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Publication Date	2017-06-12
Publisher	CIREN International Conference and Exhibition on Electricity Distribution

AN ANALYTICAL METHOD TO ASSESS THE IMPACT OF DISTRIBUTED GENERATION AND ENERGY STORAGE ON RELIABILITY OF SUPPLY

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ABSTRACT

Efficient integration of Distributed Generation (DG) and Energy Storage Systems (ESS) to distribution networks can help improve the reliability of supply. In order to evaluate the impact of these technologies on reliability several Monte Carlo simulation techniques have been proposed in recent years, yet none of the analytical methods that are known to be more computationally efficient. This paper proposes an analytical formulation for assessing the reliability impact of energy storage supporting DG in supply restoration of isolated network areas. To validate the proposed method and evaluate the impact of DG and energy storage on reliability a real distribution network was used and the simulation results provided.

INTRODUCTION

Increased levels of customer supply reliability represent a norm in modern distribution networks and new ways to respond to fault conditions are constantly sought. A fault can isolate network areas from the bulk supply point and interrupt the supply of their designated load points (LPs). The effective integration of Distributed Energy Resources increases options for the restoration of power supply in these isolated areas and consequently enhances their supply reliability. DG equipped with the required controllers could be operated in islanded mode in order to restore the interrupted supply. However, many of these DG units represent renewable resources and their variability often limits their capacity to restore the supply at all times under failure conditions. By integrating ESS combined with intermittent DG and by enabling the controllers to operate in islanded mode the impact of supply interruptions on distribution networks can be significantly reduced. In order to quantify the reliability impact of these technologies, an extension of the methods used for reliability evaluation is required.

Analytical and Monte Carlo Simulation are the two approaches frequently used to assess the reliability of distribution networks [1]. Within the integration of renewable and variable DG, Monte Carlo simulation has been preferred to analytical methods since its greater flexibility and accuracy in modelling the time-dependency of load and generation [2]. However, the high computation times needed by the simulation approach represent a handicap for distribution network planners. In order to

overcome this limitation some alternative and more efficient analytical methodologies have been proposed in recent years [3]–[6]. The methods were focused on proposing analytical formulations capable of modelling the chronological dependency between generation and load. Representative yearly values of load and generation based on power levels and their probabilities were used in [3], [4] for evaluating the reliability impact of variable DG in islanded operation mode. Nevertheless, yearly values assumed that neither load nor generation fluctuates during the restoration period after a fault in the network. By using hourly representative values of load and variable generation [5], [6] this limitation can be overcome and accurate results similar to those provided by Monte Carlo simulation can be obtained.

The limitation in the restoration of the interrupted supply introduced by the variability of certain renewable DG can be alleviated by using energy storage technologies. In order to assess the reliability impact of energy storage, methodologies based on Monte Carlo simulation have been proposed in [7], [8] because of their flexibility and accuracy to model the chronological charge and discharge processes of the ESS. However, no analytical method capable of preserving the time-dependency of load and generation needed to model the charge and discharge of ESS has been found in the literature.

This paper proposes an analytical method to assess the reliability impact of DG and energy storage technologies applied in the restoration of the interrupted supply in isolated areas of a distribution network. It uses hourly representative values of load and variable generation to model the ESS charge and discharge chronologically. The main contributions are the reduction of computation times compared to Monte Carlo simulation and the strategy proposed for operating energy storage in support of DG during supply restoration. The simulation results of the reliability improvement obtained by applying different DG technologies and different sizes of energy storage to a real distribution network will be used to demonstrate and evaluate the proposed methodology.

METHODOLOGY

This section explains the analytical methodology proposed to assess the reliability impact of distribution networks when capacities of DG and ESS operated in islanded mode are used to restore the interrupted supply.

Reliability assessment of distribution networks

Reliability assessment methodologies aim to identify which LPs are affected by different fault conditions and what is their impact on customer interruptions. Average reliability indices for LPs are determined in (1) by aggregating the effect of all network contingencies:

$$\lambda_{LPi} = \sum_{j=1}^N \lambda_j; U_{LPi} = \sum_{j=1}^N U_j; r_{LPi} = \frac{U_{LPi}}{\lambda_{LPi}} \quad (1)$$

Where λ_{LPi} , r_{LPi} and U_{LPi} are the reliability indices of load point i , N is the number of contingencies in the network that cause interruption of supply in LPi ; and λ_j , r_j and U_j are the average failure rate, outage duration and annual unavailability of contingency j .

