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Micro-Grids Reliability Enhancement Under Different Penetration Levels of Hybrid DG Units

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Abstract – Novel mechanism of customized adequacy formulation is proposed in order to enhance micro grids system reliability. The mechanism accounts for 2-levles of load curtailment, and is mainly based on probabilistic load profile and hybrid Distributed Generation (DG) units modeling. The two load curtailments are needed in order to ensure adequate technical constraints at steady state condition during islanding mode of operation. The effectiveness of the proposed formulation has been verified using system independent analytical expressions for the evaluation of both reliability and Expected Energy Not Served (EENS) indices. The evaluation has examined the impact of different penetration levels of Hybrid DG Units in case study islands. Results show the enhancement of the overall distribution system reliability and the recommended conditions for successful islanding mode of operation.

Keywords: Micro grids, Distribution system reliability, EENS, Analytical models, Distributed generation, Islanding

1. Introduction

Distributed Generators (DG units) are small-scale power generation units located on a distribution system close to the point of power consumption, especially based on renewable energy sources. Energy regulators have been pushing for market integration of renewables worldwide during the recent years [1]. Research aims continuously to maximize the efficiency of renewable DG units. For instance in [2] a new control strategy is presented to extract the maximum marine current energy. Besides the environmental concern, the possibility of supplying electrical power at peaking periods, and reducing electricity costs, DG units can significantly contribute in the enhancement of power system reliability, as well as power quality levels in smart grids [3]. Reliability of distribution systems has become a very important issue, not only from technical viewpoint, but also from economical one, for both users and network operators.

As for Systems Reliability Evaluation in [4] and [5] annual interruption frequency and duration at load points (LPs) of a network where islanded operation of DG units is allowed are explained by means of practical examples only, derived from specific networks, without providing system independent general expressions that can be applied at any electrical network configuration. The work in [6] proposed a systematic approach for reliability assessment with general analytical expressions. Such expressions have been provided for the calculation of annual interruption frequency and duration for LPs of traditional networks, without considering the presence of DG units. Then in [7], these expressions have been provided considering the presence of dispatchable DG units only, and not the renewable ones. Later on, [8] proposed more detailed systematic analytical expressions for a distribution network where islanded operation of micro-grids is allowed with both renewable and dispatchable DG units; nevertheless, correlation among different loads, and protection devices failure have been neglected.

In the present work, islanding mode of operation is assumed to be allowed [9], hence islands adequacy assessment is of concern, as well as islanding success and failure conditions.

As for DG units Adequacy Assessment in a micro-grid, during islanding mode of operation, [9] considers that any deficit in generation during islanding mode will result into islanding failure, without considering either load shedding or load curtailment.

In [10], only user load disconnection, known as load shedding, has been considered. Then in [8], both load shedding, and load reduction, known as load *curtailment* have been taken into account for the adequacy assessment during islanding mode of operation. However, this previous work did not ensure adequate reactive power supply and established steady state operation during islanding mode of operation by neglecting operational steady state constraints.

In this paper, reliability evaluation for a distribution system has been performed by using system independent analytical expressions, under various scenarios characterized

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by different dispatchable and renewable DG units penetration levels. Hence, accordingly, reliability indices have been evaluated for both peak and average load case scenarios. Two load curtailment mechanisms are applied in islanding operation mode to ensure island adequacy and service continuity. The proposed first load curtailment is needed to ensure adequate reactive power supply and steady state operation for micro-grids in order to allow safe islanding when the dispatchable DG units rating in a micro-grid is less than a certain percentage (defined as 60% for diesel) of the micro-grid peak load at time of islanding; however, this percentage might vary based on the dispatchable DG units technology. In this way, the probability of successful islanding operation is increased, since islanding operation could easily fail without the introduction of this further load curtailment. Then, a second curtailment could be required during islanding operation, for service continuity, according to the new (after first curtailment) load and generation level of the considered micro-grid. Further, new adequacy formulation has been adopted during islanding mode of operation, in order to take into account the degree of load correlation and different load curtailment levels. Afterwards, reliability indices and EENS, for the system under study, are evaluated.

In this work, failure rates of protection devices, such as circuit breakers (CBs) and sectionalizers, have been taken into consideration for the evaluation of both reliability indices and EENS; unlike the assumption made in [11] and [12], where protection devices are considered fully reliable. Further, N-1 contingency has been assumed which means that a fault is repaired before a subsequent one occurs [13].

This work is based on the assumption that no fuses are installed in the system, which is a practical assumption for a MV system with 27.6 kV and higher.

In the following section, reliability evaluation methodology is discussed. Then in Section 0, probabilistic models for loads, dispatchable and renewable DG units are presented. In Section 5 a novel DG units adequacy assessment procedure, during islanding operation, is proposed. After that, in Section 6 a modified EENS evaluation technique is proposed. Finally, in Sections 7 to 0 a case study and related conclusions are presented.

2. Reliability Evaluation Methodology

The adopted methodology for distribution system reliability indices assessment is based on calculating firstly the base parameters defined as annual frequency of interruption and duration at each LP i, given respectively by [14]:

$$\lambda_i = \sum_{k=1}^{n_k} \lambda_{i,k} \quad U_i = \sum_{k=1}^{n_k} U_{i,k} \tag{1}$$

Then reliability indices are calculated as follows:

$$SAIFI = \frac{total\ number\ of\ customer\ interruptions}{total\ number\ of\ customers\ served} = \frac{\sum_{i=1}^{n_{LP}} \lambda_i N_i}{\sum_{i=1}^{n_{LP}} N_i} \tag{2}$$

$$SAIDI = \frac{sum\ of\ customer\ interruption\ durations}{total\ number\ of\ customers} = \frac{\sum_{i=1}^{n_{LP}} U_i N_i}{\sum_{i=1}^{n_{LP}} N_i} \tag{3}$$

And defined as system average interruption frequency and duration indices that indicate average number of interruptions and average outage duration for each customer, respectively.

Base parameters could be calculated using a system dependent classical method, explained in [4], and described through general examples only. They could be also calculated using a restoration time-based classification of LPs in a distribution system with DG units, presented in [16].

