Escalera, A., Prodanović, M. & Castronuovo, E. D. (2019). Analytical methodology for reliability assessment of distribution networks with energy storage in islanded and emergency-tie restoration modes. *International Journal of Electrical Power & Energy Systems, 107*, 735–744.

DOI: 10.1016/j.ijepes.2018.12.027

International Journal of Electrical Power and Energy Systems xxx (2018) xxx-xxx

Contents lists available at ScienceDirect

International Journal of Electrical Power and Energy Systems

journal homepage: www.elsevier.com

Analytical methodology for reliability assessment of distribution networks with energy storage in islanded and emergency-tie restoration modes

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ARTICLE INFO

Keywords:
Analytical technique
Distributed generation
Distribution networks
Energy storage
Reliability assessment

ABSTRACT

A wide scale deployment of energy storage systems in power networks for energy balancing applications would lead to network reliability improvements. After a fault occurs in a network, energy storage would be able to help restore supply in the network areas isolated from the primary substation or in those re-connected to adjacent feeders of limited transfer capacity by emergency ties. The reliability improvements introduced by energy storage need to be evaluated and quantified for both restoration modes. The objective of this paper is to assess the energy storage contribution in these restoration modes and to seek analytical, less computationally intensive solutions for such evaluation. The proposed analytical technique uses a probabilistic model of energy storage to assess the charge and discharge processes over a fault duration and the related operational strategy. In this way, reliability indices are calculated by taking into account the energy storage actions during a fault as well as the time-evolution of renewable generation and demand. These features lead to more realistic modelling of energy storage in analytical techniques. The proposed analytical technique was firstly validated by using a case study where the results obtained by Monte Carlo Simulation were used as a reference. Then, the proposed technique was applied to a distribution network to assess the reliability improvement provided by energy storage and to demonstrate the effectiveness and accuracy of the proposed approach.

Nomenclature

Indices

i	index of load points
j	index of failures in network components
rs	index of representative time-intervals of renewable generation and demand
h	index of time-steps in a representative time-interval
dg	index of distributed generators (DGs) in a downstream area
lpi	index of load points in a downstream area
tie	index of the emergency ties of limited transfer capacity in a downstream area
s	index of the energy storage systems (ESSs)
cr	index of restoration-states of DGs and ESSs
t	index of time-steps in the restoration-evaluation time
ts	index of time-steps with generation shortage

Sets and numbers

N_i	number of load points in a network
N_j	number of failures in network components
N_{rs}	number of representative time-intervals of a year
$N_{h,rs}$	number of time-steps in the representative time-interval rs
N_{dg}	set of DGs in a downstream area
N_{lpi}	set of load points in a downstream area
N_{tie}	set of emergency ties of limited transfer capacity in a downstream area
N_s	set of ESSs in a downstream area
N_{cr}	number of restoration-states in a downstream area
Sp	set of ESSs with higher priority of use

Parameters

λ_j	annual average rate of failure j
r_j	average repair time of failure j
La_i	annual average demand of load point i

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https://doi.org/10.1016/j.ijepes.2018.12.027
Received 15 June 2018; Received in revised form 25 October 2018; Accepted 12 December 2018
Available online xxx
0142-0615/ © 2018.

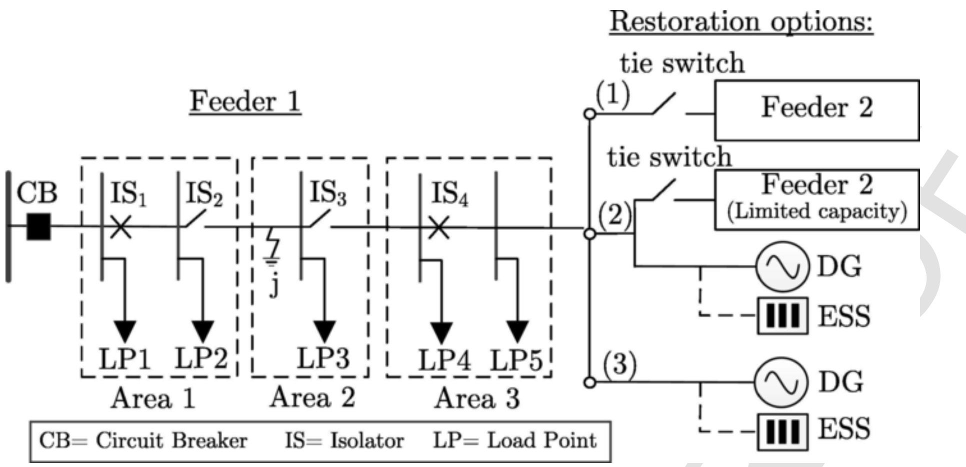

Fig. 1. Example showing different network areas created after the fault isolation and options for supply restoration of Area 3.

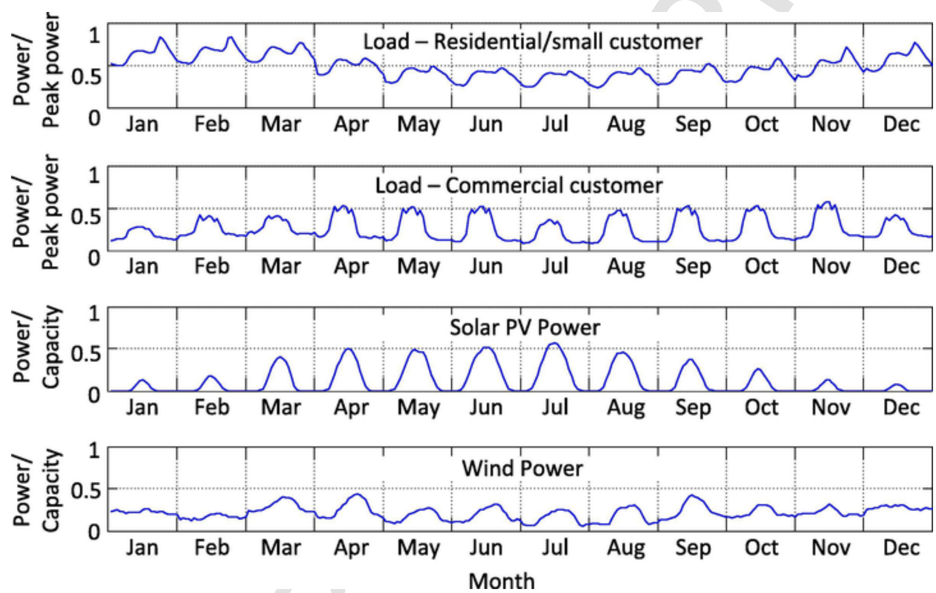

Fig. 2. Representative time-intervals in one year (12 months × 24 h). Power referred to annual peak load or generation capacity (data from [32]).

Table 1
Example of restoration-states in a downstream area with DGs and ESSs.

State	DG_1	DG_{dg}	DG_{Ndg}	ESS_1	ESS_s	ESS_{Ns}	p_{cr}
1	0	α_{dg}^{1}	0	0	α_{s}^{1}	0	p_1
…	…						…
cr	1	α_{dg}^{cr}	0	0	α_{s}^{cr}	0	p_{cr}
…	…						…
N_{cr}	1	α_{dg}^{Ncr}	1	1	α_{s}^{Ncr}	1	p_{Ncr}

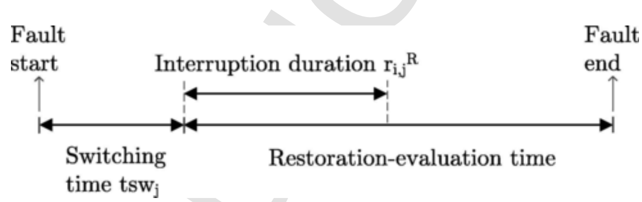

Fig. 3. Definition of time-intervals during a fault in a downstream area.

