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Weighting Transmission Loading Relief Nodal Indexes for the Optimal Allocation of Distributed Generation in Power Systems

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Abstract

This paper presents a methodology for the optimal location of distributed generation (DG) in power systems using the Weighted Transmission Loading Relief (WTLR) nodal indexes. These indexes are used to guide a GRASP metaheuristic in charge of the optimal allocation of different DG units in a transmission network. The objective consists on minimizing the most negative WTLR indexes, which results in an increase of the system security. Several tests are presented in a representative prototype of the Colombian power system, evidencing the effectiveness of the proposed methodology. Results show that a proper allocation of DG units minimizes system overloads both in normal operation and under contingencies.

Keywords: Power systems, nodal indexes, distributed generation, GRASP

1 Nomenclature

The nomenclature used throughout the document is listed here for quick reference.
Sets:
Ω_b: Set of buses.
Ω_l: Set of lines.
Ω_g: Set of centralized generators.
Ω_c: Set of contingencies.
Ω_{GDn}: Set of new distributed generators.

Parameters:
$\bar{f_l}$: Maximum power flow limit in line l [MW].
x_l^{pu}: Reactance of line l [p.u].

Variables:
$Nviol$: Number of overloads in normal operation and under contingency.
$overload_{sys}$: Sum of system overloads in normal operation and under contingency [MW].
PCO_l: Overload of line l in normal condition [MW].
$PCO_{l,c}$: Overload of line l under contingency c [MW].
f_{lij}: Power flow in line l connected between nodes i, j in normal operation [MW].
$f_{lij,c}$: Power flow in line l connected between nodes i, j under contingency c [MW].
ISF_l^i: Injection shift factor of line l with respect to bus i in normal operation.
$ISF_{l,c}^i$: Injection shift factor of line l with respect to bus i under contingency c.
$LODF_{l,c}$: Load outage distribution factor of line l for contingency c.
DG_i: Distributed generation in bus i [MW].
CG_i: Centralized generation in bus i [MW].
Z_i: Binary variable indicating the allocation of a DG unit in bus i.
$\overline{DG}_i$: Maximum distributed generation capacity in bus i [MW].
$\overline{CG}_i$: Maximum centralized generation capacity in bus i [MW].
θ_i: Voltage angle in bus i [rad].
$\bar{\theta}$: Maximum voltage angle in bus i [rad].

1 Introduction

Distributed generation can be understood as the production of electricity by small-scale generation technologies in the distribution network or near the end user. There are many studies regarding the impacts of DG in both distribution and transmission systems. In [1] the authors propose an analytical method for optimally installing multiple DG technologies to minimize power losses in distribution systems. Different DG types are considered and their power factors are also taken into account. Other analytical methods for the optimal allocation of DG are also presented in [2] and [3]. The main advantage of analytical methods lies in fact that, along with classic mathematical techniques, the optimality of the solutions found is guaranteed. However, they usually resort to simplifications and linearization regarding the modelling of the network which makes their solutions less close to reality than other methods such as metaheuristic techniques. These techniques are better suited to deal with nonlinear and nonconvex optimization problems such as the optimal allocation of DG. Several metaheuristic techniques have been explored in this regard. In [4] the authors present a hybrid method based on optimal reactive power control and genetic algorithms to optimally allocate photovoltaic DG in a distribution system. In [5] the authors use an artificial bee colony algorithm for the optimal allocation of DG seeking power loss minimization; a similar methodology is presented in [6] using particle swarm optimization. Other metaheuristic techniques such as firefly algorithm [7] and tabu search [8] have also been applied to the optimal location of DG. The technical literature referring to DG studies is very extensive. A review on the impacts of DG and the methods for its correct location and sizing can be consulted in [9] and [10].

