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Reliability enhancement through optimal placement of photovoltaic power plant and battery energy storage in distribution system

K.Džodić[1], J. Krstivojević[1], O. Abarrategi[2], P. Eguia[2]

[1] Department of Power Systems
School of Electrical Engineering, University of Belgrade
Belgrade, 11000 (Serbia)

[2] Department of Electrical Engineering
University of the Basque Country (UPV/EHU)
Plaza Ing. Torres Quevedo 1, 48013 Bilbao (Spain)
Phone/Fax number:+0034 946014971

Abstract. Integration of distributed generation (DG) units could reduce the duration of power outage for a certain number of consumers in distribution networks after a network failure. Prerequisites are that i) the DG unit has the technical characteristics that enable its islanded operation, the degree of automation of the distribution network allows it and ii) it is in accordance with the current technical regulations of the country. The extent to which integration of distributed sources can improve reliability depends on the DG size, type, and the point of common coupling. Besides, an energy storage system could be installed along with DG unit, so that energy supply availability during fault periods can be secured. This paper proposes an algorithm based on mixed-integer linear programming (MILP) approach for optimal placement of photovoltaic power plant (PVPP) and battery energy storage system (BESS). The optimal location is determined so that expected non supplied energy is minimized. The uncertainties in the estimation of production of PVPP, load and BESS state of charge (SoC) were taken into account by Monte Carlo simulations (MCS).

Key words. Distribution system, PV plant, battery energy storage, MILP, Monte Carlo simulation.

1. Introduction

In recent decades, the integration of renewable energy sources (RES) in distribution networks, in form of small-scale DG units, has posed many challenges in the distribution system planning. Assessing the reliability of distribution systems is a complex problem, which is influenced by a number of factors, including failure rate, component repair or replacement times, system configuration, degree and load variability, and now even generation variability. Numerous studies have been conducted regarding how the integration of DG units affects the reliability of the distribution system [1], [2]. The RES generation is influenced by multiple factors such as meteorological conditions and geographical location. As pointed out in [1], [2], the application of a universal model to all forms of RES, or the employment of models designed for traditional generators, are subjected to significant obstacles.

In this paper, the DG unit of interest is a PV power plant (PVPP). Due to their low operating costs, scalability, quiet operation and other benefits, PVPPs are widespread DG technology, with applications ranging from low and medium voltage (MV) to high voltage networks. For example, by feeding electricity directly into the MV level, PVPPs can back up supply, especially in areas where the grid infrastructure is less robust. This integration can lead to improved reliability and supplying costumers even when there is failure in the distribution network. The optimal location to place a PVPP depends on the topology of the network, positions of automation devices, consumer loads, as well as the size of the unit installed. Still, PVPPs cannot assure stable supply for an isolated island, so that voltage and frequency are maintained within permissible range, meaning that additional infrastructure is needed. In [3], it was shown the BESS effect for the system in terms of non-supplied energy reduction. Therefore, the simultaneous integration of PVPP and BESS (PVPP+BESS) is explored, to mitigate the shortfall in energy supply to either one node or island containing several load points. To achieve best reliability improvement, connection points should be chosen strategically.

This paper proposes a methodology for determining the optimal location for installation of PVPP+BESS in order to minimize energy not supplied to end-users. The proposed approach incorporates the uncertainty modelling through the combined use of MILP and Monte Carlo simulation. Section 2 presents the fault treatment process, MILP formulation and uncertainty modelling. In Section 3 the proposed approach is applied to the RBTS Bus 4 system. Conclusions are drawn in Section 4.