$La_{i,j}$	average demand of load point i during failure j
p_{rs}	annual probability of representative time-interval rs
p_h	probability of time-step h in a representative time-interval

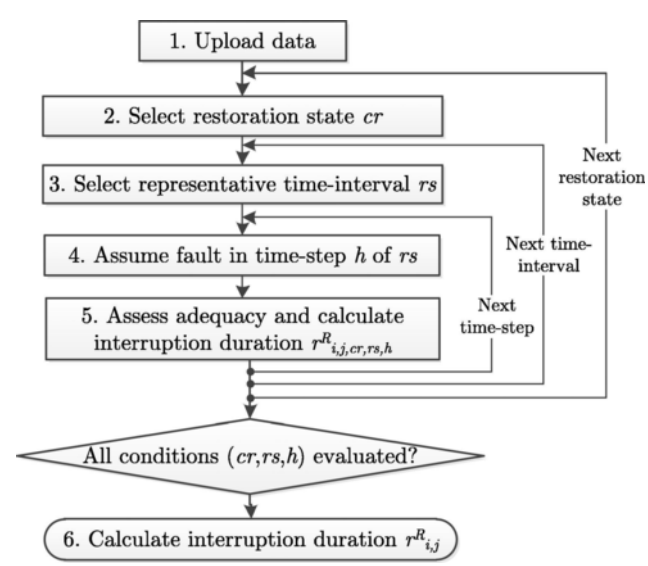

Fig. 4. Procedure to calculate interruption duration $r_{i,j}^{R}$ in downstream areas with DGs and energy storage.

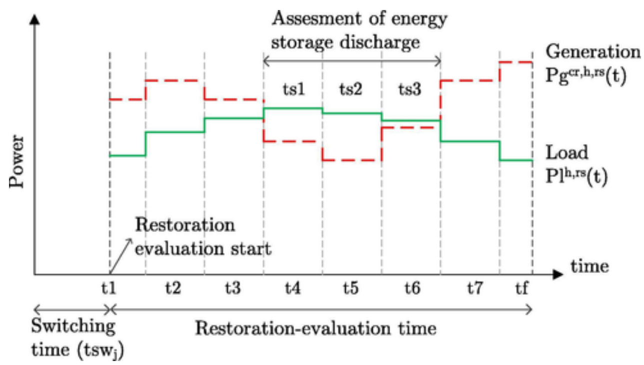

Fig. 5. Example of generation and load profiles evaluated during a fault.

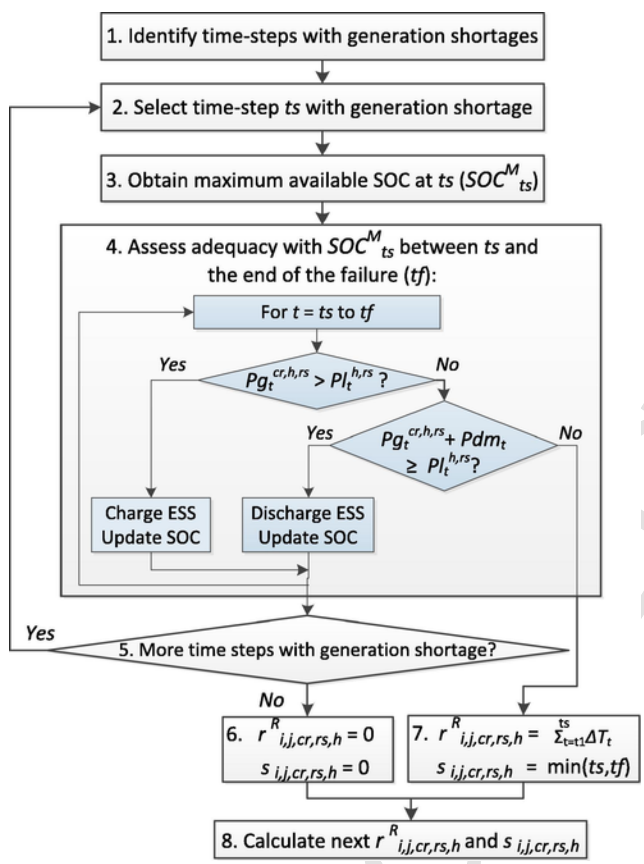

Fig. 6. Proposed procedure to evaluate energy storage performance and restoration strategy during a fault.

p_{cr}	probability of restoration-state *cr*
α^{cr}_{dg}	state of the DG (up = 1, down = 0)
α^{cr}_{s}	state of the ESS device (up = 1, down = 0)
FOR_{dg}	forced outage rate of DG *dg*
FOR_s	forced outage rate of ESS *s*
tsi_j	time to identify and isolate failure *j*
tsr_j	time to restore the supply in areas upstream of failure *j*
t_{tie}	switching time of the tie switches in a downstream area
st_{dg}	maximum starting times of all the DGs used in the restoration
st_s	maximum starting times of all the ESSs used in the restoration
$P^{h,rs}_{lpi,t}$	power demanded by load point *lpi* at time-step *t*
$P^{h,rs}_{dg,t}$	power generated by DG *dg*
$P^{h,rs}_{tie,t}$	transfer capacity of emergency tie *tie*
ΔT_t	duration of time-step *t*
ηc_s	charge efficiency of ESS *s*
ηd_s	discharge efficiency of ESS *s*
C_s	capacity of ESS *s*
$\underline{SOC}_s$	minimum SOC limit of ESS *s*
$\overline{SOC}_s$	maximum SOC limit of ESS *s*
$\overline{Pc}_s$	maximum charge power of ESS *s*
$\overline{Pd}_s$	maximum discharge power of ESS *s*

Variables

λ_i	failure rate of load point *i*
$\lambda_{i,j}$	failure rate of load point *i* caused by failure *j*
ENS_i	annual energy-not-supplied to load point *i*
ENS^*_i	energy-not-supplied to load point *i* considering the fluctuations of demand during failures
$ENS^R_{i,j}$	energy-not-supplied to load point *i* during failure *j* (excluding switching time)
$p_{h,rs}$	annual probability of time-step *h* in representative time-interval *rs*
$Pc_{s,t}$	charging power of ESS *s* at time-step *t*
$Pd_{s,t}$	discharging power of ESS *s* at time-step *t*
Pdm_t	maximum power that can be discharged from all the ESSs at time-step *t*
$Pg^{cr,h,rs}_t$	aggregated power generation in a downstream area at time-step *t*
$Pl^{h,rs}_t$	aggregated power demand in a downstream area at time-step *t*
r_i	outage duration of load point *i*
$r_{i,j}$	outage duration of load point *i* caused by failure *j*
$r^D_{i,j}$	interruption duration of load point *i* in an area downstream of failure *j*
$r^R_{i,j}$	interruption duration of load point *i* in an area downstream of failure *j* (excluding switching time)
$r^R_{i,j,cr,rs,h}$	interruption duration (excluding switching time) caused by failure *j* when registered at time-step *h* of representative time-segment *rs* and restoration-state of devices *cr*
$rc_{s,t}$	ratio of power available to charge ESS *s* at time-step *t*
$rd_{s,t}$	ratio of power required to be discharged from ESS *s* at time-step *t*
$s_{i,j,cr,rs,h}$	last time-step interrupted at failure *j* registered at time-step *h* of representative time-segment *rs* and restoration-state of devices *cr*
$SOC_{s,t}$	state of charge (SOC) of ESS *s* at time-step *t*
SOC^M_{ts}	maximum stored energy available at time-step *ts*
tsw_j	switching time of an area downstream of failure *j*
U_i	annual unavailability of load point *i*