The location and sizing of DG can be seen from the point of view of the distribution or transmission network. When it is analyzed from the point of view of the transmission network, DG can be modeled as a net reduction of the demand in a given node [11]. In this paper, the objective of introducing DG in the power system is to improve its security. The latter is expressed in terms of the Weighted Transmission Load Relief (WTLR) nodal indexes. These indexes were initially proposed in [12] and can be used to verify if the installation of new DG units contributes to improve the security of the system. The WTLR indexes indicate the approximate change in the total overload of the system (in normal conditions and under contingency) that would be obtained with an additional injection of 1 MW in a particular bus. Such indexes can take negative or positive values. The receiving ends of overloaded elements have negative WTLR indexes, indicating that injecting power in these nodes produces counter flows that relieve the overload. The emitting ends of overloaded elements have positive indexes, indicating that injecting power in these nodes would worsen the overload. To reduce overloads in normal and under contingency conditions, key nodes can be selected to install DG in such a way that the magnitude of the WTLR indices is reduced; if the magnitude of these indices tends to zero, it means that there are no overloads in normal operation or under contingencies. In order to properly allocate DG, a GRASP (Greedy Randomized Adaptive Search Procedure) metaheuristic was implemented.

To test the effectiveness of the proposed methodology, a 93-bus prototype of the Colombian power system is used. Results show that the strategic allocation of DG units contributes significantly to the reduction of the WTLR indexes, indicating that the reliability of the system is improved.

2 Mathematical Model

The WTLR indexes quantify the level of overloads for normal conditions and under single contingencies (N-1 criterion). The magnitude of the index is proportional to the overloads. The objective function, given by (1) consists on minimizing the absolute value of the WTLR indexes. If these indexes tend to zero, it means that there are not overloads, neither in the base case, nor under any single contingency. The proposed optimization problem is given by (1)-(17).

$$Min \sum_{i \in \Omega_b} |WTLR_i| \tag{1}$$

Subject to:

$$WTLR_i = \frac{Nviol}{overload_{sys}} \left(\sum_{l\epsilon\Omega_l} ISF_l^i PCO_l + \sum_{l\epsilon\Omega_l} \sum_{c\epsilon\Omega_c} ISF_{l,c}^i PCO_{l,c} \right) \qquad \forall i \in \Omega_b \tag{2}$$

$$PCO_l = \sum_{l\epsilon\Omega_l} \left(f_{lij} - \bar{f}_l \right) \leftrightarrow f_{lij} > \bar{f}_l \qquad \forall l \in \Omega_l \tag{3}$$

$$PCO_l = 0 \leftrightarrow f_{lij} \leq \bar{f}_l \qquad \forall l \in \Omega_l \tag{4}$$

$$PCO_{l,c} = \sum_{l\epsilon(\Omega_l)} \left(f_{lij,c} - \bar{f}_l \right) \leftrightarrow f_{lij,c} > 1.2 * \bar{f}_l \qquad \forall l \in \Omega_l, \forall c \in \Omega_c \tag{5}$$

$$PCO_{l,c} = 0 \leftrightarrow f_{lij,c} \leq 1.2 * \bar{f}_l \qquad \forall l \in \Omega_l, \forall c \in \Omega_c \tag{6}$$

$$f_{lij,c} = f_{lij} + LODF_{l,c} f_c \qquad \forall l \in \Omega_l, \forall c \in \Omega_c \tag{7}$$

$$ISF_{l,c}^i = ISF_l^i + LODF_{l,c} ISF_c^i \qquad \forall l \in \Omega_l, \forall c \in \Omega_c \tag{8}$$

$$overload_{sys} = \sum_{l\epsilon(\Omega_l)} PCO_l + \sum_{c\epsilon\Omega_c} \sum_{l\epsilon(\Omega_l)} PCO_{l,c} \qquad \forall l \in \Omega_l \tag{9}$$

$$\left(\sum_{l\epsilon\Omega_l} f_{lji} \right) - \left(\sum_{l\epsilon\Omega_l} f_{lij} \right) + DG_i z_i + \sum_{i\epsilon\Omega_{GC}} GC_i = d_i \qquad \forall i \in \Omega_b \tag{10}$$

