International Journal of Sustainable Energy, 2017
Vol. 36, No. 5, 473–488, http://dx.doi.org/10.1080/14786451.2015.1043913

Impact of penetration schemes to optimal DG placement for loss minimisation

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(*Received 27 February 2015; accepted 18 April 2015*)

This paper examines the impact of different penetration schemes to the optimal distributed generation placement problem for loss minimisation. The four variables of the problem are presented and a concept based on degrees of freedom (DoF), representing the number of the variables that undergo any kind of limitation during the solution process, is introduced. Four commonly utilised penetration schemes subject to various limitations are examined and compared with a fifth penetration scheme, which is unconstrained and is proposed as the optimal one. All schemes are implemented under a local-particle swarm optimisation-variant algorithm and applied on the IEEE 33 and IEEE 118 bus systems. The results indicate that the proposed penetration scheme with four DoF provides the optimal solution both in terms of loss minimisation and voltage profile improvement.

Keywords: optimal distributed generation placement; penetration schemes; PSO; loss minimisation

1. Introduction

The penetration of distributed generation (DG) power units in distribution networks (DNs) has been considered as an efficient way to exploit the benefits of sustainable energy promoted by distributed energy resources. In that sense, the installation of either small/medium-sized conventional power units or renewable energy sources (RESs) is increasing constantly, while engineers and researchers are investigating ways to define optimal allocation methodologies regarding both the sizing and siting of these power units. In most cases, appropriate consideration of DG installation can highly benefit the network in terms of loss reduction (Ackermann and Knyazkin 2002), voltage profile improvement (Abou El-Ela, Allam, and Shatla 2010) and reliability improvement (Mohandas, Balamurugan, and Lakshminarasimman 2015). On the other hand, high penetration levels could potentially cause problems to several operational characteristics of DNs, especially due to reverse power flow leading to excessive losses and feeder overloading (Méndez Quezada, Rivier Abbad, and Gómez San Román 2006). Thus, optimisation tools which provide both optimal locations and capacity of DG units to be installed should be highly appreciated by distribution system operators (DSOs).

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The optimal distributed generation placement (ODGP) problem generally deals with the determination of the optimum locations and sizes of DG units to be installed into existing DNs, subject to electrical network operating constraints, DG operation constraints as well as investment constraints (Georgilakis and Hatziargyriou 2013). In this paper, the ODGP problem of power resources in DNs towards loss minimisation is examined by focusing on the penetration scheme definition. So far, most of the proposed methodologies and algorithms for optimal siting and sizing of DG units are implemented subject to predefined constraints that are related to the number, the locations and the capacity of these units. However, the problem in these cases is that the solution itself is biased and the optimal solution refers to loss reduction given the aforementioned limitations, rather to loss minimisation based on the actual optimal number, location and size of the required DG units. For example, in Abou El-Ela, Allam, and Shatla (2010), Leeton et al. (2010), Abu Mouti and El-Hawary (2011a), and Kumar and Thakur (2014) an upper and lower limit for active and/or reactive as well as apparent power is used for each DG. That means that the proposed solution of the required DG capacity leading to minimum losses is restricted due to these limitations and thus it could be under question. In Hung, Mithulananthan, and Bansal (2010) and Hung and Mithulananthan (2013) a constraint is applied, concerning the total power of the DGs not exceeding the total active power load. In Abu-Mouti and El-Hawary (2011b) the total apparent power of the DGs must be within pre-established thresholds (i.e. between 10% and 80% of the total apparent power load). In Lee and Park (2009) the total active power of DGs must also be less than a pre-set limit which is also the algorithm's termination criterion. Finally, in Hu et al. (2013) there are constraints for both the active power of each DG and for the total active power of the DGs. More specifically, the active power of each DG must not exceed a pre-set threshold, and the total active power, of the DGs to be established, must be less than a prefixed fraction of the total active power load (i.e. penetration). A different approach addresses the problem of optimal siting and sizing as two separate optimisation problems and treats them as such in a sequential order (Iyer, Ray, and Ramakumar 2006; Viral and Khatod 2015). Finally, a different penetration scheme relates the optimal solution with the number of DG units to be optimally allocated. More specific, in Moradi and Abedini (2012), Moradi, Reza Tousi, and Abedini (2014) the problem is solved until a specific predefined number of DG units yield minimum losses.