1. Introduction

A principal cause of power interruptions in distribution systems is component failures [1]. They affect the reliability of supply and have a significant economic impact on customers and distribution companies [2]. Reliability is, therefore, a fundamental parameter to be evaluated in the planning of distribution networks [3,4]. When faults prevent the customer supply from the primary substation, corrective actions are implemented to restore the supply until the failed components are repaired [5]. A conventional solution is to reconfigure the network in order to transfer power from adjacent feeders to unsupplied areas, for example, by closing a tie switch [6]. However, distribution networks are not always equipped with these functionalities and even if they are, the available transfer capacity may be limited. In these cases the integration of Distributed Generation (DG) in distribution networks creates

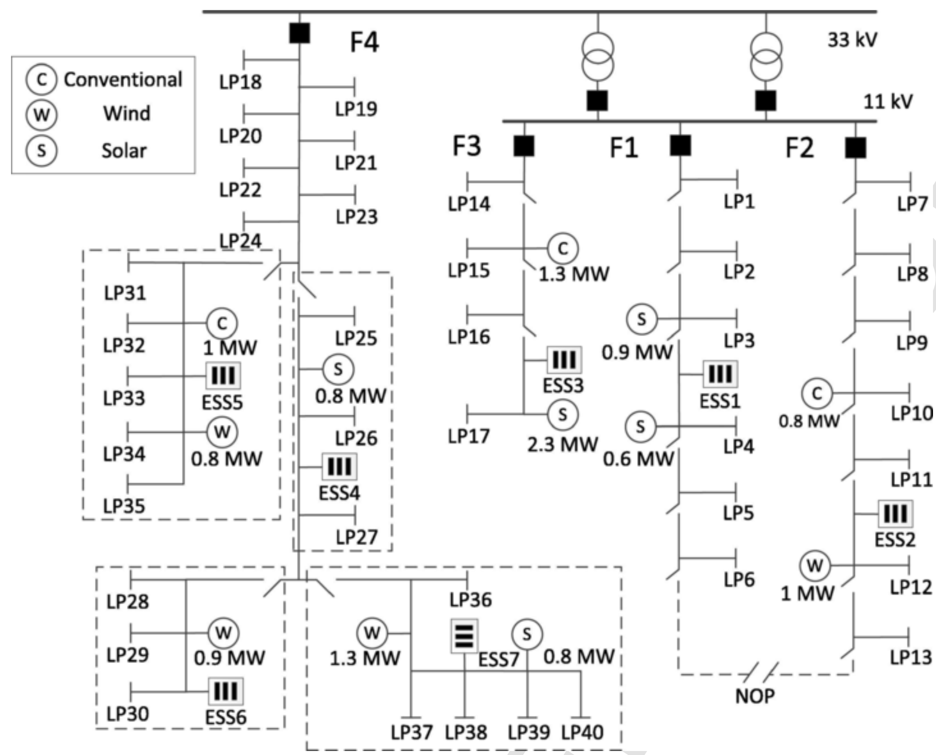

Fig. 7. Single-line diagram of the test network (Bus 6).

Table 2
Reliability parameters of the DGs.

Type	λ	r	Start time
	(failures/year)	(h/failure)	(h)
Conventional	1	48	0.75
Wind	4.17	60	0.25
PV	2	90	0.25

Table 3
Capacities (C_s) in MWh and rated powers of ESSs ($\overline{Pc_s}, \overline{Pd_s}$) in MW for the Scenario ($DG + Storage \times 1$).

	ESS1	ESS2	ESS3	ESS4	ESS5	ESS6	ESS7
C_e	0.26	0.16	1.13	0.38	0.41	0.45	1.05
$\overline{Pc_e}$	0.05	0.03	0.23	0.08	0.08	0.09	0.21
$\overline{Pd_e}$	0.05	0.03	0.23	0.08	0.08	0.09	0.21

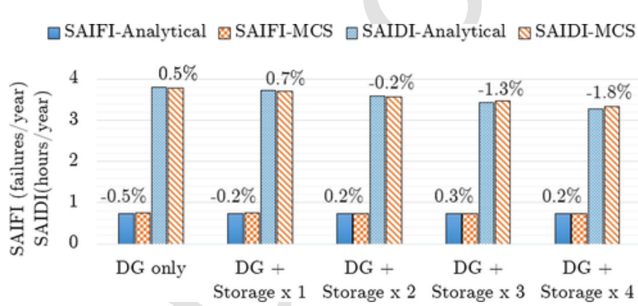

Fig. 8. Comparison between the results obtained by the proposed analytical technique and by the MCS. Differences in% referred to MCS results.

new solutions for the restoration of supply [7,8]. It is important to notice that a significant part of this locally installed DG in future will be from renewable, variable energy sources. In such scenario, the integra-

Table 4
Comparison between the computation times obtained for the proposed analytical technique and the MCS.

Scenario	Monte Carlo (s)	Analytical (s)
DG only	222.8	1.4
DG + Storage × 1	247.1	3.5
DG + Storage × 2	248.5	4.8
DG + Storage × 3	273.2	6.5
DG + Storage × 4	288.1	8.6

Table 5
SAIDI in the evaluated scenarios.

Scenario	F1	F2	F3	F4	Total
DG only	0.934	0.925	0.928	8.258	3.798
DG + Storage × 1	0.927	0.919	0.867	8.094	3.73
DG + Storage × 2	0.919	0.916	0.828	7.729	3.583
DG + Storage × 3	0.91	0.91	0.796	7.338	3.425
DG + Storage × 4	0.905	0.906	0.764	6.966	3.277

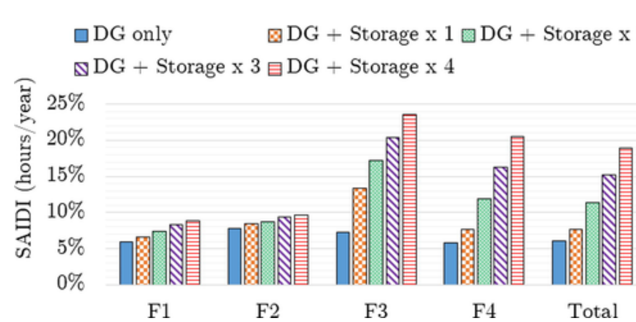

Fig. 9. SAIDI reduction (%) in the evaluated scenarios.

Table 6
ENS* (MWh) in the evaluated scenarios.