$$\sum_{i\epsilon\Omega_b} DG_i = \max DG \qquad \forall i \in \Omega_b \tag{11}$$

$$f_{lij} = \frac{(\theta_i - \theta_j)}{x_l^{pu}} \qquad \forall l \in \Omega_l \tag{12}$$

$$0 \leq CG_i \leq \overline{CG}_i \qquad \forall k \in \Omega_g \tag{13}$$

$$0 \leq DG_i \leq \overline{DG_i} \leftrightarrow z_i = 1 \qquad \forall k \in \Omega_{GDn} \tag{14}$$

$$-\bar{\theta} \leq \theta_i \leq \bar{\theta} \qquad \forall i \in \Omega_b \tag{15}$$

$$z_i \ binary \qquad \forall k \in \Omega_{GDn} \tag{16}$$

$$\theta_i = 0 \qquad \forall i \in \Omega_b \ /i = ref \tag{17}$$

The objective function given by (1) is subject to a set of constraints. Equation (2) defines the WTLR indexes. Equations (3) and (4) describe the conditions for determining the overloads under normal operation, while (5) and (6) describe the conditions for determining the overloads under single contingencies. In this case, overloads of up to 120% of the maximum capacity limit are allowed. Equation (7) allows the calculation of the post-contingency power flows of each line for each contingency through the LODF. Equation (8) represents the ISF of each line with respect to each node for each contingency. Equation (9) is used compute the total system overload. Equation (10) is the nodal balance constraint. Equation (11) determines the maximum allowable participation of DG. Equation (12) represents the DC linearization of power flows. Equations (13) and (14) represent the maximum limits of centralized and DG. The latter can only be taken into account if the associated binary variable is one. Equation (15) represents the limits of voltage angle. Equation (16) indicates the binary nature of variable z_i; and finally equation (17) indicates the reference angle. The mathematical model described by (1)-(17) is approached using a metaheuristic technique. In this case, due to its ease of implementation and effectiveness to deal with non-convex problems a GRASP metaheuristic was developed.

3. Implemented GASP metaheuristic

The implemented GRASP metaheuristic is composed of three phases (preprocessing, constructive phase and local search), which are explained below.

3.1 Preprocessing: In this stage, the WTLR indexes are calculated. With this information, the network buses are classified in order of criticality. Additionally, they are filtered by minimum demand, bar type and nodal index sign. This is done taking into account the following criteria: 1) DG units can only be located in buses with a minimum demand of 5MW; 2) only load buses are allowed to receive DG and 3) only nodes with negative WTLR indexes are considered as candidates for DG. This is because if a given bus has a negative index it means that a power injection in that node would alleviate post-contingency overloads.

3.2 Constructive phase: in this phase, a Reduced List of Candidates (RLC) is defined as a percentage of the buses suitable for DG implementation. These buses are randomly selected from those filtered in the preprocessing stage. A proposed solution (DG implementation plan) is then built with this list. A candidate solution is coded as a vector containing the indexes of buses where to allocate DG. The first element of the candidate solution is the bus with the lowest WTLR index, the rest of the elements are randomly selected from the RLC, until a specified limit of DG participation is reached. Once the DG assignment is completed, the objective function, given by (1) is evaluated.

3.3 Local search: Based on the solution found in the previous stage, a local search for better solutions is performed. The local search consists of changing the worst nodal index of the current solution for the best non-selected index of the RLC. Once this is done, the objective function is evaluated and it is checked if the new solution is better than the previous one; if the solution is better, it is saved; otherwise, it is discarded. The solution resulting from this stage is stored in a list of elite solutions.

4 Tests and Results

A 93-bus prototype of the Colombian power system was used to validate the proposed methodology. This system has 115 lines, 44 load buses and 48 generation buses. The data of this system can be consulted in [13]. A schematic of the system is presented in Figure 1.