2. Methodology

A. Fault treatment process

The principle of DG operation in the distribution network in response to a fault, impacts the development of fault treatment procedures. Three basic interface modes for DGs were presented in [4], whereby, a mode of dynamic island creation is considered in this paper. A diagram illustrating the distribution feeder configuration in this interface mode is shown in Fig. 1. In this operational mode, DG can provide power for additional loads along the feeder line, in accordance with its available capacity. As depicted in Fig. 1, following a distribution feeder failure, circuit breaker CB1 and CB2 will open, and DG will step in, to supply power to load A. Subsequently, remote circuit switch RCS1 is disconnected to isolate the fault, and depending on DG available production, it is determined whether to reconnect CB2 to energize load C. This mode facilitates the enhancement of power supply reliability within the distribution system. End-users in load A won't feel any supply interruption due to the fault, while those in load C experience the interruption of duration equal to time needed for RSC to isolate the island, T_s. For end-users in load B, the interruption lasts as long as fault repair, T_f.

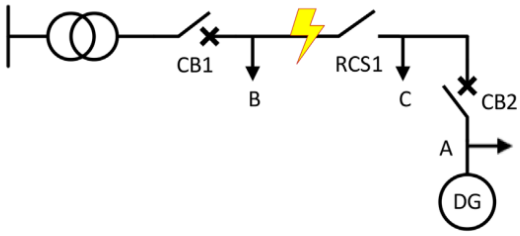

Fig. 1. Dynamic creation of island after fault, [4]

B. MILP formulation

The optimization aims to minimize reliability indicator Expected Energy Not Supplied (*EENS*), defined by following expression, [5]:

$$\min EENS = \sum_{i=1}^{N_p} P_i \sum_{j=1}^{N_l} \lambda_j d_{ij} \ , \qquad (1)$$

where N_p is the number of nodes in network, N_l is the number of components that when failured will interrupt power at load point *i*, λ_j is the failure rate of the *j*-th component, d_{ij} is the failure duration at load point *i* when failure at element *j* happens, and P_i is the load at node *i*. The variable d_{ij} can take the values T_s, T_f, or zero, depending on node's relative position to the faultand island supplied by PVPP+BESS.
The binary variable ind_i indicates whether or not node *i* is optimal for PVPP+BESS placement, by assigning it value 1. Also, the node without PVPP+BESS working in the island is indicated by setting the binary variable isl_i to the value 1.

The following equality constraint dictates that there should be only one PVPP+BESS placed in the network:

$$\sum_{i=1}^{N_p} ind_i = 1 \ . \qquad (2)$$

Besides, power balance in the island is ensured by:

$$P_{PV} + P_{batt} - \sum_{i=1}^{N_p} P_i \cdot ind_i - \sum_{i=1}^{N_p} P_i \cdot isl_i \geq 0 \ , \qquad (3)$$

$$-P_{batt}^{nom} \leq P_{batt} \leq P_{batt}^{nom} \ , \qquad (4)$$

where P_{PV} is generation power fom PVPP, P_{batt} is charging/discharging power limited by nominal storage power P_{batt}^{nom}. Positive P_{batt} values refer to discharging mode, while negative are for charging.

Another two auxiliary constraints are added to ensure distinction between node with PVPP+BESS system and nodes without it, but working in the same island:

$$ind_i + isl_i \leq 1, \ , \qquad (5)$$

$$-ind_i + isl_j \leq 0, \qquad (6)$$

where in (6) $\forall_j$ belonging in the same zone as *i*.

Nodes equipped with PVPP+BESS, and other nodes within the island could experience the reduced duration of failure. However, if the battery lacks sufficient energy at the time of the fault, the failure will last for the duration of the battery discharging (T_{isl}), which is determined by the following expression:

$$T_{isl} = \frac{W_{batt}^{nom}(SoC - 0.2)}{P_{batt}} \ . \qquad (7)$$

where W_{batt}^{nom} refers to nominal BESS energy capacity, and SoC is a percentage that indicates the current level of energy in a battery compared to its maximum capacity with values in the range [0.2, 1] p.u. Usually, maintaining a minimum SoC of 20% ensures the battery does not fully deplete, helping to prolong its lifespan and reliability.

The optimization results in optimal node for integrating PVPP+BESS and optimal *EENS* value obtained.