In this work, a wider system independent classification has been adopted, which is based on the relative positions of LPs, faulted branch or component, and protection devices of a generic distribution network [8]. This methodology classifies five different cases for the calculation of LPs annual interruption frequency and duration with or without both dispatchable and renewable DG units, as detailed in [8].

3. Micro-grid Probabilistic Modeling during Islanding Mode of Operation

3.1 Annual load modeling

Since LPs power demand level varies during a year, and is not always the peak value, an annual load modelling is required. An annual model shows different load demand levels associated with their probability of occurrence during a year. Load levels are assumed to be constant during a given time, and change discretely for every time interval. Table 1 shows an annual load model with ten levels of power. The first column contains load level

Table 1. Annual load model

Level	Power Demand (%)	$\rho_{j,l}^{L}$
1	100	0.01
2	85.30	0.056
3	77.40	0.1057
4	71.30	0.1654
5	65	0.1654
6	58.50	0.163
7	51	0.163
8	45.10	0.0912
9	40.60	0.0473
10	35.10	0.033

number; the second column shows load demand level in percentage of peak load; and, the last column shows the probability related to each load level [17].

3.2 Annual dispatchable DG units modeling

Since dispatchable DG units are very similar to a traditional generating systems connected to a transmission supply, they can assume an annual model based on DG units hardware availability [18]. Through the historical data of a generating unit, it is possible to estimate a forced outage rate (FOR) that defines the probability to have the unit on forced outage at some distant time. Hence, the probability of being available for a dispatchable DG is simply the complement of its FOR, which is equivalent also to the ratio between the mean time to fail (MTTF) and the mean time between failures (MTBF), as follows [15]:

$$\rho_{AV,d} = 1 - FOR = \frac{MTTF}{MTBF} \tag{4}$$

Table 2 shows the annual model for a dispatchable DG characterized by two power output levels, both when FOR hardware is neglected and when it is considered.

3.3 Annual renewable DG units modeling

Renewable DG units are much more difficult to be modeled with respect to dispatchable ones. This difficulty is due to the uncertainty of the DG units primary source (e.g. wind or solar irradiance), which leads to complication in finding the suitable annual model that well describes the behavior of the renewable DG. Wind turbines are very commonly used as renewable DG; their output power efficiency and quality are being improved as shown in [22, 23]. In [24] significant performance improvement is achieved by acting on the output power regulations technique. In [25] and [26] the improvement of the turbine controllability and reliability to enhance overall efficiency is shown. In [27] an accurate representation of an actual wind turbine load is presented

Table 3 shows an annual generation model for wind-based DG [17], where each power output level as a percentage of power rating is associated to both probabilities: ($\rho_{d,l}^{G}$), when FOR is considered, and ($\rho_{d,l}^{R}$), when FOR is not taken into account. The used wind speed data are average hourly values, and wind speed variations within an hour are not considered.

Table 2. Annual generation model for a dispatchable DG

Level	Power Output (kW)	$\rho_{d,l}^{D}$ (%)	$\rho_{d,l}^{G}$ (%)
1	0	0	2
2	$P_{GN,d}$	100	98

Table 3. Annual generation model for a wind DG

Level l	Power Output (%)	$\rho_{d,l}^{R}$	$\rho_{d,l}^{G}$
1	100	0.0761	0.073
2	94.96	0.0252	0.024
3	84.97	0.0331	0.032
4	74.97	0.0457	0.044
5	64.97	0.04837	0.046
6	54.98	0.0783	0.075
7	44.98	0.0923	0.089
8	34.98	0.1136	0.109
9	19.99	0.105	0.101
10	14.99	0.1137	0.109
11	4.99	0.0648	0.062
12	0	0.2039	0.236

4. Assessment of Micro-grids Adequacy during Islanding Mode of Operation

According to [19], during islanding mode of operation, dispatchable DG units penetration level in an island should be equal to at least 60% of total micro-grid peak load demand at time of islanding; otherwise islanding is not allowed. The main reason behind this condition is to ensure both required reactive power, and steady state operational constraints (through voltage and frequency control during islanding).

In order to allow islanding when the previous condition is not verified, part of the total island load should be curtailed until the above condition is verified. Thus a first curtailment level is defined, and since islanding might occur at any load level, and not necessarily at peak load, the first load curtailment is defined with reference to the actual micro-grid load at time of islanding ($P_{j,l}^{L}$) by the following expression:

$$P_{j,l,curt\,1}^{L} = P_{j,l}^{L} - \frac{P_{j,disp}^{G}}{0.6} \tag{5}$$

Therefore, a remaining load demand in island j ($P_{j,l}^{L_{new}}$), after first curtailment, will represent the new load demand to be considered for the assessment of island j adequacy probability. This new power load demand is given by the following expression:

$$P_{j,l}^{L_{new}} = P_{j,l}^{L} - P_{j,l,curt\,1}^{L} \tag{6}$$

The adequacy assessment of DG units, which belongs to a specific island, expresses how much those DG units are able to supply the micro-grid load during possible islanding mode of operation.

An analytical formulation is now presented to assess DG units adequacy in each portion of the network to be operated in islanding mode. The *adequacy probability* of DG units, installed in a potential island, is calculated based on the following parameters, related to the island under study:

- loads correlation probabilistic modelling;
- dispatchable DG units probabilistic modelling;

- renewable DG units probabilistic modelling;
- rating of each DG unit in the island; and
- load demand of the micro-grid at time islanding.

A similar formulation has been previously presented in [8] without considering both loads correlation and a first load curtailment that island *j* might require to observe the previously discussed technical constraints. The formulation is based on the combination of all possible operating conditions of LPs and DG units with their probabilities. In this work, correlation between loads has been taken into consideration, which means that for an island *j*, only one annual load model for all micro-grid LPs is considered.