In this work, the impact of DG penetration in the optimal solution is examined based on the concept that for the most efficient approach, all variables engaged in the solution procedure should not undergo any kind of limitations. Thus, it is essential to ensure that the number, the location and the size of the DG units will be determined by the solution algorithm, given only the objective function to be minimised (i.e. the power losses) and satisfying the technical constraints (i.e. node voltage margins and branch current limits, respectively). For this reason, the presented algorithm examines how the application of five different penetration schemes affects the optimal siting and sizing of DG units and the resulted reduction in distribution losses, aiming to prove that the more restricted the variables of the problem are, the less efficient the improvement will be. The four penetration schemes are defined based on the approaches of Iyer, Ray, and Ramakumar (2006), Lee and Park (2009), Abou El-Ela, Allam, and Shatla (2010), Hung, Mithulananthan, and Bansal (2010), Hung and Mithulananthan (2013), Leeton et al. (2010), Abu Mouti and El-Hawary (2011a), (2011b), Moradi and Abedini (2012), Hu et al. (2013), Kumar and Thakur (2014); Moradi, Reza Tousi, and Abedini (2014) and Viral and Khatod (2015), while the fifth penetration scheme is proposed in order to highlight that the algorithm should not be subject to any variable constraints when the actual optimal solution is examined. All penetration schemes are implemented under a particle swarm optimisation (PSO) algorithm regarding the siting and sizing of the DG units, and are tested on the IEEE 33 and IEEE 118 bus systems.

This paper is organised as follows: in Section 2, the five scenarios about the respective penetration schemes are presented and discussed. In Section 3, the problem formulation along with the solution algorithm are presented and analysed. In Section 4, the results regarding the application of the five penetration schemes on two benchmark DNs are illustrated. Finally, Section 5 is devoted to conclusions.

2. Penetration schemes

The ODGP problem is ideally solved when all four variables that compose the solution, that is, the number of DG units, their locations, the size of each DG unit and the aggregated DG capacity are optimised simultaneously. The latter is very crucial because if these aforementioned variables are optimised sequentially, usually the optimal locations are sought first, then the solution is highly possible to be biased (Iyer, Ray, and Ramakumar 2006). Therefore, it is essential to ensure that the solution algorithm is capable of dealing with the problem by optimising all variables simultaneously, thus taking into account the variables' interdependence during the solution process. A simple example of how the sequential optimisation procedure biases the final solution is the following: some proposed methodologies, especially those trying to solve the problem under analytical approaches, seek the solution by searching the optimal location and size of only one DG unit (usually with fixed capacity) under a sequential approach for loss minimisation. The problem in these cases is that when the second DG unit is examined to be optimally located, the losses are now different from the initial problem since this new search refers to a modified network with a DG unit already installed (Hung and Mithulananthan 2013). The problem is easily demonstrated by comparing this aforementioned approach with the one that examines optimal siting and sizing of two DG units simultaneously. The basic assessment arising from an extensive literature survey is that regardless of the optimisation technique, that is, the solution algorithm, the optimal solution depends on whether the four pre-mentioned basic variables of the problem are all included in the optimisation procedure simultaneously or not (Abu Mouti and El-Hawary 2011a, 2011b; Moradi and Abedini 2012; Moradi, Reza Tousi, and Abedini 2014; Viral and Khatod 2015). Therefore, in this work, we introduce the concept 'Degrees of Freedom' (DoF) to denote how many of the four variables engaged in the solution process undergo any kind of bias. For example, if the number of DG units to be optimally sited and sized is predefined with a fixed capacity for each DG unit, then the DoF in this approach are equal to two. Based on this new definition regarding how constrained is the solution of the ODGP problem, five penetration schemes with gradually increased DoF are defined and examined in this work. The first four penetration schemes are in correspondence with published methodologies (Iyer, Ray, and Ramakumar 2006; Lee and Park 2009; Abou El-Ela, Allam, and Shatla 2010; Leeton et al. 2010; Hung, Mithulananthan, and Bansal 2010; Hung and Mithulananthan 2013; Abu Mouti and El-Hawary 2011a, 2011b; Moradi and Abedini 2012; Hu et al. 2013; Kumar and Thakur 2014; Moradi, Reza Tousi, and Abedini 2014; Viral and Khatod 2015), while the fifth one is proposed in order to validate that as the DoF increase in number, the improvement is more evident.