C. Probabilistic approach

Probabilistic approach is a general method to address the uncertainties in a various range of engineering problems.
The power generation from a PVPP plant is a direct function of the site's weather conditions like solar irradiance, temperature, cloudiness, wind speed, and humidity. The beta probability density function (PDF) is highlighted as the most appropriate for capturing the variability of solar irradiance. The model is defined as follows [6]:

$$PDF(S) = \begin{cases} \frac{\Gamma(k'+c')}{\Gamma(k')\Gamma(c')} S^{k-1}(1-S)^{c'-1}, 0 \leq S \leq 1 \\ 0, \ \ otherwise \end{cases} \qquad (8)$$

Where *k'* and *c'* are parameters of beta PDF and *S* is normalized solar irradiation power.

In this study, the horizontal irradiation profile of a PVPP with a rated capacity of 1 MW, situated nearby Belgrade (Lat. 44.82° N, Lon. 20.28° E, altitude: 99 m a.s.l.) and assessed over a typical meteorological year, was determined by [7]. The beta PDF's parameters were derived based on the obtained hourly time series data (Fig. 2), and are estimated to be: $k' = 0.926$ and $c' = 1.087$. These parameters were used while generating PVPP available generation at the moment of fault.

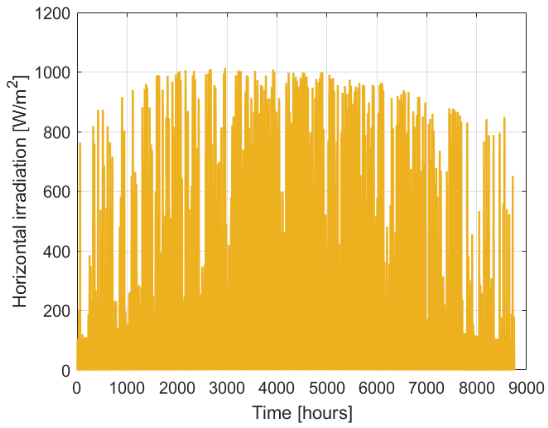

Fig. 2 Solar horizontal irradiation time series with an hourly resolution

In addition, the uncertainty of load and SoC were also taken into account by a uniform distribution model. The load in each node is randomly assigned in the range of [80,100]% of the base load, while the SoC value of BESS in the moment of fault is randomly assigned from the uniform distribution in the range [20,100]%.

D. Algorithm

The proposed algorithm for reliability enhancement through optimal placement of PVPP and BESS in distribution system is Monte Carlo simulation (MCS). The basic MCS concept involves running many simulations using uncertain variables and then aggregating the results to understand possible future outcomes. The algorithm is performed through the following steps:

1) Specify PDFs for uncertain parameters, namely: P_{PV}, P_i and *SoC*.

2) Set a maximum number of iterations.

3) Sample the uncertain parameters to generate specific numeric values for optimization input.

4) Solve MILP problem for each sampled set of input variables.

5) Record the optimal values obtained from each MILP problem solution.

6) Analyze the distribution of these optimal values to understand the solution space under uncertainty.

7) Present the results as probability distributions of optimal node to the decision maker.

The algorithm's flowchart is shown in Fig. 3.

3. Simulation

A. Initial Data

Previously described algorithm is tested on Roy Billinton Test System (RBTS) Bus 4, shown in Fig. 4. Nodes are labeled with numbers in black and branches are marked with numbers in red color. It is fed from a primary substation 33/11 kV/kV connected to three supplying points where each supply point is connected to a set of 11 kV feeders. The RBTS Bus 4 is described in detail in [8], while Table I provides a summary of system data such as a set of load points, CBs and RSCs positions. There is a CB at the beginning of each feeder, marked with a square, and RCS somewhere around the middle of each feeder's length, marked by circles on Fig. 4. Only single, permanent faults in the distribution network lines were considered. Permanent failure rate for lines is 0.065 f/yr.km. Fault repair time, T_f, is assumed to be 1 hour, while the RCS switching time needed to isolate the island, T_s, is 0.1 hour. The assumption posits that upon island formation, there exists infrastructure enabling the secure and reliable operation of the isolated island.