Scenario	F1	F2	F3	F4	Total
DG only	1.125	1.214	2.012	41.05	45.4
DG + Storage × 1	1.108	1.194	1.935	39.98	44.22
DG + Storage × 2	1.097	1.189	1.873	38.47	42.63
DG + Storage × 3	1.085	1.178	1.810	36.73	40.81
DG + Storage × 4	1.078	1.174	1.739	35.07	39.06

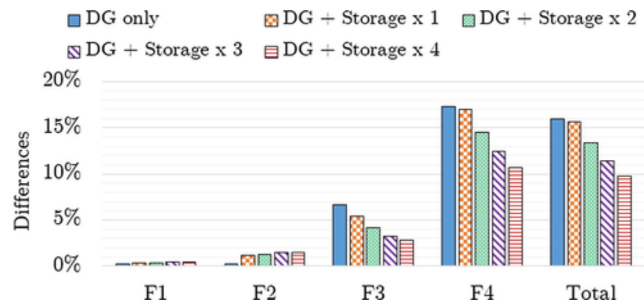

Fig. 10. Differences between ENS and ENS*. Values in% referred to ENS*.

Table 7
Results of the annual cost-benefit analysis for energy storage in miles of $ per year.

Scenario	ENS	ENS	Storage	Benefit/
	Cost	Benefit	Cost	Cost
DG only	60.4	–	–	–
DG + Storage × 1	58.5	1.9	165.2	1.1%
DG + Storage × 2	55.7	4.7	330.4	1.4%
DG + Storage × 3	52.5	7.9	495.6	1.6%
DG + Storage × 4	49.4	11	660.7	1.7%

tion of energy storage systems ensures sustained power levels to support the restoration from renewable sources.

The DG and energy storage offer several options to restore the supply in distribution networks. One of them is to provide power to the areas isolated by faults and that cannot be connected to alternative feeders (islanded operation) [9]. Another is to support the restoration from adjacent networks or feeders with emergency ties but of limited transfer capacity (tie-supported operation) [10,11]. The contribution of energy storage to reliability in these two restoration options needs to be assessed during the planning stage and, consequently, network planners require new evaluation tools.

There are two main probabilistic approaches used to assess the reliability of distribution networks: analytical and Monte Carlo simulation (MCS) [1]. MCS approach samples the stochastic occurrence of faults and this principle facilitates the assessment of the variability and time-evolution of renewable generation and demand during faults in a probabilistic framework [12,13]. In this way, the chronological operation of energy storage can be modelled in the reliability evaluation. However, a large number of simulation iterations and long computation times are required to obtain the results, representing the main disadvantage of MCS [14]. Despite the large computational times, MCS has been widely used to assess energy storage in reliability studies for distribution systems [15–18]. In [15] energy storage devices in the distribution network were evaluated as an instrument to improve the reliability of bulk power systems. In [16] the reliability improvement of a rural distribution network with an energy storage system in the primary substation was sought. The energy storage was coordinated with renewable DG in [17] to decrease the service interruption costs in the islanded operation. In [18] reliability of distribution networks was improved by the optimal allocation of energy storage operated in the islanded mode. However, the contribution of energy storage in tie-supported mode was not addressed by any of these references.

Analytical approaches represent a computationally-efficient alternative to MCS for the calculation of average values of reliability indices [12]. The main drawback in modelling of energy storage lies in the increased complexity required to address the variability and time-evolution of generation and demand over a fault duration [19]. An effective modelling solution is to define probabilistic states of stored energy over the fault duration [19,20]. However, these models do not include the charge and discharge processes of energy storage over the fault duration. Consequently, they cannot be used to apply strategies for energy storage operation during the supply restoration. Although there have been several analytical methods proposed in literature to assess the reliability of distribution networks with renewable DG in both islanded [21–26] and tie-supported modes [27], only a few papers reported on the application of analytical methods to energy storage assessment. In [28] an analytical method was proposed to assess the reliability improvement introduced by a renewable DG unit with an energy storage system operated in the islanded mode during faults. In [20] the reliability of rural distribution networks including energy storage and photovoltaic systems was also evaluated in the islanded mode. However, in these references the contribution of energy storage in tie-supported restoration mode was not evaluated, and the chronological charge and discharge processes over the fault duration were not modelled. Therefore, the analytical methodologies have to be extended to include these features.

In this paper, a novel analytical technique to assess the impact of energy storage on reliability of distribution networks is proposed. This impact is evaluated along with DG and emergency ties for islanded restoration mode as well as for tie-supported mode. The probabilistic evaluation takes into account the variability and the time-dependent fluctuations of renewable generation and demand during the fault and models the chronological charges and discharges of energy storage in order to support generation shortages and reduce the interruption duration. Finally, all these features are included in the calculation of the reliability indices. Based on the previous works, the main contributions of this paper can be summarized as follows:

- A novel methodology is proposed to specifically assess the contribution of energy storage to reliability of distribution networks. This contribution is evaluated under islanded network conditions as well as in presence of emergency ties of limited transfer capacity (tie-supported mode).
- In comparison to the existing analytical techniques, the proposed methodology provides more realistic computation of reliability indices because it has the following incremental extensions: (a) it allows probabilistic modelling of chronological charges and discharges of energy storage during a fault, (b) it properly assesses the time-dependent fluctuations of renewable generation and demand and (c) it specifically models the strategy to restore the supply during a fault.
- The proposed analytical technique is validated by using comparative case studies, demonstrating its accuracy and computational efficiency.
- The contribution of energy storage to reliability is evaluated in islanded and tie-supported restoration modes for different levels of energy storage penetration.

The organization of this paper is as follows: the methodology proposed is described in Section 2. It introduces the calculation of the reliability indices in presence of energy storage and how to address the time-dependent performance of the storage during faults. Section 3 presents the models used in the analytical technique, while Section 4 describes the analytical method for energy storage evaluation. In Section 5, the case study is presented. Finally, the conclusions are drawn in Section 6.

2. Reliability assessment methodology

2.1. Reliability indices

Reliability indices are used to quantify the impact of interruptions on distribution networks [29] for both load points and areas. The reliability indices of the load points in a network (index i) are the failure rate, the average outage duration, the annual unavailability, and the energy-not-supplied. They are calculated according to:

$$\lambda_i = \sum_{j=1}^{N_j} \lambda_{i,j}, \quad U_i = \sum_{j=1}^{N_j} \lambda_{i,j} r_{i,j}, \quad r_i = \frac{U_i}{\lambda_i}, \tag{1}$$

$$ENS_i = La_i \cdot U_i \tag{2}$$

The area indices determined are the System Average Interruption Frequency Index (SAIFI), System Average Interruption Duration Index (SAIDI) and Energy Not Supplied (ENS). These indices are typically used in reliability assessments and are calculated from load point reliability indices in the way described in [29].

2.2. Calculation of load point reliability indices

For the calculation of reliability indices, the zone branch methodology has been implemented because it permits the evaluation of complex fault isolation and restoration processes [5]. This methodology simulates the operation of protection devices when a fault occurs and identifies the areas of the network with different impacts on reliability. Fig. 1 shows an example of three types of areas created after fault isolation j: Area 1 or upstream of the fault, Area 2 or inside the fault, and Area 3 or downstream of the fault [30,25].

In these areas, failure rate $\lambda_{i,j}$ is equal to zero if the interruption lasts less than a certain time threshold (for example, five minutes in [29]). Otherwise, $\lambda_{i,j}$ is equal to the failure rate of the component that causes the fault (λ_j) [31].