Firstly, the adequacy probability of the DG units installed in island *j*, formed after the upstream protection device *A* has tripped, is evaluated using island *j* new load demand. In this way, the resulting probability is not expressing the real state of island *j*, since the considered load is not the actual power demand of island *j*. Thus the formulation would be computed, as follows:

$$\rho_{A,j} = \sum_{m=1}^{N_j} \frac{min\left(P_{j,m}^{L_{new}}\, ; P_{j,m}^{G}\right)}{P_{j,m}^{L_{new}}} \rho_{j,m} \tag{7}$$

where:

$N_j = nl_{L,j} * \prod_{d=1}^{NG_j} nl_{G,d}$ is the number of working points at which island *j* can operate; i.e. the number of combinations considering the annual load model and DG units with their $nl_{L,j}$ and $nl_{G,d}$, respectively;

$P_{j,m}^{L_{new}} = P_{j,l_1}^{L_{new}}\ or\ P_{j,l_2}^{L_{new}}\ or \ldots P_{j,l_{10}}^{L_{new}}$ island *j* load demand at the *m*-th combination, which corresponds to any of island *j* load levels because of the load correlation;

$P_{j,m}^{G} = P_{1,l}^{G} + P_{2,l}^{G} + \cdots \ldots \ldots + P_{NG_j,l}^{G}$ is the total generated power out of any category of DG units available in island *j* at the *m*-th combination (e.g. $P_{1,6}^{G} + P_{2,8}^{G} + \cdots + P_{NG,5}^{G}$);

$\rho_{j,m} = \rho_{j,l}^{L} * \rho_{1,l}^{G} * \rho_{2,l}^{G} \ldots \ldots \ldots \rho_{NG_j,l}^{G}$ is the probability related to the *m*-th combination of island *j* (e.g. $\rho_{j,m} = \rho_{j,4}^{L} * \rho_{1,6}^{G} * \rho_{2,8}^{G} \ldots \ldots \ldots \rho_{NG_j,5}^{G}$).

Obviously:

$$\sum_{m=1}^{N_j} \rho_{j,m} = 1 \tag{8}$$

Considering working point *m*, if the total available power output is:

1. Equal to or greater than the total power demand, then the local DG units can supply all local LPs. Hence $min\left(P_{j,m}^{L_{new}}; P_{j,m}^{G}\right) = P_{j,m}^{L_{new}}$;
2. Lower than the total power demand, and then the local DG units can supply some LPs only. Hence, $min\left(P_{j,m}^{L_{new}}; P_{j,m}^{G}\right) = P_{j,m}^{G}$. In this case some customers are left unsupplied and their load demand would be further curtailed. This way, an island is formed even when the DG units in the island cannot fully supply the island load demand (after the first curtailment) at the islanding instant. To be defined, a second level of load curtailment given by:

$$P_{j,m,curt\ 2}^{L} = P_{j,m}^{L_{new}} - P_{j,m}^{G} \tag{9}$$

When for all combination of working points the total available power output is equal to or greater than the total power demand, the ρ_{oA} is equal to one ($\rho_{A,j} = 1$). On the other hand, if there are not DG units in the island, the ρ_{oA} is equal to zero ($\rho_{A,j} = 0$). In this case CB *j* does not trip because no fault current flows through it, so that no island is formed.

To be defined a *new adequacy probability* that takes care of the 1st curtailed load and expressed by the following equation:

$$\rho_{A,j,new} = \rho_{A,j} * \left(1 - \frac{P_{j,l,curt\ 1}^{L}}{P_{j,l}^{L}}\right) \tag{10}$$

5. Expected Energy Not Served Evaluation

Before going through the details of the EENS evaluation, a definition of two cases, based on the service interruption source, is firstly presented as follows:

1st case: when interruption is caused by an internal fault occurred within island *j* under study; and

2nd case: when service interruption is caused by a fault occurred upstream of island *j* under study.

The annual interruption duration for an island is function of the number of failures that might trigger a service interruption, and the required time to repair such faults in order to restore over again customers service. Interruption duration expressions for the 1st and 2nd case are described respectively as follows:

$$\begin{cases} \mathrm{U}_{j,1} = F_{j,1\_case}\ (\mathrm{n°/year}) * \mathrm{t_r}\ (\mathrm{h/fault})\ (\mathrm{h}) \\ \mathrm{U}_{j,2} = F_{j,2\_case}\ (\mathrm{n°/year}) * \mathrm{t_r}\ (\mathrm{h/fault})\ (\mathrm{h}) \end{cases} \tag{11}$$

Repair time t_r is the same for all components, and equals to 5 hours [20].

Since the test system under study is radial, consequently elements of any segment or island are connected in series, *faults* for the 1st and 2nd case are expressed respectively as follows:

$$\begin{cases} F_{j,1\_case} = \sum_{a=1}^{n_1} f_{j,a} \\ F_{j,2\_case} = \sum_{b=1}^{n_2} f_{j,b} \end{cases} \tag{12}$$

EENS due to a fault within or upstream of island *j* under study are given below in Eqs. 13 and 14, respectively. As shown, annual EENS for island *j* is given by the total load demand at level *l* of island *j* (given by $P_{j,l}^{L}$ multiplied by the annual load model probability $\rho_{j,l}^{L}$ explained in section IV) multiplied by the annual interruption duration of island *j* (given by the annual interruption duration probability,

$\rho_{U_{j,1}}$ or $\rho_{U_{j,2}}$ for 1st and 2nd case, respectively, multiplied by the number of hours per year, which is 8760

$$EENS_{j,1} = \sum_{l=1}^{nl_{L,j}} \rho_{j,l}^{L} * \rho_{U_{j,1}} * 8760 * P_{j,l}^{L} = \sum_{i=1}^{nl_{L,j}} \rho_{c1,l} * 8760 * P_{j,l}^{L} \tag{13}$$

$$EENS_{j,2} = \sum_{l=1}^{nl_{L,j}} \rho_{j,l}^{L} * \rho_{U_{j,2}} * 8760 * P_{j,l}^{L} = \sum_{i=1}^{nl_{L,j}} \rho_{c2,l} * 8760 * P_{j,l}^{L} \tag{14}$$

Where " $\rho_{j,l}^{L} * \rho_{U_{j,1}}$ and " $\rho_{j,l}^{L} * \rho_{U_{j,2}}$ result in the correlation probabilities $\rho_{c1,l}$ and $\rho_{c2,l}$, respectively.

