indicators for the low and high irradiance scenarios. It presents the variation of the voltages at the nodes of the microgrid, where N_k represents the voltage at Node k. The voltages remain in a correct operating range from 0.9 to 1.0 p.u. It shows the currents of the branches denoted by $B_{i,j}$ where i y j are the interconnecting nodes. The currents of branches B_{12}, B_{24}, B_{56} y B_{34} are equal. These current values are less than 5.5 A and are within the limits that can be tolerated by the components. It presents transformer overload denoted by T_k and conductor overload denoted by L_k. The overload does not exceed 18% of the rated capacity of transformers and conductors. And it shows the renewable fraction (RF), capacity factor (CF) and load factor (LF). These indicators meet the system objectives for certain hours of the day depending on the amount of energy supplied or load variation.

The voltages, currents, and overload show correct performance as they are within the permissible operating values in both the low irradiance scenario and the high irradiance scenario. The RF and CF indicators meet the system objectives for a greater number of hours than in the low irradiance scenario due to the increase in energy production.

For the evaluation of generation, the procedure in Section 2.D is applied to the results obtained. The data are normalized with the criteria and objectives shown in Table II. The voltages, currents, and overloads take a value of 1.0 due to compliance with the operating conditions, while RF, CF, and LF take values of 0.0 or 1.0 depending on the time of day.

Then, each indicator is assigned a weight following the DEMATEL technique. The procedure is applied for the 21 results considered, which results in the construction of a matrix of order 21 with the relationships between them. Table V lists the weights determined for each indicator.

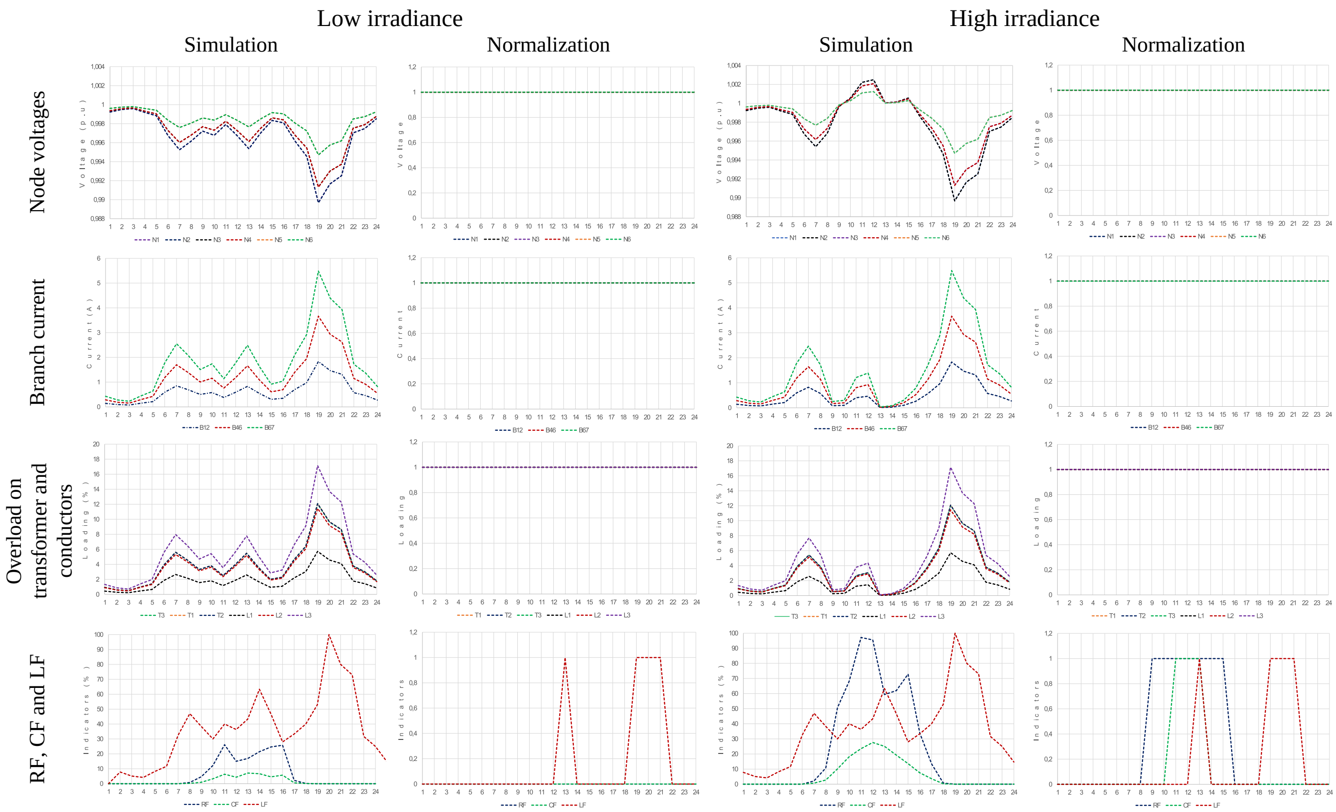

Figure 4. Performance of generation capacity indicators.

Table V. Weights of indicators.