(a) *Penetration scheme #1*: This penetration scheme adopts a very common approach regarding the total capacity of the DG units to be installed. More specific, the aggregated DG capacity to be installed is defined as a proportion of the total load capacity of the network. Moreover, the number of DG units to be optimally allocated is predefined, while the capacity of each DG unit results by dividing the aggregated DG capacity to the predefined number of the units. That means that all DG units have the same fixed nominal capacity. The DoF in this scheme are equal to one since three variables are somehow predefined, that is, the number, the size of each DG unit and the aggregated DG capacity. For this scheme, three different scenarios are examined as presented in Table 1. It has to be clarified that each penetration level is defined with respect to the total aggregated load of the network (i.e. DG capacity/Peak Load). Moreover, the selection of penetration levels for penetration schemes #1 and #2 is justified by the following: in these

Table 1. Examined scenarios for penetration scheme #1as applied in IEEE 33.

Penetration scheme #1			
Scenarios	Aggregated DG capacity as a proportion to the total load capacity (%)	Number of DG units to be optimally allocated	DG capacity for each DG unit (MW)
Scenario #1	30	3	0.372
Scenario #2	50	3	0.620
Scenario #3	70	3	0.868

schemes the total aggregated DG capacity is predefined, thus the value of the aggregated DG capacity to be installed defines the penetration level of the DG units.

It should be mentioned that penetration scheme #1 constitutes the optimal allocation of predefined DG units and thus it is far from being considered as the ODGP problem.

(b) *Penetration scheme #2*: This penetration scheme represents a variation of penetration scheme #1 with increased DoF. More specifically, the total DG capacity is again predefined as a proportion of the total load capacity of the considered network, but the number, the locations and the capacity of each DG unit are optimised by the solution algorithm. Thus, the DoF in this case are equal to three. Still, the solution could not be considered as the optimal one for the ODGP problem since the total DG capacity is predefined. The latter means that the problem in this case concerns the optimal allocation and sizing of a total predefined DG capacity but the capacity of each DG units will not be optimal since it is subject to the aggregated DG capacity.

(c) *Penetration scheme #3*: This penetration scheme aims to examine the impact of predefining the installation points of the DG units while allowing the algorithm to optimise the remaining three variables. More specifically, the installation locations provided by the penetration scheme #2 are set as fixed values regarding the siting variable of the DG units. Moreover, the number of the DG units is also predefined since one DG unit is considered for each installation point. Therefore, the DoF in this penetration scheme are equal to two, given that both the aggregated DG capacity and the size of each DG unit will be determined by the solution algorithm. The approach that focuses on the predefinition of the installation points is based on such methodologies as in Gil Mena and Martín García (2015), where specific network's nodes are prioritised based on specific sensitivity factors. The problem though is that despite the fact that all nodes of the network are prioritised based on their impact in loss reduction, only a limited number are arbitrarily considered for DG installation. Conclusively, the problem under this penetration scheme refers only to optimal sizing of DG units and again it should not be considered as the ODGP problem.

(d) *Penetration scheme #4***:** In this penetration scheme only the number of DG units is predefined. In fact, the number of DG units to be installed is not subject to any of the other variable of the problem and is arbitrarily defined. This is a case that meets many penetration strategies of DSOs since in many cases the size of the candidate DG units to be installed is relatively low, and thus out of concern, and the actual problem is to define the optimal installation locations. For this work, the penetration scheme #4 has three DoF since only the number of the units is predefined; the other three variables are optimised by the solution algorithm.