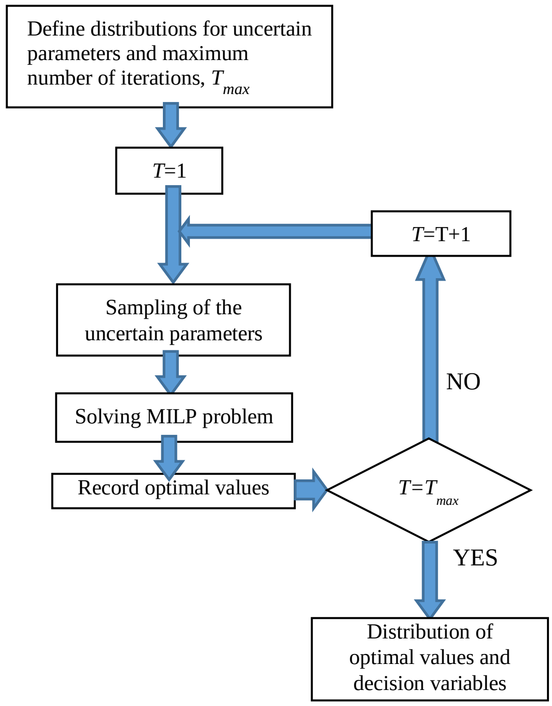

Fig. 3 Flowchart of the combination of MILP and MCS

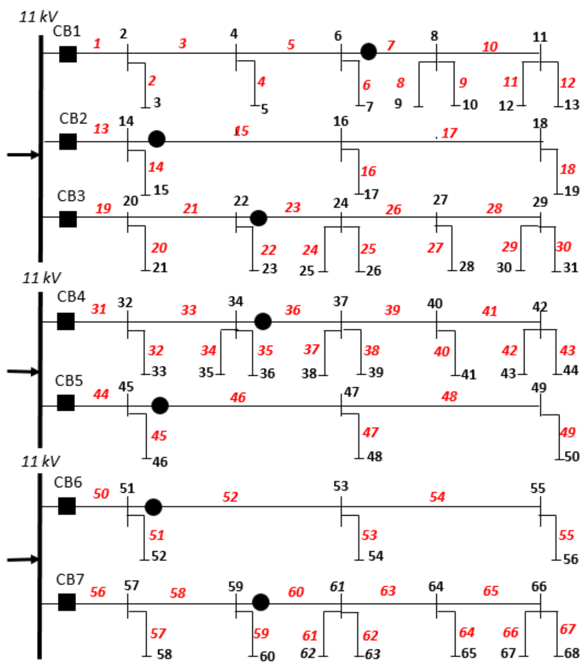

Fig. 4 Single line diagram of RBTS Bus 4 System, [8]

As per PVPP and BESS sizing, the quantities defined by the current regulations in Serbia have been adopted. It means that BESS power must amount to at least 20% of the installed active power of the power plant that uses variable RES, and the capacity of that storage must be at least 0.4 MWh/MW of the installed power of the power plant [9].

Table I. – Summary of RBTS Bus 4 data

CB locations	
Beginning of branches	1,13,19, 31, 44, 50, 56
RCS locations	
Beginning of branches	7, 15, 23, 36, 46, 52, 60
Load	
Load points	Load level per load point, avg. [MW]
3, 5, 7, 9, 21, 23, 25, 33, 35, 36, 38, 58, 60, 62, 63	0.545
10, 26, 28, 39, 41, 65, 67	0.5
15, 19, 46, 48, 50, 52, 54	1.0
17, 56	1.5
12, 13, 30, 31, 43, 44, 68	0.415

B. Results

The two criteria for selection of optimal node for PVPP+BESS integration that will result in minimal expected energy not supplied have been considered:

Criteria I: the optimal node is the one that has been obtained from the optimization solution most frequently.