The average interruption duration of the load points located in each area is determined by [1]:

$$r_{i,j} = \begin{cases} tsi_j + tsr_j & i \in Area1 \\ tsi_j + r_j & i \in Area2 \\ r_{i,j}^D & i \in Area3 \end{cases} \tag{3}$$

Eq. (3) shows that areas upstream of the fault are interrupted during the time require to identify the fault, isolate it and reconnect the area to the primary substation. The area in fault remains interrupted until the failure is repaired, while the interruption duration in areas downstream of the fault (hereafter downstream areas) depends on the presence of alternative sources to restore the supply.

2.3. Restoration of supply in downstream areas

The following scenarios (shown in Fig. 1) are evaluated for the restoration of supply in downstream areas:

1. alternative feeders and emergency ties with sufficient transfer capacity to restore all the interrupted supply [6]
2. alternative feeders and emergency ties with limited transfer capacity supported by DG and energy storage in tie-supported operation [10]
3. DG and energy storage in islanded operation [22]

Therefore, it is assumed that DG and energy storage installed in the distribution network participate in the supply restoration by operating in islanded and tie-supported modes. Energy storage helps in dealing with generation shortages originated from variable, renewable DG and extends the supply restoration. This contribution of energy storage to reliability in both restoration modes is evaluated by the proposed analytical methodology.

2.4. Incorporating energy storage in the analytical approach

The analytical methodology is used to evaluate the reliability indices when energy storage (and also DG) participates in the supply restoration of downstream areas. The chronological charge and discharge of energy storage over the fault duration are probabilistically modelled and represent one of the key challenges for the incorporation of energy storage operation in analytical approaches.

Probabilistic models of generation and demand are proposed to assess the power variability over a year (reliability indices are a yearly metric). Moreover, these models consider the chronological evolution of renewable generation and load, a requirement to simulate the time-dependent operation of energy storage during a fault. The availability of energy storage systems is also included in the evaluation. All these models are described in detail in Section 3.

Based on the probabilistic model, an analytical procedure is developed for the reliability indices calculation that includes the contribution of energy storage. The procedure performs an adequacy assessment at different fault conditions represented by renewable generation, demand and availability of DGs and ESSs. This adequacy assessment includes the performance of energy storage and the strategy used for its operation. The details of this analytical procedure are described in Section 4.

3. Proposed models for reliability assessment

3.1. Models of load and renewable generation

The models proposed for generation and load address their time-variability over a year in a probabilistic way. These models are used to evaluate the operation of energy storage under fault conditions because they take into account (a) the chronological evolution of generation and load during a fault, and (b) the variability of generation and load over a year.

The model is created by dividing the period of a year into representative time-intervals as in [21] (the reliability indices refer to probabilistic annual values). Fig. 2 shows an example where the representative time-intervals are one typical day for each month of the year. The number of representative time-intervals in one year and its time-frame (for example, day or week) are configurable.

Each representative time-interval has an annual probability ($p_{rs} = 1/12$ for the typical day of a month in Fig. 2) and is formed of power profiles (either for renewable generation or demand). The profiles are further divided in time-steps (for example, hours or fractions of hour) with their respective powers and probabilities ($p_h = 1/24$ for the hourly time-steps of a typical day in Fig. 2). The powers of the time-steps are obtained by averaging the power profiles of one or several years into representative time-intervals (one day per month in Fig. 2), while the annual probability of each time-step in a representative time-interval is calculated as:

$$p_{h,rs} = p_{rs} p_h \quad \forall rs \in \{1, \dots, \mathbf{N_{rs}}\}, h \in \{1, \dots, \mathbf{N_{h,rs}}\} \tag{4}$$

3.2. Reliability models of network components

Lines and transformers in a network are modelled by using the conventional two-state Markov model: the up state indicates normal operating conditions and the down state failure conditions [14]. The two-state model is also used for DG units and ESSs, and their annual unavailability (caused by the down state) is quantified by the unit outage forced rate (*FOR*) [1]. The power at the up state is a constant value of rated power for fully dispatchable DGs, and obtained from the probabilistic profiles of the representative time-intervals for variable renewable DGs.

The DGs and ESSs used to restore a downstream area can be in different states (up and down) when a fault occurs. The probabilistic combination of these devices with their respective states forms a set of combinatorial states defined as restoration-states, each one with a specific capacity of restoration. Table 1 shows an example of the restoration-states, where each restoration-state indicates the status of the DG and ESS devices (1 for up and 0 for down) as well as the probability of the restoration state (p_{cr}). This probability is calculated by extending the method described for DGs in [25] in order to include ESSs as follows:

$$p_{cr} = \prod_{dg\in N_{dg}} \left(\alpha_{dg}^{cr}\left(1 - FOR_{dg}\right) + \left(1-\alpha_{dg}^{cr}\right) FOR_{dg}\right) \cdot \prod_{s\in N_s} \left(\alpha_s^{cr}\left(1 - FOR_s\right) + \left(1-\alpha_s^{cr}\right) FOR_s\right) \tag{5}$$

4. Analytical procedure for energy storage evaluation

Before explaining the proposed procedure to assess reliability, the principal assumptions are described here:

- the operation of the distribution systems is radial,
- only sustained faults are evaluated,
- protection devices operate as expected and their failures are neglected,
- DG and ESS devices are disconnected when a fault occurs and re-connected once the fault is mitigated and the network reconfigured,
- the network is equipped with the appropriate protection and control systems for islanded operation,
- adequacy assessment of active power is performed without considering reactive power.

All these assumptions are commonly used in the reliability assessment of distribution networks [1,17,22,23,33].

4.1. Calculation of interruption duration

The procedure described in Section 2.2 is extended to include the contribution of energy storage to the reliability indices. This contribution is evaluated for all downstream areas and for all load points within these areas.

Fig. 3 shows an example of a time-interval registered by a load point in a downstream area when a fault occurs. After the failure occurs, the switching time tsw_j covers the time required to identify the fault, isolate it and prepare the downstream area for the restoration. Then, the time-interval between the end of the switching time and the end of the fault is defined as restoration-evaluation time because it is the time used for the evaluation of the feasibility of restoration. In addition to that, the time-intervals interrupted during the restoration-evaluation time form the interruption duration $r_{i,j}^R$. Therefore, the total duration of a load point interruption in a downstream area can be calculated as:

$$r_{i,j}^D = tsw_j + r_{i,j}^R \tag{6}$$

The calculation of the interruption duration $r_{i,j}^D$ takes into account the presence of alternative resources to restore the supply. In addition to emergency ties and DGs, the effect of energy storage is specifically included. The following options are evaluated:

1. If the downstream area is not equipped with alternative supply sources, restoration is not possible. Then, $tsw_j = tsi_j$ and $r_{i,j}^R = r_j$.
2. If the area is equipped with any emergency tie of sufficient transfer capacity, the tie is used for the restoration of supply as in [34] regardless of the presence of DG and energy storage. In this case, the interruption duration is:
$$tsw_j = \max\left(tsi_j, t_{tie}\right), \quad r_{i,j}^R = 0, \tag{7}$$
3. If the transfer capacity of emergency ties is limited, their contribution to restore the supply is evaluated in combination with the DG and the energy storage located in the downstream area. Therefore, the distributed energy resources are operated in the tie-supported mode and the switching time in this case is:
$$tsw_j = \max\left(tsi_j, t_{tie}, st_{dg}, st_s\right) \tag{8}$$
where it is assumed that all the DGs and ESSs in up state are started during the switching time to participate in the supply restoration.
4. In those downstream areas without emergency ties, the DG and the energy storage are used to restore the interrupted supply assuming the distributed resources equipped for the islanded operation. In this case, the switching time is:
$$tsw_j = \max\left(tsi_j, st_{dg}, st_s\right) \tag{9}$$
and also it is assumed that all the DGs and ESSs in the downstream area have to be started to participate in the supply restoration.