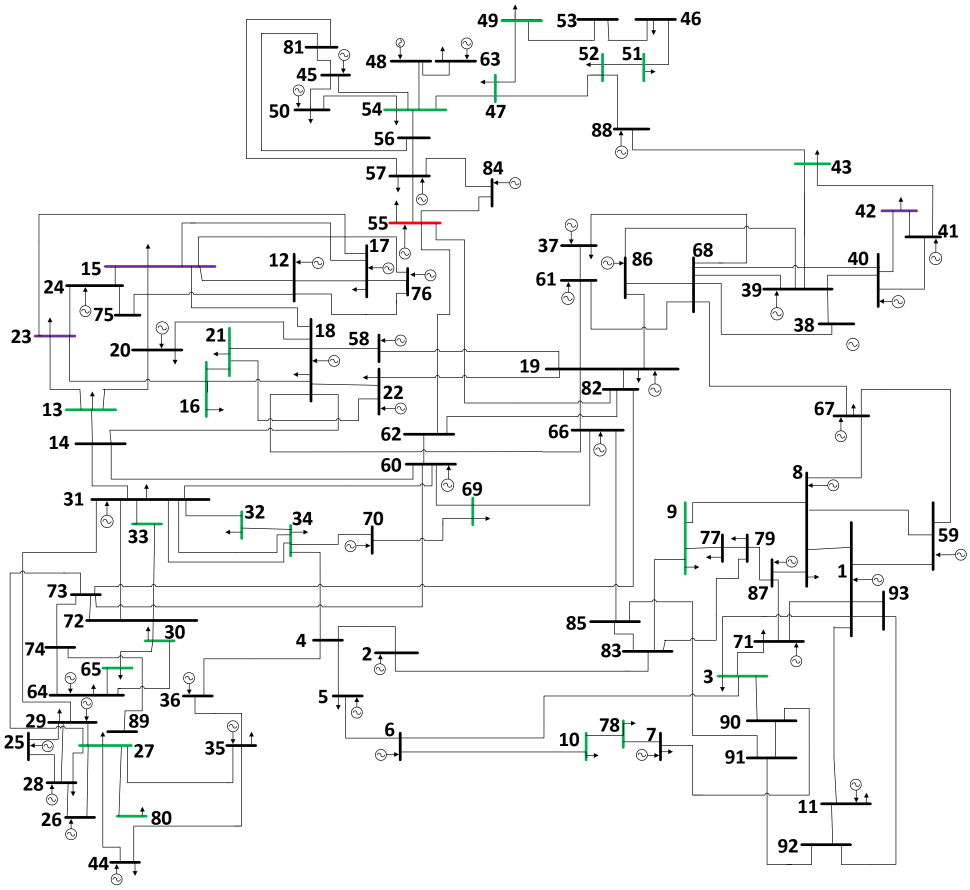

Figure 1: 93-bus representation of the Colombian power system

From the point of view of the transmission system, DG can be seen as a reduction in the net demand of a particular bus. For simplicity, the variability of some DG technologies based on renewable resources is not considered. On the other hand, several DG units located downstream of a sub-transmission or distribution network can be added up and viewed as a single equivalent generator. In this case, a total participation of DG of 100, 200 and 300 MW was considered. Furthermore, 5, 10 and 15 equivalent generators were assumed for each test. For example, when considering 300MW of DG, 5 equivalent generators of 60MW, 10 equivalent generators of 30MW and 15 equivalent generators of 20MW were assumed. The same was done for 200MW and 100MW of DG participation.

Case 1: Results considering 5 equivalent DG units

Figure 2 shows the WTLR indexes for 100MW, 200MW and 300MW of DG participation considering 5 equivalent DG units. It can be seen that as the participation of DG increases, the WTLR nodal indexes move towards zero in most of the buses. However, for bus 55, there are no improvements in the indexes with greater participation of DG. On the other hand, in the reference bus (bus 19) the WTLR index remains zero.