The result of multiplying the i^{th} correlation probability $\rho_{c1,l}$ or $\rho_{c2,l}$ times 8760 hours gives the fraction of the total interruption duration, for 1st or 2nd case fault, that occurs at the load level *l*.

The evaluation of total EENS and interruption duration with and without DG units for island *j* are presented below.

5.1 EENS evaluation without DG units

EENS and *U*, for island *j*, when no DG units are installed in it, are given by the total EENS and *U*, for island *j*, caused by the 1st and 2nd case interruption source, as reported below:

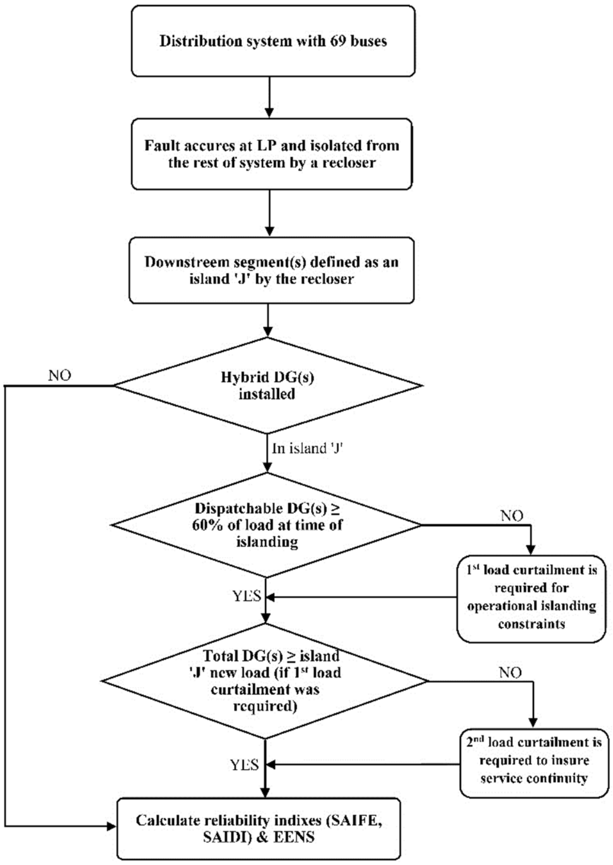

Fig. 1. Methodology flowchart

$$\begin{cases} U_{j,no\ DGs} = U_{j,2} + U_{j,1} \\ EENS_{j,no\ DGs} = EENS_{j,1} + EENS_{j,2} \end{cases} \tag{15}$$

5.2 EENS evaluation with DG units

For what concern DG units penetration level, is assumed to adopt case 2 of the 1st scenario discussed in section 0.

EENS for island *j* depends on the interruption origin, so that:

EENS when faults occur within island j (1st case):

$$\begin{cases} U_{j,DG1} = U_{j,1} \\ EENS_{j,DG1} = EENS_{j,1} \end{cases} \tag{16}$$

EENS when faults occur upstream of island j (2nd case):

$$\begin{cases} U_{j,DG2} = U_{j,2} \\ EENS_{j,DG2} = \begin{pmatrix} \sum_{l=1}^{nl_{L,j}} (\rho_{j,l}^{L} * P_{j,l,curt\ 1}^{L}) + \\ + \sum_{m=1}^{N_j} (\rho_{j,m} * P_{j,m,curt\ 2}^{L}) \end{pmatrix} U_{j,2} \end{cases} \tag{17}$$

Finally the adopted methodology for the evaluation of both reliability indices and EENS is briefly illustrated in Fig. 1

6. Case Study

Based on [21], a 69-buses considered as a test system for this work. Such system consists of 8-lateral distribution feeder with a few modifications in the connection scheme in order to ensure a radial system configuration for the distribution network. Total nominal feeder load is 3.8MW.

In order to simplify the reliability assessment procedure, segmentation concept will be adopted, which means that LPs will not be treated separately, however the system will be modeled as a set of segments. Each segment is defined as a set of LPs or components whose entry component is a switch or a protective device.

In this way, any faulted part of a segment will have the same effect on the rest of the system, and similarly all LPs of a segment will be affected equally by any fault occurring in the rest of the system [9].

The system layout, after segmentation has been performed, is shown in Fig. 2, where 6 segments have been identified according to the installed reclosers positions as explained earlier. After segmentation has been performed, peak power demand for each segment, $P_{seg\ i,peak}^{L}$, are identified and presented in Table 4.

When a fault occurs upstream of recloser $R_{j,i}$, installed at load point LPi, it is opened manually to isolate the

Table 4. Segments power demand

	Seg 1	Seg 2	Seg 3	Seg 4	Seg 5	Seg 6
$P_{seg,peak}^{L}$(kVA)	1962.1	42.9	605.6	92.4	797	603.55

Table 5. Segments included in each island

Island j	$R_{j,i}$	Segments Included in Island j
Island 1	$R_{1,0}$	Segment 1; 2; 3; 4; 5; 6
Island 2	$R_{2,31}$	Segment 2
Island 3	$R_{3,4}$	Segment 3; 5; 6
Island 4	$R_{4,68}$	Segment 4
Island 5	$R_{5,50}$	Segment 5
Island 6	$R_{6,11}$	Segment 6