After a fault in radial distribution networks, the protection devices are activated in order to mitigate and isolate the fault. Depending on the network configuration and the technology of the protection devices, three areas of the network constituted by LPs affected in a similar way can be identified. Area 1 is represented by the LPs upstream the fault section. They will be interrupted during the switching time required to isolate the fault and reconnect the substation supply. Area 2 includes the LPs located in the fault section and they will be interrupted during the repair time of the failed components. Finally, LPs located downstream the fault section constitute the Area 3. Their interruption time is the repair time unless alternative restoration solutions like Normally-Open Points (NOP) or DG would be available. In case of supply restoration by NOP being available, their contribution on reliability indices is determined according to [1].

Restoration of supply by Distributed Generation

DG equipped with the controls required to operate in islanded mode is an effective solution to restore the interrupted supply in network areas isolated from the main substation. Since variability of renewable generation and its correlation with the load during the fault time are required to be analysed accurately, an analytical formulation based on [5] has been proposed. In this way, the computational requirements are less intensive than Monte Carlo simulation techniques.

Distributed Generation and Load Modelling

An hourly model made of representative time-segments [5] has been proposed for evaluating the time-dependent patterns of load and renewable generation. For example, a typical day or week of every month over a year can be used.

Restoration strategy

The restoration strategy proposed assigns higher supply priority to critical loads. It means that available generation is used to restore firstly the most critical loads while avoiding repeated interruptions to restored customers. Partial restoration of LPs is not applied at hours in which the demand of a LP cannot be supplied completely by DG. Also, repetitive interruptions in restored customers are avoided during the restoration process. This involves that

supply could be restored in consecutive hours with enough generation starting in the last hour of the fault duration and going backwards over time. Once an hour with generation shortage is identified, it is set as the last hour of interruption and restoration is possible in the following hours of the fault period. The time intervals with enough generation but unable to avoid repetitive interruptions are not considered in the restoration. The duration of interruptions, therefore, is attempted to be reduced by DG while the number of interruptions is preserved. For example, in Fig. 1 interrupted supply of LP1 (more critical than LP2) after a fault in time instant t_1 is restored by DG during the whole fault period. However, restoration of LP2 is limited to the interval between time steps t_3 and t_4 according to the proposed strategy. Although generation is larger than demand between t_1 and t_2 , DG restoration is not applied during this interval because a new interruption would be registered between t_2 and t_3 .

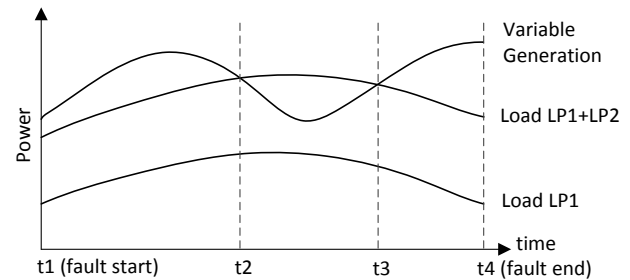


Fig. 1 Generation and demand evolution in an isolated area under fault conditions

Calculation of interruption duration

The available DG and the interrupted load during the fault period are evaluated in order to determine the number of hours of restored and interrupted supply. The hourly model of load and generation described above as well as the restoration strategy are considered. As a result, the average annual unavailability of every LP interrupted by fault j after assessment of restoration capability by DG is calculated by using (2). It is proportional to the average failure rate of fault j (λ_j) and the average interruption duration after DG restoration ($ID_{DG i,j}$).

$$U_{LPi,j} = \lambda_j ID_{DG i,j} \quad (2)$$

The fault can be registered under different generation states and at different hours of the representative time-segments. These conditions affect the DG capability to restore the interrupted supply. Consequently, the procedure illustrated in Fig. 2 is applied to quantify the contribution of generation states and time-dependency on the average interruption duration in the affected LPs. Generators in the isolated area can be operational or under fault conditions and they are represented by a set of generation states defining their power and annual availability [1]. The capability of each generation state to restore the interrupted supply during the fault period is evaluated assuming the fault can be registered in every hour of the representative time-segments. As a result, the

average interruption duration of the affected LPs is determined using (3).

$$ID_{DG\ i,j} = \sum_{GS=1}^{N_{GS}} P_{GS} \sum_{RS=1}^{N_{RS}} P_{RS} \sum_{h=1}^{N_h} P_h ID_{DG\ i,j,GS,RS,h} \quad (3)$$

Where P_{GS} is the probability of fault j happening under generation state GS , P_{RS} is the probability of fault j happening under the representative time-segment RS , P_h is the probability of fault j happening under hour h of representative time-segment RS , and $ID_{DG\ i,j,GS,RS,h}$ is the average interruption duration of LP_i under fault j , generation state GS and hour h of the representative time-segment RS .