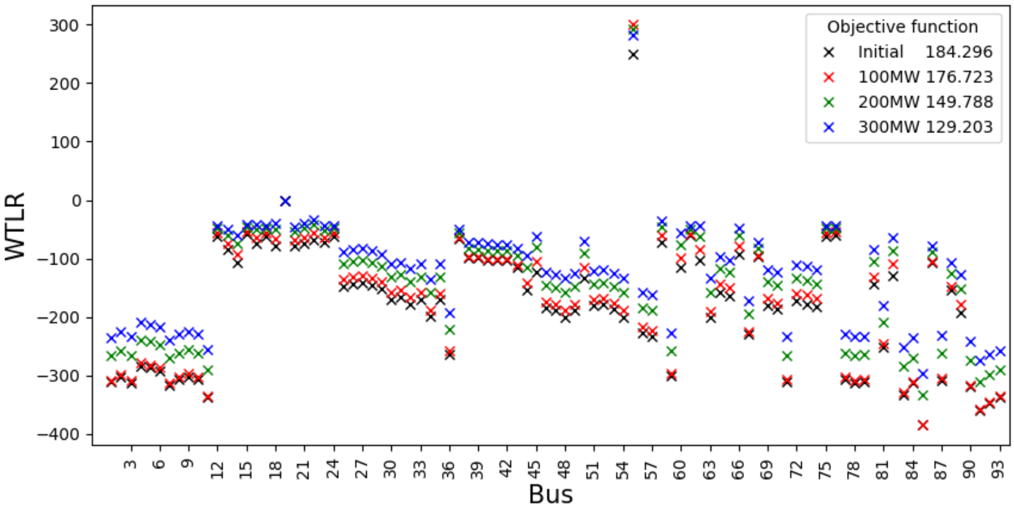

Figure 2: WTLR nodal indexes for case 3

Case 2: Results considering 10 equivalent DG units

Figure 3 shows the WTLR indexes for 100MW, 200MW and 300MW of DG participation, considering 10 equivalent DG units. When contrasting with Figure 2 it can be observed that by increasing the number of DG units (although the participation of DG remains the same) greater reductions in the WTLR indexes are achieved. As in the previous case, there are no improvements in the indexes in bus 55.

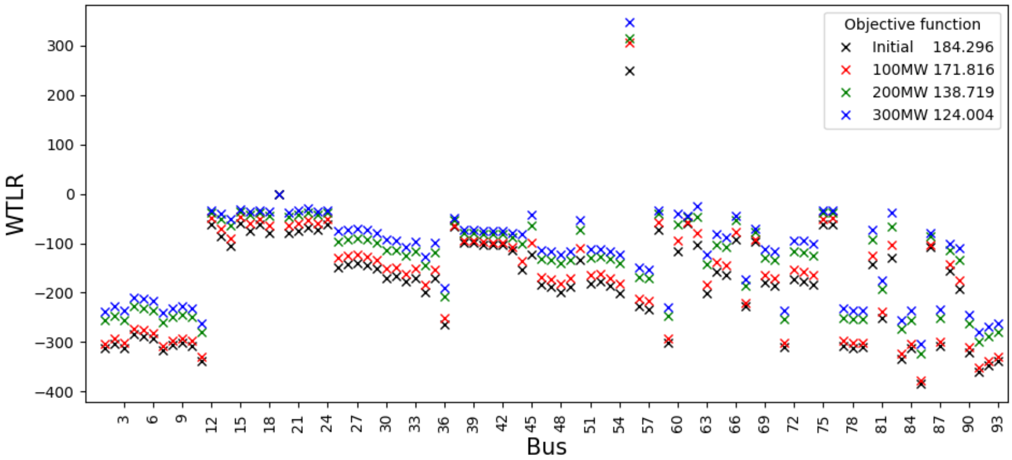

Figure 3: WTLR nodal indexes for case 3

Case 3: Results considering 15 equivalent DG units

Figure 4 illustrates the WTLR indexes for 100MW, 200MW and 300MW of DG participation, considering 15 DG equivalent units. Comparing with cases 1 and 2, it can be observed that as the number of DG units increases, the WTLR indexes decrease. This trend occurs for different levels of participation of DG as reported in Table 1. A summary of results is presented in Table 2. It can be seen that the algorithm always allocated DG in buses 15, 23 and 42. In Figure 1 these buses are marked in purple to differentiate them from other buses; additionally, the candidate buses to locate DG are marked in green, and bus 55 is marked in red. The latter was the only bus in which there were no improvements of the WTLR indexes.