Criteria II: the optimal node is the one with minimal average *EENS* value.

Maximum number of iterations is set to be 10 000. Different PVPP capacity was considered, from 1 to 5 MW, with proportional increase in BESS power and capacity.

The reliability indicator *EENS* for base case of RBTS Bus 4, without any additional equipment but those described in Table I equals to 14.14 MWh/yr.

For the five analyzed cases of integrating PVPP+BESS with different capacities, the results of optimal integration nodes as well as the average values of *EENS* are presented. Fig. 5 and Fig. 6 illustrate the optimal distribution of nodes and the dispersion of *EENS* values for PVPP capacities of 2 and 3 MW, respectively.

Table II presents a summary of the results for Criteria I and Criteria II.

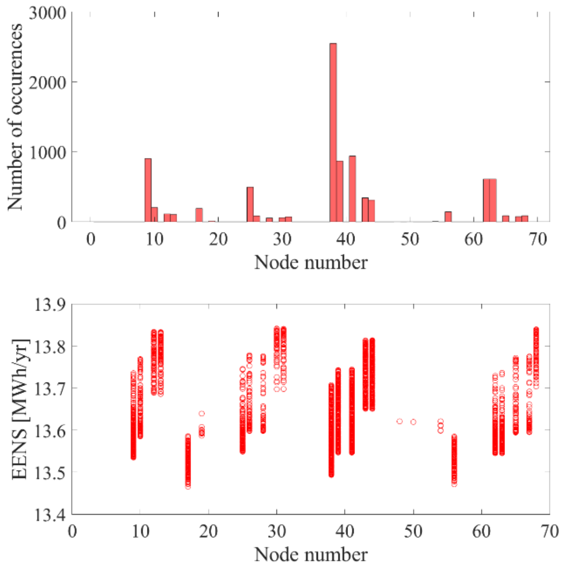

Fig. 5 Optimal nodes and *EENS* dispersion for PVPP of 2 MW

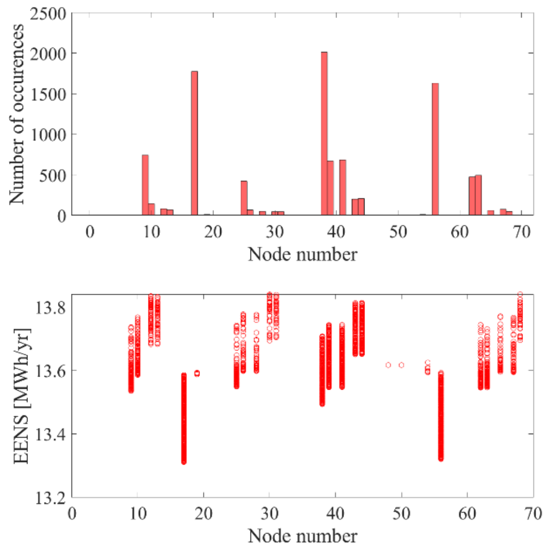

Fig. 6 Optimal nodes and *EENS* dispersion for PVPP of 3 MW

Table II. – Simulation results overview

Case 1: PVPP of 1 MW rated power		
BESS rated power [MW]/ capacity [MWh]	**Criteria I**	**Criteria II**
0,2 MW/ 0,4 MWh	Optimal node: **38** avg. *EENS* **13.578 MWh/yr**	Optimal node: **38** avg. *EENS:* **13.578 MWh/yr**
Case 2: PVPP of 2 MW rated power		
BESS rated power [MW]/ capacity [MWh]	**Criteria I**	**Criteria II**
0,4 MW/ 0,8 MWh	Optimal node: **38** avg. *EENS:* **13.5455 MWh/yr**	Optimal node: **17** avg. *EENS*: **13.5278 MWh/yr**
Case 3: PVPP of 3 MW rated power		
BESS rated power [MW]/ capacity [MWh]	**Criteria I**	**Criteria II**
0,6 MW/ 1,2 MWh	Optimal node: **38** avg. *EENS:* **13.5426 MWh/yr**	Optimal node: **17** avg. *EENS*: **13.434 MWh/yr**
Case 4: PVPP of 4 MW rated power		
BESS rated power [MW]/ capacity [MWh]	**Criteria I**	**Criteria II**
0,8 MW/ 1,6 MWh	Optimal node: **17** avg. *EENS*: **13.4197 MWh/yr**	Optimal node: **17** avg. *EENS*: **13.4197 MWh/yr**
Case 5: PVPP of 5 MW rated power		
BESS rated power [MW]/ capacity [MWh]	**Criteria I**	**Criteria II**
1 MW/ 2 MWh	Optimal node: **17** avg. *EENS*: **13.4169 MWh/yr**	Optimal node: **17** avg. *EENS*: **13.4169 MWh/yr**