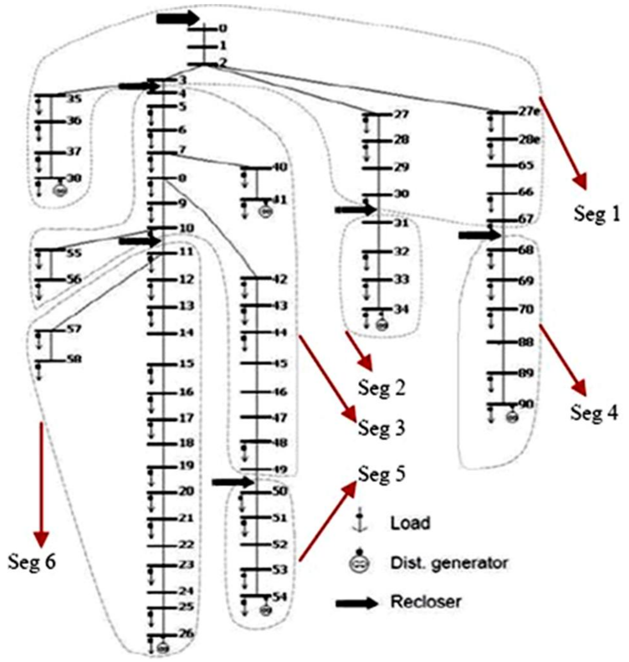

Fig. 2. Network segments defined by dashed lines

downstream system from the fault. Therefore, all of the downstream segments would be forming potentially a micro-grid or island *j*. Accordingly, system reclosers are reported in Table 5, along with their respective islands and the segments forming each island.

7. Reliability Evaluation Results

To be assumed firstly that two DG units are installed in each segment at buses 26, 34, 38, 41, 54 and 90. Such DG units are one dispatchable (diesel) of rating 200kVA, and another renewable (wind-based) of rating 200kVA.

For reliability indices calculation, all system branches failure rates are firstly calculated based on their length and the average failure rate per unit length [20] as follows:

$$\mathrm{f_k = f_{l.u} * l_k * 1.61} \tag{18}$$

Where 1.61 is a conversion factor from one mile to one kilometer, and the repair time per one failure is equal for all branches, and is given by 5 hours as reported in [20].

In order to perform a sensitivity analysis for the system

Table 6. 1st Scenario DG units penetration percentage

1st Scenario	DG Unit Type	
	Dispatchable per Segment (Diesel)	Non-Dispatchable per Segment (Wind-Based)
Case 1	75%	25%
Case 2	50%	50%
Case 3	25%	75%

Table 7. 1st Scenario DG units penetration levels for each island

		1st Scenario		
		Case 1	Case 2	Case 3
Island 1	Diesel (kW)	1800	1200	600
	Wind (kW)	600	1200	1800
Island 2	Diesel (kW)	300	200	100
	Wind (kW)	100	200	300
Island 3	Diesel (kW)	900	600	300
	Wind (kW)	300	600	900
Island 4	Diesel (kW)	300	200	100
	Wind (kW)	100	200	300
Island 5	Diesel (kW)	300	200	100
	Wind (kW)	100	200	300
Island 6	Diesel (kW)	300	200	100
	Wind (kW)	100	200	300

behavior, hence for the system reliability, two scenarios are proposed, with different penetration levels of hybrid DG units. Given that two levels of load curtailment are adopted in this analysis (to observe the technical constraints, required for a safe operation of micro-grids, and service continuity as described earlier); therefore, is considered that the adopted penetration levels will not violate any of the operational constraints. The proposed scenarios are described as follows:

1st Scenario: In this scenario, the total penetration level of DG units in each segment has been maintained constant, however the penetration percentage for each DG category (dispatchable and non-dispatchable) has been changed through three case studies, as shown in Table 6. Table 7 then reports the ratings for the DG units installed in each island, both dispatchable and non dispatchable ones, for each case study. In Table 8 to Table 10, results of this first scenario for the three cases are shown. For each case, and for each island, 1st load curtailment (at peak load), max 2nd load curtailment, and adequacy probability at different operation conditions are reported.

2nd Scenario: In this scenario, the penetration percentage for each DG category (dispatchable and non-dispatchable) has been maintained constant, however the total penetration level of DG units in each segment has been changed through three case studies, as shown in Table 11. After that Table 12 tabulates the ratings for the DG units installed in each island, both dispatchable and non-dispatchable ones, for each case study. Results of the three cases of this second scenario are shown in Table 13 to Table 15 presenting same parameters as for the 1st scenario.

Table 8. 1st Scenario – case 1

Island j	$P^L_{j,peak}$ (kVA)	$P^L_{j,peak,curt1}$ (kVA)	$P^L_{j,curt2max}$ (kVA)	$\rho_{A,j}$ (%)	$\rho_{A,j,peak,new}$ (%)	$\rho_{A,j,new}$ (%)
Island 1	4103.67	1103.7	3000	94.47	69.06	93.14
Island 2	42.9242	0	42.92	99.46	99.46	99.46
Island 3	2191.05	691.048	1500	94.09	64.41	91.58
Island 4	92.4238	0	92.42	99.25	99.25	99.25
Island 5	797.042	297.041	500	93.78	58.83	89.11
Island 6	603.547	103.546	500	95.91	79.46	95.62

Table 9. 1st Scenario – case 2

Island j	$P^L_{j,peak}$ (kVA)	$P^L_{j,peak,curt1}$ (kVA)	$P^L_{j,curt2max}$ (kVA)	$\rho_{A,j}$ (%)	$\rho_{A,j,peak,new}$ (%)	$\rho_{A,j,new}$ (%)
Island 1	4103.67	2103.67	2000	96.07	46.82	82.64
Island 2	42.9242	0	42.9242	99.55	99.55	99.55
Island 3	2191.05	1191.05	1191.05	96.06	43.84	80.17
Island 4	92.4238	0	92.4238	99.45	99.45	99.45
Island 5	797.042	463.71	333.333	96.06	40.17	76.84
Island 6	603.547	270.21	333.333	96.08	53.07	87.16

Table 10. 1st Scenario – case 3

Island j	$P^L_{j,peak}$ (kVA)	$P^L_{j,peak,curt1}$ (kVA)	$P^L_{j,curt2max}$ (kVA)	$\rho_{A,j}$ (%)	$\rho_{A,j,peak,new}$ (%)	$\rho_{A,j,new}$ (%)
Island 1	4103.67	3103.7	1000	97.39	23.73	61.19
Island 2	42.9242	0	42.9242	99.58	99.58	99.58
Island 3	2191.05	1691	500	97.39	22.22	59.68
Island 4	92.4238	0	92.4238	99.52	99.52	99.52
Island 5	797.042	630.375	166.667	97.39	20.36	57.82
Island 6	603.547	436.88	166.667	97.39	26.89	64.35