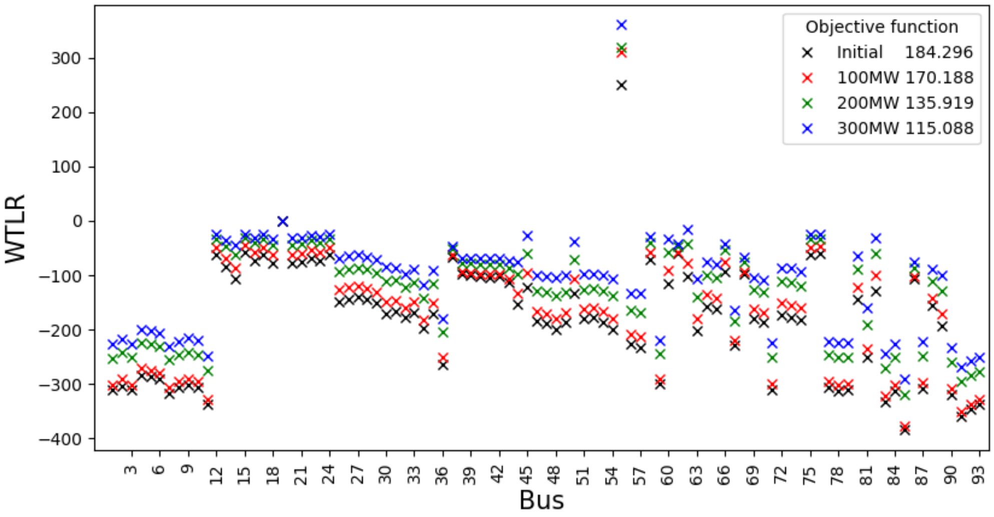

Figure 4: WTLR nodal indexes for case 3

Table 1. Percentage reduction of the objective function with respect to the initial case for different levels of DG participation and number of DG units.

	100MW	% Reduction	200MW	% Reduction	300MW	% Reduction
5	176,723415	4,11%	171,815604	6,77%	170,187619	7,66%
10	149,787894	18,72%	138,718894	24,73%	135,919375	26,25%
15	129,2028	29,89%	124,003565	32,71%	115,087807	37,55%

Table 2. Location of DG units for different levels of participation.

	5 DG units			10 DG units			15 DG units		
Bus	100MW	200MW	300MW	100MW	200MW	300MW	100MW	200MW	300MW
80	x						x	x	x
69						x	x	x	x
65						x	x	x	
52				x	x		x	x	x
51							x		x
49									
47									
43	x	x		x		x	x	x	x
42	x	x	x	x	x	x	x	x	x
34									
33				x			x	x	x
32				x	x			x	x
30					x	x	x	x	x
27				x	x	x	x	x	x
23	x	x	x	x	x	x	x	x	x
21		x	x	x	x		x	x	x
16			x		x	x	x	x	x
15	x	x	x	x	x	x	x	x	x
13				x	x	x	x	x	x

5 Conclusions

This paper presented a methodology for the optimal location of DG in power systems by means of a GRASP metaheuristic. The WTLR nodal indexes were used to guide the search. The tests carried out in a 93-bus prototype of the Colombian power system showed the applicability and effectiveness of the proposed approach. It was found that the optimal allocation of DG resulted in an important decrease of the WTLR nodal indexes. This indicates that overloads in normal operation and under contingencies are reduced due to the presence of DG. It was also observed that as the participation of DG was distributed in a greater number of buses, the decrease of the WTLR nodal indexes was greater. It is worth mentioning that the DG does not always have a positive impact in the network, in preliminary tests it was verified that the inappropriate location and sizing of the DG worsens the operating conditions in both normal and under contingencies. The latter highlights the usefulness of specialized methodologies for the correct location of the DG as the one described in this paper. In a future work, the impact of the variability of the GD on the security of the system will be studied and other optimization techniques will be implemented to compare its performance.