Indicator	Weight	Indicator	Weight
N1	0.0553	B67	0.0482
N2	0.0542	T1	0.0457
N3	0.0517	T2	0.0425
N4	0.0620	T3	0.0391
N5	0.0490	L1	0.0534
N6	0.0579	L2	0.0550
B12	0.0521	L3	0.0512
B24	0.0556	RF	0.0345
B34	0.0469	CF	0.0345
B46	0.0549	LF	0.0345
B56	0.0391		

Finally, the capacity is evaluated for each hour of the day by multiplying the normalized indicators and the assigned weights.

Figure 5 presents the generation performance for the scenarios studied for one day. The performance at low irradiance is in the range of 0.91 to 0.95 with an average value of 0.92, which indicates a high performance according to Table IV. In the high irradiance scenario, it obtains a performance in a range between 0.91 to 1.0, with an average of 0.933, which is a better performance than in the low irradiance scenario. These results allow for obtaining an average performance of the generation capacity of 0.926. The low points are due to non-compliance with the renewable fraction, capacity factor, and load factor.

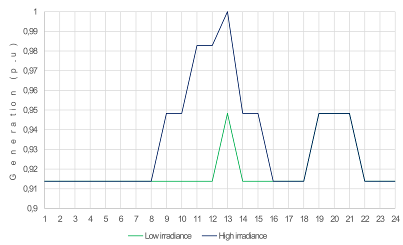

Figure 5. Performance of the generation.

The RF and CF indicators can be in a desirable range with increasing power supply [25]. As stated by Jamil *et al.* [26], the capacity factor can increase with higher efficiency values of the photovoltaic panels and by reducing energy losses due to dirt. Also, the indicator increases with high irradiance as indicated by the analysis performed.

A high load factor is desirable, which indicates higher utilization of the installed capacity of the microgrid [8]. The load factor for the studied microgrid is low due to peak loads. Therefore, the existence of a component that can withstand peak demand avoids oversizing the energy sources.

B. Analysis of protection capacity

Table VI shows the currents in the branches of the microgrid due to single-phase fault (1φ) and three-phase fault (3φ) caused in the nodes. The currents are less than the breaking capacities of the protections shown in Table III. In addition, the currents circulating in the system shown in Figure 4 are lower than the nominal values of the protections.

Table VI. Branch current due to single-phase and three-phase fault (A)

	B12		B24		B34		B46		B56		B67	
	1φ	*3φ*	*1φ*	*3φ*	*1φ*	*3φ*	*1φ*	*3φ*	*1φ*	*3φ*	*1φ*	*3φ*
N1	71	84	69	84	0	0	67	84	0	0	67	84
N2	0	0	79	99	0	0	77	99	0	0	77	99
N3	0	0	2	0	100	117	96	117	0	0	95	117
N4	0	0	2	0	0	0	117	148	0	0	116	148
N5	0	0	2	0	0	0	3	0	166	193	161	193
N6	0	0	2	0	0	0	4	0	0	0	231	296

Data normalization converts to 1.0 for all results that meet the following criteria: being less than the current rating and the protection-breaking capacity value. In contrast, it converts to zero the results that do not comply. Table VII shows the normalized values of the currents.

Table VII. Normalized fault currents.

	B12		B24		B34		B46		B56		B67	
	1φ	3φ	1φ	3φ	1φ	3φ	1φ	3φ	1φ	3φ	1φ	3φ
N1	1	1	1	1	1	1	1	1	1	1	1	1
N2	1	1	1	1	1	1	1	1	1	1	1	1
N3	1	1	1	1	1	1	1	1	1	1	1	1
N4	1	1	1	1	1	1	1	1	1	1	1	1
N5	1	1	1	1	1	1	1	1	1	1	1	1
N6	1	1	1	1	1	1	1	1	1	1	1	1

For the protection analysis, it is possible to determine the ratios and weights of each branch of the system with the DEMATEL technique. In this study, all the results comply with the criteria and when normalized they take the value of 1.0, therefore, the protection capacity has a valuation of 1.0.

The study of protection by conventional analysis can work well, in which fault detection is performed by comparing fault currents with a threshold value. However, it is necessary to take into consideration that the integration of distributed resources adds complexity to the analysis of the fault's current direction and magnitude [18], [27].

The study of protection performance in larger systems than the one presented can be performed following the same steps described above. The analysis would involve the consideration of a larger number of points for recording results due to the increase in the number of nodes and branches. Consequently, the data processing would be more extensive.

Likewise, the evaluation of generation capacity for larger systems involves the study of the behavior of all power sources and connected loads. In general, the procedure can be applied to other electrical systems, however, the effort required for the analysis will depend on their characteristics.

4. Conclusions

The paper presents a procedure to evaluate the generation and protection of a grid-connected microgrid. The performance for generation is determined for each hour of a day for high and low irradiance scenarios. And the protection performance is determined for single-phase and three-phase electrical faults.

The generation shows high performance in both low-irradiance and high-irradiance scenarios. Voltages, currents, and overload are within the correct operating values during the day. On the other hand, the renewable fraction and capacity factor perform better at high irradiance.

The protection achieves high performance for single-phase fault and three-phase fault scenarios at all nodes of the microgrid. The current values are within the values allowed by the protection devices.

The study can continue with the application of the procedure presented in other technical aspects of a microgrid such as operation or control. In addition, other microgrid topologies, modes of operation, and consequently other evaluation indicators could be considered.

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