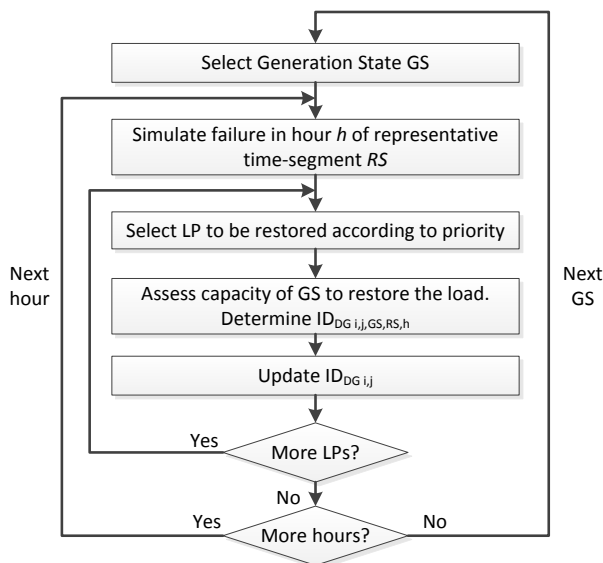


Fig. 2. Procedure to calculate interruption duration of LPs

Reliability impact of Energy Storage

Supply restoration by using the proposed restoration strategy has the shortcoming that those intervals with generation shortage limit the duration of the supply restoration. For example, in Fig. 1 the generation shortage between time steps t_2 and t_3 make unfeasible the restoration of LP_2 from t_1 to t_3 , despite sufficient generation is available between t_1 and t_2 . By supporting DG with energy storage in these time intervals with generation shortage (from t_2 to t_3 in Fig. 1) restoration during the fault time can be extended and reliability can be improved.

While techniques for reliability assessment of energy storage impact in literature use Monte Carlo simulation, here we propose an analytical formulation. The methodology described for DG in previous section can be extended in order to include the evaluation of energy storage supporting DG.

Assessment of Energy Storage supporting DG in supply restoration

Different operation strategies can be applied to model the charge and discharge of the ESS. In this paper, ESS is

operated by using the same restoration strategy previously applied to DG and by adapting it according to the following conditions. Firstly, ESS is operated to get the maximum extension of the restoration duration starting from the most critical LP and then the remaining energy stored is used to restore the next most critical LP, and so on. Secondly, evaluation process of energy storage supporting DG during the fault period starts in the last hour with generation shortage and move forward reversely to the chronological evolution of time considering the available energy stored at every hour. In this way, repeated interruptions are avoided.

Consequently, the procedure described in subsection *Calculation of interruption duration* is adapted to include the impact of energy storage. In particular, the assessment of the interruption duration under generation state GS and fault registered in hour h ($ID_{DG\ i,j,GS,RS,h}$) is extended to include the energy storage support. For a certain hour t with generation shortage, maximum available state of charge (SOC) of the ESS devices to support DG in hour t and subsequent hours of the fault period is determined. It is calculated by simulating the chronological charge and discharge of ESS devices for every hour since fault starts until hour $t-1$. The initial SOC at the beginning of the failure for reliability requirements is established [9] while hourly charge and discharge are determined by considering the generation excesses and the energy demanded from ESS devices by more critical LPs in hours preceding t .

Then, the capacity of this maximum available SOC to supply the generation shortage at all hours from t until the end of the fault period is evaluated. If the available SOC is sufficiently large to supply the generation shortage, then the restoration time is extended to include hour t . Otherwise, the supply cannot be restored at hour t and the interruption duration of LP_i under failure registered at hour h ($ID_{DG\ i,j,GS,RS,h}$) extends from the failure start until hour t . Once the restoration of hour t is not possible even with the support of energy storage, the next critical LP is assessed by taking into account the load and the energy storage demand of more critical LPs previously restored. The described procedure is repeated for all the LPs within the isolated area and their contribution to interruption duration $ID_{DG\ i,j}$ is obtained.