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References

[1] K. Mahmoud, N. Yorino, A. Ahmed, Optimal Distributed Generation Allocation in Distribution Systems for Loss Minimization, *IEEE Trans. Power Syst.*, **31** (2016), 960-969. https://doi.org/10.1109/tpwrs.2015.2418333

[2] P. Kumawat, Sarfaraz, A. Tandon, An analytical approach for optimal allocation of DG unit in distribution system, *2016 IEEE 7th Power India International Conference (PIICON)*, (2016), 1-6. https://doi.org/10.1109/poweri.2016.8077396

[3] R. K. Hosseini and R. Kazemzadeh, Optimal DG allocation by extending an analytical method to minimize losses in radial distribution systems, *2011 19th Iranian Conference on Electrical Engineering*, (2011), 1-6.

[4] I. Kim, Optimal distributed generation allocation for reactive power control, *Transm. Distrib. IET Gener.*, **11** (2017), 1549-1556. https://doi.org/10.1049/iet-gtd.2016.1393

[5] F. S. Abu-Mouti and M. E. El-Hawary, Optimal Distributed Generation Allocation and Sizing in Distribution Systems via Artificial Bee Colony Algorithm, *IEEE Trans. Power Deliv.*, **26** (2011), 2090-2101. https://doi.org/10.1109/tpwrd.2011.2158246

[6] A. M. El-Zonkoly, Optimal placement of multi-distributed generation units including different load models using particle swarm optimization, *IET Gener., Transm. Distrib.*, **5** (2011), 760-771. https://doi.org/10.1049/iet-gtd.2010.0676

[7] K. Nadhir, D. Chabane, B. Tarek, Firefly algorithm for optimal allocation and sizing of Distributed Generation in radial distribution system for loss minimization, *2013 International Conference on Control, Decision and Information Technologies (CoDIT)*, (2013), 231-235. https://doi.org/10.1109/codit.2013.6689549

[8] K. Nara, Y. Hayashi, K. Ikeda, T. Ashizawa, Application of tabu search to optimal placement of distributed generators, *2001 IEEE Power Engineering Society Winter Meeting. Conference Proceedings (Cat. No.01CH37194)*, (2001), 918-923. https://doi.org/10.1109/pesw.2001.916995

[9] Z. A. Kareem, W. F. W. Ahmad, J. Jasni, N. I. A. Wahab, A review on optimal location of distributed generation techniques in electrical network, *2016 IEEE International Conference on Power and Energy (PECon)*, (2016), 632-636. https://doi.org/10.1109/pecon.2016.7951637

[10] P. Sharma and A. Tandon, Techniques for optimal placement of DG in radial distribution system: A review, *2015 Communication, Control and Intelligent Systems (CCIS)*, (2015), 453-458. https://doi.org/10.1109/ccintels.2015.7437959

[11] M. J. Rider, J. M. Lopez-Lezama, J. Contreras, A. Padilha-Feltrin, Bilevel approach for optimal location and contract pricing of distributed generation in radial distribution systems using mixed-integer linear programming, *IET Gener., Transm. Distrib.*, **7** (2013), 724-734. https://doi.org/10.1049/iet-gtd.2012.0369

[12] S. Grijalva and A. M. Visnesky, The effect of generation on network security: spatial representation, metrics, and policy, *IEEE Trans. Power Syst.*, **21** (2006), 1388-1395. https://doi.org/10.1109/tpwrs.2006.879286

[13] A. H. Escobar, Análisis crítico de los aspectos de modelado matemático en el planeamiento de la expasion a largo plazo de sistemas de transmisión, UNESP, Ilha Solteira, 2008.

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