The average interruption duration $r_{i,j}^R$ in points (3) and (4) enumerated above is calculated by using the probabilistic procedure shown in Fig. 4. This procedure takes into account (a) the availability of DGs and ESSs and (b) the variability of renewable generation and demand during the fault. The first is evaluated by using the combinatorial restoration-states of devices described in Section 3.2 and the second by using the representative time-intervals explained in Section 3.1. The calculation steps in Fig. 4 are described as follows. First, the required data including the restoration-states and the representative time-intervals are uploaded. Then, restoration-state *cr* with probability p_{cr} is selected and its capacity to provide the interrupted supply evaluated. This evaluation is performed at different renewable generation and demand conditions during the fault given by each representative time-interval *rs*. In addition, the component failures can happen at different moments over the year and they are simulated by assuming a fault can occur at every time-step *h* of the representative time-interval *rs* with probability $p_{h,rs}$. For each of these particular conditions (restoration-state *cr*, representative segment *rs* and time step *h*), an adequacy assessment is performed to calculate the interruption duration $r_{i,j,cr,rs,h}^R$ modelling the charges and discharges of energy storage during the fault. Finally, overall interruption duration $r_{i,j}^R$ aggregates all the values of $r_{i,j,cr,rs,h}^R$ taking into account the probabilistic conditions as Eq. (10) shows.

$$r_{i,j}^R = \sum_{cr=1}^{N_{cr}} p_{cr} \sum_{rs=1}^{N_{rs}} \sum_{h=1}^{N_{h,rs}} p_{h,rs}\ r_{i,j,cr,rs,h}^R. \tag{10}$$

4.2. Adequacy assessment with DG and energy storage

This section describes the adequacy assessment performed to calculate the interruption duration $r_{i,j,cr,rs,h}^R$ in (10). It corresponds to step 5 in Fig. 4 and evaluates the operation of energy storage during the fault in order to provide uninterrupted power supply under generation shortages.

4.2.1. Profiles of generation and demand during the fault

The adequacy assessment starts by quantifying the aggregated power profiles of demand and generation in the downstream area during the fault duration. These profiles are calculated for all the restoration-states of devices and for different conditions of renewable generation and demand over a year as follows:

$$Pl_t^{h,rs} = \sum_{lpi \in N_{lpi}} P_{lpi,t}^{h,rs} \quad \forall t, \tag{11}$$

$$Pg_t^{cr,h,rs} = \sum_{dg \in N_{dg}} \alpha_{dg}^{cr} P_{dg,t}^{h,rs} + \sum_{tie \in N_{tie}} \alpha_{tie}^{cr} P_{tie,t}^{h,rs} \quad \forall t \tag{12}$$

where the transfer capacity of a feeder ($P_{tie,t}^{h,rs}$) is determined in such a way that the network constraints are preserved [10,11]. It takes into account the demand, the DGs and the ESSs located in that adjacent feeder and in the area interconnected via the emergency ties.

Fig. 5 shows an example of the aggregated profiles of generation ($Pg_t^{cr,h,rs}$) and load ($Pl_t^{h,rs}$) in a downstream area during a fault. After the switching time ends, the capability to restore the supply is evaluated over the restoration-evaluation time (from *t*1 to *tf*). If the duration of the representative time-intervals is shorter than the fault, these time-intervals are repeated as many times as necessary to cover the duration of the fault.

4.2.2. Energy storage model

The charge and discharge processes of an energy storage during the fault are modelled chronologically by using (13)–(16), assuming the ESSs has an initial state of charge when the fault occurred.

$$SOC_{s,t+1} = SOC_{s,t} + \left(Pc_{s,t}\eta c_s - \frac{Pd_{s,t}}{\eta d_s} \right) \frac{\Delta T_t}{C_s} \tag{13}$$

$$\underline{SOC}_s \leqslant SOC_{s,t} \leqslant \overline{SOC}_s \tag{14}$$

$$Pc_{s,t} = \begin{cases} \min\left(\left(Pg_t^{cr,h,rs} - Pl_t^{h,rs} \right) rc_{s,t}, \overline{Pc}_s \right) & Pg_t^{cr,h,rs} > Pl_t^{h,rs} \\ 0 & Pg_t^{cr,h,rs} \leqslant Pl_t^{h,rs} \end{cases} \tag{15}$$

$$Pd_{s,t} = \begin{cases} \min\left(\left(Pl_t^{h,rs} - Pg_t^{cr,h,rs} \right) rd_{s,t}, \overline{Pd}_s \right) & Pg_t^{cr,h,rs} < Pl_t^{h,rs} \\ 0 & Pg_t^{cr,h,rs} \geqslant Pl_t^{h,rs} \end{cases} \tag{16}$$

Eq. (13) models the chronological evolution of the SOC taking into account the energy charged and discharged in every cycle and (14) keeps the SOC within the operational limits. The power to charge an energy storage device is calculated by using (15), where the first term ($\left(Pg_t^{cr,h,rs} - Pl_t^{h,rs} \right) rc_{s,t}$) represents the amount of power excess available to be charged in storage *s* after other storage devices with larger priority have been charged, and the second term ($\overline{Pc}_s$) the limit of charging power. The power discharged from a storage device is determined in (16). In this equation, the first term ($\left(Pl_t^{h,rs} - Pg_t^{cr,h,rs} \right) rd_{s,t}$) represents the total power required to get adequacy that has not been supplied yet by other storage devices with larger priority of discharge, and the second term ($\overline{Pd}_s$) the limit of discharging power.

Each time an ESS is charged or discharged, the ratio of the total power available for charging an storage device is updated by:

$$rc_{s,t} = 1 - \frac{\sum_{s \in \mathbf{Sp}} Pc_{s,t}}{Pg_t^{cr,h,rs} - Pl_t^{cr,h}} \quad \forall t \in Pg_t^{cr,h,rs} > Pl_t^{h,rs} \tag{17}$$

and the ratio of the total power required to be discharged from a storage device by:

$$rd_{s,t} = 1 - \frac{\sum_{s \in \mathbf{Sp}} Pd_{s,t}}{Pl_t^{h,rs} - Pg_t^{cr,h,rs}} \quad \forall t \in Pg_t^{cr,h,rs} \leqslant Pl_t^{h,rs}, \tag{18}$$

With respect to the priority of ESSs use, it is assumed in this paper that the ESSs with lower SOC are charged first while those ESSs with larger SOC are discharged first (SOC ranges between 0 and 1 as it measures the ratio between the stored energy and the storage capacity).

4.2.3. Restoration strategy with energy storage

Fig. 6 shows the procedure proposed to calculate average interruption duration $r_{i,j,cr,rs,h}^R$ defined in (10) and also the time-step from which restoration starts, $s_{i,j,cr,rs,h}$, used later in (22) for the calculation of the energy-not-supplied. A specific strategy is applied to operate the energy storage in order to reduce the duration of the interruptions and avoid repetitive interruptions of customers already restored [35]. In this way, the impact of this restoration strategy can be addressed by the analytical technique and quantified in the reliability indices.