Table 11. 2nd Scenario DG units penetration level

2nd Scenario	DG Unit Type	
	Dispatchable per Segment (Diesel) (kW)	Non-Dispatchable (Wind-Based) per Segment (kW)
Case 1	300	300
Case 2	200	200
Case 3	100	100

Table 12. 2nd Scenario DG units penetration levels for each island

		2nd Scenario		
		Case 1	Case 2	Case 3
Island 1	Diesel (kW)	1800	1200	600
	Wind (kW)	1800	1200	600
Island 2	Diesel (kW)	300	200	100
	Wind (kW)	300	200	100
Island 3	Diesel (kW)	900	600	300
	Wind (kW)	900	600	300
Island 4	Diesel (kW)	300	200	100
	Wind (kW)	300	200	100
Island 5	Diesel (kW)	300	200	100
	Wind (kW)	300	200	100
Island 6	Diesel (kW)	300	200	100
	Wind (kW)	300	200	100

Since islanding mode of operation might occur at any demand load level, out of the ten states that define the annual load model, as explained previously in section 4, $P^L_{j,l,curt\,1}$, $P^L_{j,m,curt\,2}$, $P^L_{j,curt\,2\,max}$, $\rho_{A,j}$, and $\rho_{A,j,new}$ have been all computed for each load level that island j could be exposed to.

On the other hand, $P^L_{j,peak,curt\,1}$ and $\rho_{A,j,peak,new}$ have been evaluated considering that islanding occurs at the peak level demand of island j under study. Such assumption represents the peak load case scenario that islanding might occur at.

Afterwards, based on LPs relative position, with respect to both protection devices and faulted branches, annual interruption frequency $\lambda_{i,k}$ and duration $U_{i,k}$ for all LPs are calculated according to the appropriate case formulation of the adopted methodology.

Finally, Reliability Indices (i.e SAIFI and SAIDI) of the system are calculated using equations 1 and 2. The indices have been computed once during grid connection mode, when no DG units are installed anywhere, and another time for each of the three study cases of the two proposed scenarios during islanding mode and after installing DG units.

Table 16 shows the final results of the test system reliability indices in different case scenarios as described earlier, for both peak load case (islanding occurs at peak load) and average case (islanding might occur at any annual load model) conditions.

In Fig. 3 the results of reliability indices (SAIFI and SAIDI) for the different scenarios and cases are presented in comparison.

To be noted from the previous graph that when operating in grid connected mode of operation (without DG units connected to the system), reliability indices (SAIFI and SAIDI) assessment assume same results at both average and peak load conditions. Besides, reliability indices are inherently high with respect to the other cases where DG

Table 13. 2nd Scenario – case 1

Island j	$P^{L}_{j,peak}$ (kVA)	$P^{L}_{j,peak,curt1}$ (kVA)	$P^{L}_{j,curt2max}$ (kVA)	$\rho_{A,j}$ (%)	$\rho_{A,j,peak,new}$ (%)	$\rho_{A,j,new}$ (%)
Island 1	4103.67	1103.7	3000	96.59	70.61	95.24
Island 2	42.9242	0	42.9242	99.58	99.58	99.58
Island 3	2191.05	691.04	1500	96.34	65.95	93.76
Island 4	92.4238	0	92.4238	99.52	99.52	99.52
Island 5	797.042	297.042	500	96.11	60.29	91.33
Island 6	603.547	103.547	500	97.45	80.73	97.14

Table 14. 2nd Scenario – case 2

Island j	$P^{L}_{j,peak}$ (kVA)	$P^{L}_{j,peak,curt1}$ (kVA)	$P^{L}_{j,curt2max}$ (kVA)	$\rho_{A,j}$ (%)	$\rho_{A,j,peak,new}$ (%)	$\rho_{A,j,new}$ (%)
Island 1	4103.67	2103.67	2000	96.07	46.82	82.64
Island 2	42.9242	0	42.9242	99.55	99.55	99.55
Island 3	2191.05	1191.05	1191.05	96.06	43.84	80.17
Island 4	92.4238	0	92.4238	99.45	99.45	99.45
Island 5	797.042	463.709	333.333	96.06	40.17	76.84
Island 6	603.547	270.213	333.333	96.08	53.07	87.17

Table 15. 2nd Scenario – case 3

Island j	$P^{L}_{j,peak}$ (kVA)	$P^{L}_{j,peak,curt1}$ (kVA)	$P^{L}_{j,curt2max}$ (kVA)	$\rho_{A,j}$ (%)	$\rho_{A,j,peak,new}$ (%)	$\rho_{A,j,new}$ (%)
Island 1	4103.67	3103.7	1000	96.05	23.41	60.35
Island 2	42.9242	0	42.9242	99.47	99.47	99.47
Island 3	2191.05	1691	500	96.05	21.92	58.86
Island 4	92.4238	0	92.4238	99.25	99.25	99.25
Island 5	797.042	630.375	166.667	96.05	20.08	57.02
Island 6	603.547	436.88	166.667	96.05	26.52	63.46

Table 16. Reliability indices final results

Scenarios			Reliability Indices			
			Using $\rho_{A,j,peak,new}$ (peak load condition)		Using $\rho_{A,j,new}$ (average load condition)	
			SAIFI_1	SAIDI_1	SAIFI_2	SAIDI_2
Without DG units			2.44	12.21	2.44	12.21
With DG Units	1st Scenario	ase1	1.50	7.52	1.09	5.49
		Case 2	1.80	9.01	1.27	6.34
		Case 3	2.11	10.56	1.56	7.79
	2nd Scenario	Case 1	1.48	7.42	1.07	5.33
		Case 2	1.80	9.01	1.27	6.34
		Case 3	2.12	10.58	1.57	7.86

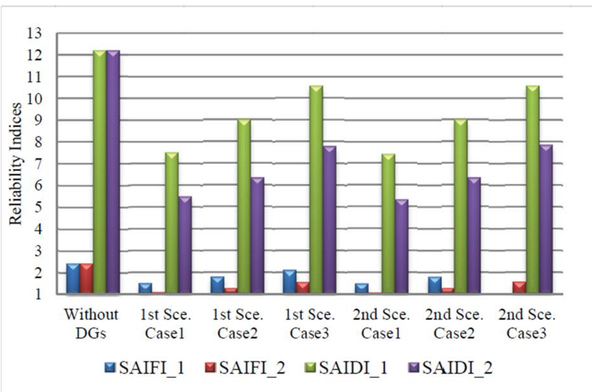

Fig. 3. Reliability indices under different scenarios

units are installed and operating in islanding mode of operation. The reason is that the values of both frequency of interruption and duration in this case are not affected by the improvement of system adequacy, which is related to the instalment of DG units.