Charge and discharge simulation of ESS devices

During the fault period, the available power from intervals with generation excess (P_{char}) is used to charge the ESSs and the required power to balance the generation shortage (P_{disch}) is used to discharge the ESS according to (4) and (5) respectively. Rated powers to charge ($P_{ESS,rate}^{char}$) and discharge ($P_{ESS,rate}^{disch}$) the ESS devices are considered, while maximum and minimum permissible levels of charge SOC_{max} and SOC_{min} in (6) are preserved.

$$SOC = SOC + \min(P_{char}, P_{ESS,rate}^{char}) \quad (4)$$

$$SOC = SOC - \min(abs(P_{disch}), P_{ESS,rate}^{disch}) \quad (5)$$

$$SOC_{min} \leq SOC \leq SOC_{max} \quad (6)$$

CASE STUDY: RELIABILITY IMPACT OF DG AND ENERGY STORAGE

Test Network

The proposed methodology was applied to a real 15 kV distribution network feeder. Originally, the network did not include DG units but they have been allocated for analysis as Fig. 3 shows.

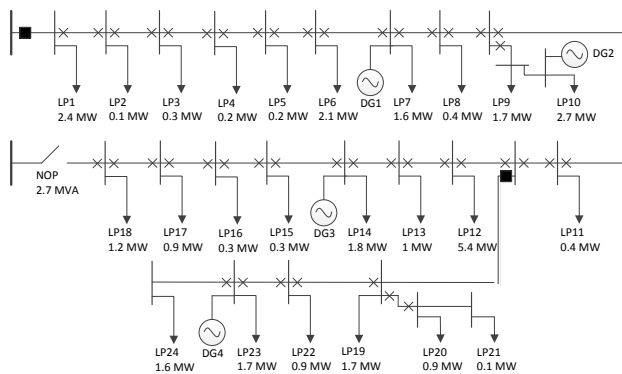


Fig. 3 Topology of the test network

Reliability indices of components in the network are $\lambda=0.04$ failures/year km, $r=8$ hours/failure for lines; and $\lambda=0.015$ failures/year, $r=10$ hours/failure for secondary substations. Protection devices and NOP are assumed to be 100% reliable and their switching time is 1 hour. Hourly load demanded over a year was modelled by the typical day of each month. It was assumed all LPs having the same profile shape.

The System Average Interruption Duration Index (SAIDI) is the reliability index analysed because it provides useful information to quantify the impact of DG and energy storage on interruption duration. In the original network, SAIDI was 7.36 hours of interruption by customer in a year (designed as Ref Case in Fig. 4).

Reliability impact of DG

Contribution of DG to restore the interrupted supply was evaluated by allocating four generators (DG1-DG4) in the original network as Fig. 3 shows. Their parameters affecting reliability are summarized in TABLE 1. Conventional, PV and wind generation technologies were compared in three scenarios assuming the same technology of all DG units in each scenario. Representative time-segments based on typical days of each month in the year were used for PV and wind generation similarly to load modelling. DG rated power of 25, 50, 75 and 100% the yearly load peak were evaluated in order to compare the reliability impact at different levels of DG integration.

TABLE 1. Related-reliability parameters of DG units

DG unit	λ (f/yr)	r (hr/f)	Start time
Conventional	1	48	1
PV	1	90	0.5
Wind	1	60	0.5

Comparison of generation technologies demonstrated that conventional and wind generation introduced significant reliability improvement compared to the original network. SAIDI reductions from 30 to 73% for conventional technology and from 16 to 62% for wind technology were obtained at DG rated powers between 25 and 100% of yearly peak load. However, SAIDI reductions for PV DG at these rated powers were limited from 3.6 to 14%. The variability of the generation profile was the main cause of this limitation.

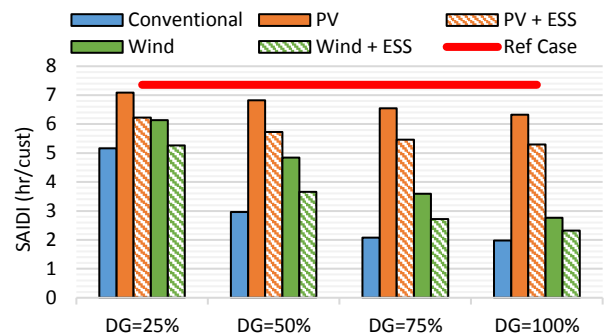


Fig. 4. SAIDI variation for DG and Energy Storage integration

Reliability impact of Energy Storage supporting DG

One ESS was installed with each PV and wind DG unit described previously. The aim was to evaluate the reliability impact of energy storage supporting DG during periods of generation shortage under fault conditions. Size of ESS was determined by means of the storage capacity and the rated power of charge and discharge. In order to relate the storage capacity of ESS and the size of DG units, the Storage Capacity Ratio (SCR), defined as the ratio between the capacity of the ESS and the rated power of the DG, was used. The analysed rated powers to charge and discharge the ESS were assumed to be equal and they were selected by taking into consideration the power demanded by the LPs in the network. The ESS were assumed to be completely charged when the fault occurred.