Results of the optimization, as expected, include only the nodes located downstream of the RSCs. In general, Criteria I and II give different optimal nodes for connection, but there are also cases when the results are identical. Implementing Criteria I, node 38 is the optimal one for PVPP+BESS integration up to PVPPs of 3 MW rated power. When integrating PVPPs with either a rated power of 4MW or 5MW, node 17 emerges as the optimal choice in both cases. In case of implementation of Criteria II for integrating PVPP+BESS, the optimal solution is node 17 for PVPPs rated at 1MW, whereas for PVPPs with a rated power range from 2MW to 5MW, node 38 is identified as the optimal solution.

It can be concluded that implementation of Criteria I results in choosing nodes with lower load levels, but that are more likely to have consumption covered by available PV production and battery energy. However, the application of Criteria II results in a solution that leads to the largest reduction in *EENS*, although this occurs less frequently across iterations.

On Fig. 7 the percentage ratio between average *EENS* and the base value of *EENS* for each case is depicted. The *EENS* value decrease with integration of larger PVPP+BESS capacities. The greatest reduction can be expected with 5 MW in PVPP and 1 MW BESS/2 MWh capacity and it amounts 5.11% compared to the base *EENS* value.

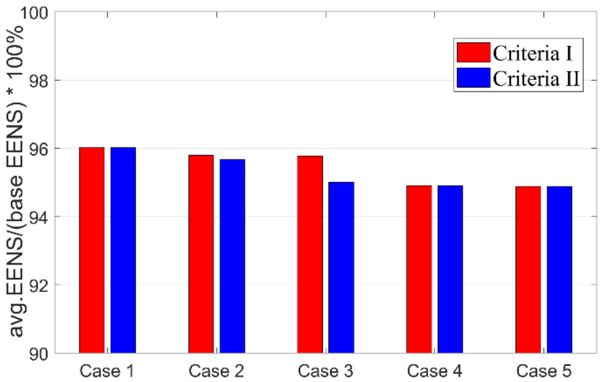

Fig. 7 The percentage ratio between average *EENS* and the base value of *EENS*

4. Conclusion

In this paper, a methodology for reliability enhancement through optimal location of PVPP and BESS in distribution system is presented. Improvement of reliability is achieved by determining which node is optimal in the network for connecting the PVPP and BESS system, aiming to minimize the value of the *EENS* indicator. The paper introduces an algorithm for implementing the proposed methodology. The algorithm's performance was tested and demonstrated on a test distribution system RBTS Bus 4. The advantage of the proposed methodology is that it incorporates combined use of MILP and Monte Carlo simulation, which considers uncertainties in estimating consumer load, PVPP production and BESS state of charge.

Future studies will focus on extending the proposed methodology to finding multiple nodes for DG and BESS integration. Additionally, efforts will be directed towards the development of an algorithm for the simultaneous placement of DG units and automation devices.

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