The stages in Fig. 6 are described as follows. Firstly, during a fault the time-steps with generation shortage are identified by performing an adequacy assessment of the generation and load profiles calculated in Section 4.2.1. Then, the capacity of energy storage to support the time-steps with generation shortages is evaluated, selecting these time-steps one by one as stage 2 in Fig. 6 indicates (the selected time-step is designed as *ts*). The evaluation starts, for example, in the last time-step with generation shortage (*t*6 in Fig. 5) and, once assessed, previous time-steps are selected for the evaluation in reverse chronological order (*t*5 and *t*4 in Fig. 5). These criteria pursue avoiding repetitive interruptions of already restored customers since a fault is commonly recorded during the switching time.

The following step (step 3) is to determine the maximum stored energy available at time-step *ts*, and it is obtained as:

$$SOC_{ts}^M = \sum_{s \in N_s} SOC_{s,ts}^M. \tag{19}$$

The value of $SOC_{s,ts}^M$ is calculated by using (13) and (14) and considering the discharge power $Pd_{s,t}$ between *t*1 and *ts* - 1 is 0.

In the fourth step, the contribution of SOC_{ts}^M to restore the supply between time-step *ts* and the end of the fault (*tf*) is evaluated. In each time-step, if generation exceeds the demand ($Pg_t^{cr,h,rs} > Pl_t^{h,rs}$), the energy storage is charged by a power determined by (15). By contrast, the energy storage is discharged at a time-step with generation shortage if the maximum power that can be discharged from all the ESSs (designed as Pdm_t and calculated by (20)) is sufficient to supply the generation shortage, i.e., the condition $Pg_t^{cr,h,rs} + Pdm_t > Pl_t^{h,rs}$ is fulfilled. In such a case, the discharge power is calculated by (16). In the charge and discharge cycles the SOC is updated by using (13) and (14).

$$Pdm_t = \sum_{s \in Ns} \min\left(\frac{(SOC_{s,t} - \underline{SOC_s}) C_s \eta d_s}{\Delta T_t}, \overline{Pd_s} \right) \quad t = ts, \ldots, tf \tag{20}$$

If the ESSs supplies all the generation shortage during the analysed time interval (from *ts* to *tf*), the restoration of supply at time-step *ts* is considered feasible and then the evaluation continues to the previous time-steps with generation shortage (go to step 2 in Fig. 6). On the contrary, if all the supply from *ts* to *tf* is not restored, no further time-steps with generation shortages are assessed. This latter situation corresponds to step 7 in Fig. 6 and means that the supply remains interrupted from the start of the fault until time-step *ts*.

In the case of energy storage can provide all the generation shortages (step 6), the interruption duration $r_{i,j,cr,rs,h}^R$ is 0. Finally, the evaluation continues with the calculation of the next values of $r_{i,j,cr,rs,h}^R$ and $s_{i,j,cr,rs,h}$ until all the combinations of faults conditions (defined by *cr*,*rs* and *h*) are evaluated.

4.3. Calculation of ENS

The analytical techniques in literature such as [31] typically calculate the ENS by considering the average customer load as in (2). The methodology proposed in this paper also calculates the ENS of the load points located in Areas 1 and 2 of Fig. 1 by using their average load. However, the calculation of the ENS for the load points within the areas downstream of the fault (or Area 3 in Fig. 1) takes into account the variability of the load interrupted during the fault. The energy-not-supplied calculated by this procedure (ENS_i^*) is determined by (21) and (22) and provides more realistic evaluation compared to the procedure based on average values.

$$ENS_i^* = \lambda_{i,j}\sum_{j=1}^{N_j}\left(La_{i,j}tsw_j + ENS_{i,j}^R\right) \tag{21}$$

$$ENS_{i,j}^R = \sum_{cr=1}^{N_{cr}} p_{cr}\sum_{rs=1}^{N_{rs}}\sum_{h=1}^{N_{h,rs}} p_{h,rs}\sum_{t=t1}^{s_{i,j,cr,rs,h}} Pl_t^{h,rs}\Delta T_t \tag{22}$$

5. Case study

5.1. Test network

The aim of the case study is to validate the proposed analytical methodology and to evaluate the contribution of energy storage to reliability. This is done by applying the proposed methodology to Bus 6 of Roy Billinton Test System shown in Fig. 7 representing a typical test case used for testing methodologies for reliability assessment of distribution networks [36]. By using this test system, the restoration by islanded operation (feeders F3 and F4) and by tie-supported operation through alternative feeders (feeders F1 and F2) can be both evaluated.

The DGs in Fig. 7 were introduced to the original network in [36]. The type of these DG resources (conventional, wind or solar) and their capacities are shown in Fig. 7, while the reliability parameters are given in Table 2.

The ESSs shown in Fig. 7 were also introduced to the original network in [36] and four scenarios of energy storage integration were evaluated. The ESSs in the first scenario (DG and nominal storage capacity, in further text referred to as *DG + Storage* × 1), had the energy storage capacity and rated powers of charge and discharge defined as in Table 3. The ESSs in the other three scenarios (*DG + Storage* × 2), (*DG + Storage* × 3) and (*DG + Storage* × 4) had storage capacities and rated powers 2, 3 and 4 times larger than those defined for the first scenario. The fifth scenario had only DG without energy storage (referred to as *DGonly*) and was used to compare the impact of energy storage on reliability.

The ESSs were assumed to be redox flow batteries with the following features. The minimum and maximum SOC of ESSs were 10% and 100% of the total storage capacity respectively. Energy storage charge (η_c) and discharge (η_d) efficiencies were equal to 0.9. The initial SOC of ESSs at the moment of the fault was assumed to be at 0.55, i.e., the half of the available storage capacity was reserved for restoring the supply when required. The starting time of the ESSs was of 1 min. Moreover, the failures in the ESSs were neglected, an assumption typically used in the literature[17].

The reliability data of the components used in the network were obtained from [37]. The lines in the network were aerial, while the components of the substation and protection devices were assumed to be fully reliable. The switching time required for secure operation of the protection devices was 1 h [37].

Under fault conditions in feeder F4, the protection devices were operated in order to create the downstream areas between the dashed lines in Fig. 7. The representative time-intervals shown in Fig. 2 were used to model the load and renewable generation. Commercial load profiles were also used for the farm load points in [36]. The capacity of feeders F1 and F2 was 2.1 MW, a value that provoked transfer restrictions between these feeders via the tie switch. The tie switch was assumed to be perfectly reliable to restore the supply when needed.

5.2. Validation of the analytical technique

In order to validate the analytical methodology proposed in this paper, the results reported by the analytical technique were compared to those obtained by sequential MCS [14] under the same scenarios. This comparison was performed because MCS allows to address the chronological variability of generation and demand over time and, thus, the energy storage charge and discharge processes during faults [16,17].

The properties of the MCS used for the validation allow an accurate comparison of the results provided by the two techniques. These properties are:

- It is a sequential MCS [14] in order to assess time-variability of generation and demand during faults.
- Reliability models of the components are the same as those used in the proposed analytical technique (2 states, up and down).
- Failure rate of each component is assumed to be exponentially distributed (a common assumption in MCS techniques to represent the failures of components over their life-time [38]).
- Repair times are assumed to be equal to the average repair times in order to allow an appropriate comparison between the two techniques.
- The restoration strategy was the same as the one proposed in the analytical technique. However, the hourly profiles of generation and demand over a whole year were considered by the MCS technique instead of the representative time-intervals used by the proposed analytical technique (note that power profiles over years were used to obtain the representative time-intervals).
- Coefficient of variation of 1.5% was used as the stop criteria for the MCS [38].