A significant SAIDI reduction is shown in Fig. 4 when energy storage was combined with DG. In these results, ESS was sized with SCR equal to 2 and rated powers of 2 MW. Integration of ESS in PV DG of rated power over 25% reduced SAIDI in one hour of interruption by customer (14%) approximately. Relevant reduction were also obtained for wind DG scenario integrating energy storage, stressing the reduction of 1.18 hours (16%) in SAIDI at 50% of DG rated power.

Storage Capacity and Rated Power Assessment

The impact of energy storage parameters like capacity and rated power on reliability is addressed in this section. Firstly, energy storage with SCR from 0.5 to 2 were

analysed at a 2 MW constant charge/discharge rated power. SAIDI results for wind DG case are given in Fig. 5. While SAIDI reductions were recorded at all analysed SCR values for DG rated powers of 25 and 50%, increasing the storage capacity over SCR larger than 1 at DG rated power of 75 and 100% could not reduce SAIDI because the rated power of ESS was limiting the restoration, both in PV and wind DG. For example, the SAIDI reductions obtained at SCR equal to 1 in Fig. 5 were 24% and 16% at wind DG rated power of 75 and 100%, respectively

Secondly, the impact of ESS rated powers from 0 to 3 MW was addressed at constant SCR of 2. The reliability improvement caused by the ESS rated powers was more significant than the storage capacity assessed previously, as comparison of Fig. 5 and Fig. 6 shows for wind DG. The SAIDI reductions when compared to the case without energy storage were more significant at DG rated power equal to 50 and 75%. Increasing the ESS rated power in 0.5 MW reduced a 5-6% the SAIDI for wind DG and around 4% for PV DG. However, this SAIDI reduction was limited at DG rated power of 25%, and ESS rated power over 1.5 MW because of the storage capacity and generation limitations.

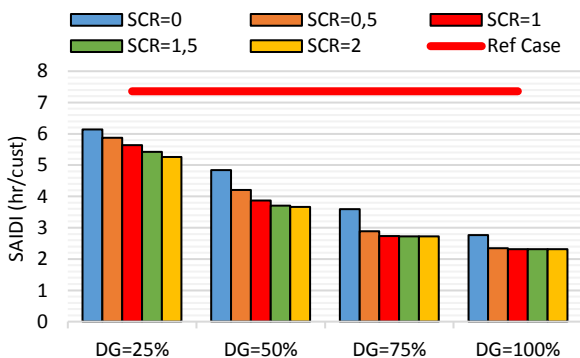


Fig. 5. SAIDI at different storage capacity values (Wind DG)

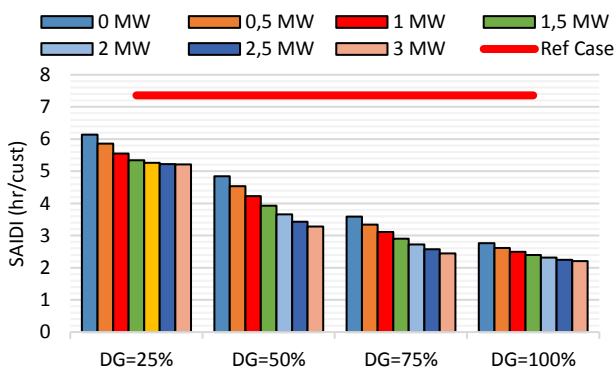


Fig. 6 SAIDI at different storage rated power values

CONCLUSIONS

Penetration of DG and energy storage in distribution networks is increasingly relevant and their impact on reliability of supply needs to be assessed. This paper proposes a new analytical formulation to assess the

reliability impact of energy storage supporting DG for restoration of interrupted supply in isolated network areas under fault conditions. It has been explained how the restoration strategy proposed takes into account the hourly time dependent patterns of load and renewable generation during the fault in order to assess the potential of DG and simulate the charge and discharge of ESS.

The reliability impact of a real distribution network with integrated DG and ESS has been evaluated by using the proposed methodology. It was found both conventional and wind DG technologies were capable of improving reliability significantly, unlike PV whose contribution was limited. It was shown that by integrating energy storage, the restoration capability of PV and wind can be increased providing in most cases a better solution compared to only increasing the rated power of generation. Additionally, the sensitivity analysis of storage capacity and storage rated power demonstrated the bigger impact of the rated power on network reliability compared to the size of storage capacity.

Acknowledgments

The authors kindly acknowledge the support of the Spanish Ministry of Economy and Competitiveness project RESmart (ENE2013-48690-C2-2-R).

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