When DG units are installed in the system, reliability indices have been calculated after considering system adequacy probability. When islanding occurs at average load levels, reliability indices assume better results with respect to the case when adequacy probability is calculated when islanding occurs at peak load level. The reason being is that more load curtailment is usually required when islanding occurs at peak load level, which negatively affects the reliability indices results. Therefore, the presence of DG units, when islanding is allowed, has a remarkable impact on the enhancement of the system's reliability indices (refer to Fig. 3 above).

Furthermore, allowing two levels of load curtailment, whenever needed, improves the overall system reliability, and insures different micro-grids a safe operation and service continuity in islanding mode.

8. Expected Energy Not Served Evaluation Results

Applying the aforementioned proposed methodology, EENS evaluation is performed. Based on the adopted test system, components that are responsible for an interruption occurrence for island *j*, in general, are of different nature. In fact, they could be *switches*, *branches* belonging to different segments, or main supply *substation*. System

Table 17. System components involved in a service interruption

		Possible Service Interruption Source		
		Segment Seg	Recloser $R_{j,i}$	Substation
Island 1	1st case	Seg 1; 2; 3; 4; 5; 6	$R_{1,0}$; $R_{2,31}$; $R_{3,4}$; $R_{4,68}$; $R_{5,50}$; $R_{6,11}$.	-
	2nd case	-	-	Substation
Island 2	1st case	Seg 2	$R_{2,31}$	-
	2nd case	Seg 1	$R_{1,0}$	Substation
Island 3	1st case	Seg 3; 5; 6	$R_{4,68}$; $R_{5,50}$; $R_{6,11}$	-
	2nd case	Seg 1	$R_{1,0}$	Substation
Island 4	1st case	Seg 4	$R_{4,68}$	-
	2nd case	Seg 1	$R_{1,0}$	Substation
Island 5	1st case	Seg 5	$R_{5,50}$	-
	2nd case	Seg 1; 3	$R_{1,0}$; $R_{3,4}$	Substation
Island 6	1st case	Seg 6	$R_{6,11}$	-
	2nd case	Seg 1; 3	$R_{1,0}$; $R_{3,4}$	Substation

Table 18. EENS Related parameters under different cases

Island j	$P^{L}_{j,peak}$ (kVA)	Fault Within Island j (1st Case)		Fault Upstream Island j (2nd Case)			
		$U_{j,1}$ (h)	$\mathrm{EENS}_{j,1}$ (MWh)	$U_{j,2}$ (h)	$P^{L}_{j,l,curt\,1}$ (kVA)	$P^{L}_{j,m,curt\,2}$ (kVA)	$\mathrm{EENS}_{j,2}$ (MWh)
1	4103.67	47.9	120.994	0.5	573.4	57.6	1.263
2	42.9242	8.83	0.23327	2.98	0	0.08	0.079
3	2191.05	33.9	45.8459	2.98	362.3	28.9	4.014
4	92.4238	2.60	0.14802	2.98	0	0.22	0.169
5	797.042	5.07	2.48899	16.2	159.4	9.64	7.948
6	603.547	15.7	5.83113	16.2	56.02	9.53	6.018

Table 19. Total EENS final results for each island

Island j	$U_{j,noDGs}$ (h)	$U_{j,DG1}$ (h)	$EENS_{j,noDGs}$ (kWh)	$EENS_{j,DG1}$(kWh)	$EENS_{j,DG2}$(kWh)
Island 1	48.41	47.91	122256.36	120993.62	315.485
Island 2	11.81	8.830	311.8982	233.26957	0.23687
Island 3	36.98	33.99	49859.49	45845.919	1164.45
Island 4	5.579	2.602	317.3206	148.01812	0.64715
Island 5	21.28	5.074	10436.92	2488.986	2739.15
Island 6	31.90	15.69	11849.57	5831.1278	1062.15

components that might imply island j service interruption, for both 1st and 2nd cases, are reported in Table 17. Then Table 18 and Table 19 results of EENS evaluation are presented, along with some related calculation parameters. The assessment is performed for both grid-connected (without DG units) and islanding (with DG units) mode of operation.

Since islands 2, 3, and 4 share the same upstream components, their annual interruption duration due to an upstream fault ($U_{j,2}$) is the same. Further, for a fault occurring within an island j, both $\mathrm{EENS}_{j,1}$ and $U_{j,1}$ will not be reduced after the installation of DG units in that island j. On the other hand, when service interruption is caused by a fault upstream of island j, interruption duration $U_{j,2}$ will not change after DG units installation in island j; however the unserved power load demand in island j is reduced. That is to say $EENS_{j,2}$ is reduced to become $EENS_{j,DG2}$, which is given by the summation of 1st and 2nd load curtailment during a year (each by its corresponding probability of occurrence) multiplied by the annual interruption duration for an upstream fault ($U_{j,2}$) .