The reliability results obtained from both analytical and MCS are shown in Fig. 8, and the respective computation times required for their calculation in Table 4. The computation times for both methods were obtained by using MATLAB (MathWorks) running on a 2-core 2.4-GHz, 64 bit desktop with Windows 7 operating system. The functions 'tic' and 'toc' in MATLAB were used to start and stop the stopwatch timer.

The differences between the network reliability results reported by the two compared methods (Fig. 8) were below 0.5% for SAIFI and 1.8% for SAIDI (for the coefficient of variation in MCS of 1.5%). In addition, the differences in reliability indices for each feeder were below 1.1, 2.1 and 1.7% in feeders F1 + F2, F3 and F4 respectively. These differences were conditioned to: the exponential distribution of component failure rate used in the MCS technique, the stop criteria uncertainty of MCS, and the approximation applied to obtain the representative time-intervals of generation and demand used in the analytical technique.

The computation times in Table 4 revealed the analytical technique was 50 times faster in average for the four scenarios of energy storage application. These time differences were caused by the distinction between the approaches of the two methodologies compared. On the one hand, the analytical technique simulated every network failure only once and then assessed its impact on reliability. On the other hand, MCS sampled stochastic occurrence of network failures until the reliability indices converged to a solution, causing a network failure to be evaluated several times (for example, several hundreds or even thousands). Therefore, the results demonstrated the proposed analytical methodology represented a computationally-efficient solution for the evaluation of the impact of energy storage and renewable DG on reliability. The computation time of the analytical technique depended on several factors related to the analysed test system: the number of network failures evaluated in the study, the number of the DGs and ESSs that participated in the supply restoration of downstream areas, and the number of charge and discharge processes of energy storage devices (highly dependent on the size of the ESSs and the existence of generation shortages).

5.3. Impact of energy storage on reliability

In this section the new analytical technique was used to evaluate the impact of the energy storage penetration on the test network reliability. The impact was assessed in the downstream areas of the faults that can be restored by islanded operation and by emergency ties of limited transfer capacity (tie-supported operation). Table 5 reports the results of SAIDI in the network for the five scenarios analysed, while Fig. 9 shows the SAIDI reductions referred to the original distribution network without DG. These results were obtained for each feeder in the test network shown in Fig. 7 (*F*1 to *F*4) and for the entire test network aggregating the four feeders (shown as *Total*). The SAIFI in the analysed scenarios was the same because the interruptions were not avoided but only reduced in duration.

The results revealed a significant reduction in the SAIDI for feeders F3 and F4 that was caused by the energy storage support of the variable DG in islanded operation. For example, the integration of only DG improved the SAIDI of feeder F4 by 5.8%. With the penetration of energy storage, the SAIDI improved further from 7.7% in scenario ($DG + Storage \times 1$) to 20.6% in scenario ($DG + Storage \times 4$) with four times larger energy storage. In both feeders F3 and F4, a 3–4% of SAIDI improvement was obtained with the increase of energy storage size between consecutive scenarios.

The contribution of the energy storage to supply restoration of feeders F1 and F2 operating in tie-supported mode was lower than for those feeders operating in the islanded mode (F3 and F4). In the case of F1, the total margin of the SAIDI improvement by using distributed energy resources was 16%. The penetration of only DG improved SAIDI by 6% while the integration of energy storage increased this value to 9% in scenario ($DG + Storage \times 4$). Similar SAIDI reductions were obtained for energy storage in F2. In conclusion, energy storage in tie-supported operation improved reliability, although the results are strongly impacted by the transfer restrictions between feeders F1 and F2 at specific load and fault conditions.

5.4. Comparison of ENS results

Table 6 shows the energy-not-supplied ENS* calculated by using the new procedure proposed in this paper, and Fig. 10 shows the differences between ENS* and the ENS calculated by using (2). The first method considers the time-dependent variability of load during the fault, while the second uses the conventional approach based on the average load values. The results were also obtained for each feeder of the test network (*F*1 to *F*4) and for the entire test network (*Total*).

The differences between ENS* and ENS were significant, in particular in those areas of the network where the energy-not-supplied was larger (feeders F3 and F4). In the Bus 6, differences varied from 16% in the case of DG without energy storage to 10% in the scenario with energy storage ($DG + Storage \times 4$). It is important to notice that installing more energy storage caused a decrease in the energy-not-supplied and, consequently, the differences in the energy-not-supplied calculated by the two methods also decreased. Fig. 10 also shows that the use of the average load values overestimated the ENS in all energy storage scenarios. The results in this Section revealed the importance of considering the fluctuations of demand profiles in the time-intervals with non-restored supply.

5.5. Cost-benefit analysis

A simplified cost-benefit analysis was performed to illustrate the economic impact of energy storage when used to improve reliability. The obtained results for different scenarios of energy storage penetration are shown in Table 7. In this table, *ENScost* was calculated from ENS* results in Table 6 and from the cost functions of energy-not-supplied in [38], and *ENSbenefit* represents the reduction in *ENScost* when energy storage is integrated (referred to scenario *DGonly*). The annual storage investment of vanadium redox flow battery was obtained from [39] assuming 13 years of lifetime under normal operating conditions without failures (10.000 cycles of life, 2 cycles per day). The ratio between the annual reliability benefit and the annual cost of energy storage (*Benefit/Cost* in Table 6) shows the reliability improvement only reported between 1.1% and 1.7% of the total annual storage investment. These results confirmed that integrating energy storage in the system was not profitable when it was only used for improving reliability. For a more detailed analysis, other issues like energy storage size, location and different energy storage technologies should be analysed. The additional economic benefits obtained from the reliability improvement should be summed up with the other benefits provided by energy storage.

6. Conclusions

In this paper, a novel analytical technique for the assessment of energy storage contribution to reliability of distribution networks has been proposed. The technique introduces a set of new features for an improved and more realistic evaluation of energy storage by using the analytical approach. The first feature is its capacity to assess the impact of energy storage in network areas restored by islanded operation or by adjacent feeders of limited transfer capacity. Another novel feature is the capability to model energy storage chronological charge and discharge processes during a fault with the corresponding operating strategy applied. In addition to that, the variability and time-dependent fluctuations of renewable generation and demand are properly addressed and considered during the calculation of reliability indices.

The proposed technique was validated by comparing the obtained results with those calculated by using sequential MCS as the latter accurately addresses the chronological operation of energy storage. The results produced by the analytical technique retained the accuracy of MCS (within the range of 2%). However, the proposed technique required significantly lower computational efforts and times (reduced up to 50 times). Such performance makes the new technique a suitable candidate for the reliability assessment in network planning studies that include energy storage.

Further analyses with the proposed method revealed that increased energy storage penetration improves the reliability of distribution networks in both restoration modes (up to 14% in islanded operation and 3% in adjacent feeders of limited transfer capacity). However, more detailed cost-benefits analyses are needed to assess the economic viability of storage installations.

The main future research work includes the extension of the methodology to address properly cost-benefit analyses, resiliency evaluation and communication-system performance.

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