9. Conclusion

In this work, success condition for islanding has been improved after adopting 2 levels of load curtailment. The first load curtailment is essential to ensure adequate steady state technical constraints, and to allow safe operational islanding when dispatchable DG units rating, in a micro-grid, is less than a pre-defined percentage value of total micro-grid peak load at time of islanding. During islanding, a second load curtailment level is adopted whenever is required to ensure service continuity under different loads and DG units operation profiles. Hence a new adequacy probability has been introduced in order to take into account two levels of load curtailments and the correlation between different loads within the island under study. Based on the improved islanding success condition, a sensitivity analysis of reliability indices (SAIFI and SAIDI) has been performed for a test system with different penetration levels and ratios of hybrid DG units. As a result, allowing two levels of load curtailment, whenever is needed, enhances the overall system reliability indices, and insures different micro-grids a safe operation and service continuity in islanding mode.

EENS assessment has also been performed, adopting a new modified formulation when DG units are installed, and the island j under study is operating in islanding mode. Such formulation is based on the total annual 1st and 2nd possible curtailed loads along with their respective probabilities. Load correlation and failure rate of protection devices have been taken into consideration, at both reliability indices evaluation and EENS assessment. After adopting two levels of load curtailment, final results show the significant reduction in the yearly unserved power load demand in island *j*, and hence the significant enhancement of EENS at each island j.

Nomenclature

D Distributed Generator unit (DG) location;
$EENS_{j,1}$ EENS of island *j*, due to a fault within island *j*;
$EENS_{j,2}$ EENS of island *j*, due to a fault upstream island *j*;
$EENS_{j,DG1}$ EENS of island *j* (DG units installed in *j*) due to an internal fault (within the island);
$EENS_{j,DG2}$ EENS of island *j* (DG units installed in *j*) due to an upstream fault;
$EENS_{j,no\ DGs}$ EENS (no DG units installed in *j*) of island *j* due to an internal or upstream fault (1st & 2nd cases);
$F_{j,1\_case}$ yearly number of faults occurred within island *j*;
$F_{j,2\_case}$ yearly number of faults occurred upstream island *j*;
$f_{j,a}$; $f_{j,b}$ annual failure rate of physical components within and upstream island *j* respectively;
$f_{l.u}$ failure rate per length unit (km) for overhead lines;
f_k branch *k* failure rate;
i load Point (LP) location;
j switch location, and island index;
k branch fault location;
l_k length of branch k in miles;
m one combination, with $m \in [1, N_j]$;
N_i number of customers connected to the *i*-th LP;
N_j number of working points at which island *j* can operate (number of combinations);
NG_j number of DG units in island *j*;
$nl_{L,j}$ number of annual load model levels for island *j*;
$nl_{G,d}$ number of output power levels of DG *d*;
n_1;n_2 components n◦ within-upstream island *j* respectively;
n_k number of branches in the distribution system;
n_{LP} number of load points (LPs);
$P^G_{d,l}$ output power level *l* of DG *d*;
$P_{GN,d}$ nominal output power of DG *d*;
$P^L_{j,l}$ demand of island *j* (islanding occurs at load level *l*);
$P^{L_{new}}_{j,l}$ demand of island *j* at level *l*, after 1st curtailment;
$P^G_{j,disp}$ dispatchable DG units power generation in island *j*;
$P^{L_{new}}_{j,m}$ island *j* demand after 1st curtailment, at state *m*;
$P^G_{j,m}$ island *j* total DG units power rating, at state *m*;
$P^L_{seg\ i,peak}$ peak load demand of segment *i*;
$P^L_{j,peak}$ peak load demand of island *j* (kVA);
$P^L_{j,peak,curt\ 1}$ 1st load curtailment when islanding occurs at peak load demand of island *j* (kVA);
$P^L_{j,curt\ 2\ max}$ maximum 2nd load curtailment of island *j* (kVA);
$P^L_{j,l,curt\ 1}$ 1st load curtailment when islanding occurs at load demand level *l* of island *j*;
$P^L_{j,m,curt\ 2}$ 2nd load curtailment of island *j* at m*th* combination;
$R_{j,i}$ recloser located at LP *i* & forms downstream island *j*;
$t_{s,j}$ switching time of sectionalizer *j*;
t_r repair time for a single failure expressed in hours;
$t_{AV,j}$ time to be available for the local DG of island *j* (required time to reconnect the island DG units);
$U_{i,k}$ LP*i* annual inter. duration for a fault in location *k;*
$U_{j,1}$; $U_{j,2}$ annual interruption duration due to a fault within and upstream island *j* respectively*;*
$U_{j,no\ DGs}$ interruption duration (no DG units installed in *j*) of island *j* due to an internal or upstream fault(1st & 2nd cases);
$U_{j,DG1}$; $U_{j,DG2}$ interruption duration DG units installed in *j* of island *j* due to a fault within and upstream the same island respectively;
$\lambda_{i,k}$ LP *i* annual inter. freq. due to a fault in location *k;*
$\rho_{AV,d}$ hardware availability probability of generator *d*;
$\rho^L_{j,l}$ load level *l* probability for island *j* during a year;
$\rho^R_{d,l}$ power level *l* probability of renewable DG *d* without considering its FOR (forced outage rate);
$\rho^D_{d,l}$ power level *l* probability of dispatchable DG *d* annual model, without considering its FOR;
$\rho^G_{d,l}$ power level *l* probability of DG *d* (dispatchable or renewable) after considering its FOR;
$\rho_{A,j}$ adequacy probability for island *j* formed after switch *A* has tripped, neglecting 1st load curtailment, and islanding occurs at any load level (%);
$\rho_{j,m}$ probability of *m*-th combination for island *j*;
$\rho_{A,j,peak,new}$ new adequacy probability of island *j*, after 1st load curtailment & islanding occurs at peak load (%);
$\rho_{A,j,new}$ adequacy probability of island *j* (formed after tripping of switch *A*) when islanding occurs at any load level (%) & considering 1st load curtailment;
$\rho_{U_{j,1}}$; $\rho_{U_{j,2}}$ annual probabilities of having $U_{j,1}$ or $U_{j,2}$ respectively, given by dividing $U_{j,1}$ or $U_{j,2}$ over 8760;
$\rho_{c1,l}$; $\rho_{c2,l}$ correlation probabilities of EENS 1st and 2nd case respectively; they express service interruption probabilities at island load demand level *l*

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