(e) *Penetration scheme #5***:** This penetration scheme proposed in this work is the one that most efficiently deals with the ODGP problem. The DoF are equal to four, thus all variables are optimised by the solution algorithm simultaneously taking into account variables' interdependence. Hence, none of the variable biases the solution, given that during the solution process, the optimal number of DG units, the optimal locations for the installation of these units, the optimal aggregated DG capacity and the optimal size of each unit are all provided by the algorithm

Table 2. Description of penetration schemes.

Penetration scheme	Variables				DoF
	Number of DG units	Installation points – locations	Aggregated DG capacity	Capacity for each DG unit	
#1	Predefined	Optimised	Predefined	Predefined	1
#2	Optimised	Optimised	Predefined	Optimised	3
#3	Predefined	Predefined	Optimised	Optimised	2
#4	Predefined	Optimised	Optimised	Optimised	3
#5	Optimised	Optimised	Optimised	Optimised	4

simultaneously. Thus, the penetration scheme #5 is the one that describes the ODGP problem under the most efficient formulation and this occurs because:

- there is no limitation regarding the aggregated DG capacity to be installed, thus loss minimisation is not subject to the total penetrated DG capacity;
- there is no limitation about the number of DG units, thus all network's nodes are candidate for DG installation;
- there is no limitation about the siting of the installation points due to the previous clarification and
- there is no limitation concerning the size of each DG unit, therefore there is neither a lower nor an upper limit for the DG capacity.

All information concerning the five penetration schemes examined in this work are summarised in Table 2.

3. Problem formulation and PSO

3.1. *Problem formulation*

The objective function in the ODGP problem describes loss minimisation due to the penetration of DG units and it is presented as follows:

$$F_{\text{loss}} = \min \sum_{\substack{i,j=1 \\ i \neq j}}^{n_l} g_{i,j}(V_i^2 + V_j^2 - 2V_iV_j\cos(\theta_i - \theta_j)), \tag{1}$$

where V_i is the voltage magnitude of bus i, V_j is the voltage magnitude of bus j, $g_{i,j}$ is the conductance between buses i and j, θ_i is the voltage angle of bus i, θ_j is the voltage angle of bus j, n_l is the total number of branches in the network and F_{loss} is the target/objective function to be minimised.

The problem expressed by Equation (1) is subject to the following operational constraints:

$$V_i^{\min} < V_i < V_i^{\max}, \tag{2}$$

$$S_{\text{branch}\,j} < S_{\text{branch}\,j}^{\max}, \tag{3}$$

where $V_i^{\max}$ and $V_i^{\min}$ are the lower and upper voltage limits for each bus, and $S_{\text{branch}\,j}^{\max}$ is the apparent power level of each branch.

The ODGP problem in this work is solved by a PSO algorithm and the objective function is minimised under the aforementioned constraints. These constraints are converted in penalty terms, as proposed in Leeton et al. (2010) and Engelbrecht (2007), and thus they are embedded in the updated objective function by the formulations that follow:

$$P(x) = f(x) + \Omega(x), \tag{4}$$

$$\Omega(x) = \rho\{g^2(x) + \max[(0, h(x))]^2\}, \tag{5}$$

where $P(x)$ is the penalty function (PF), $f(x)$ is the objective function (F_{loss}), $\Omega(x)$ is the penalty term, ρ is the penalty factor, $g(x)$ is the equality constraint referring to power flow equations and $h(x)$ is the inequality constraint.

Therefore, for the problem faced in this work the updated PF could be written as follows:

$$\text{PF} = \min[F_{\text{loss}} + \rho(\Omega_P + \Omega_Q + \Omega_V + \Omega_L +)], \tag{6}$$

with Ω_P and Ω_Q refer to equality constraints and Ω_V and Ω_L to inequality constraints, respectively.

3.2. *PSO algorithm*

Loss minimisation is a non-linear optimisation problem subject to several constraints and the dimensions of the problem could highly increase when solving the problem subject to optimal siting and sizing of DG units. The conventional approaches utilising analytical methods could be complex and time consuming in this case (Valle et al. 2008). Therefore, the problem is solved via a PSO algorithm which is considered to be an effective optimisation strategy due to its ability to provide efficient solutions under minimum computational effort. PSO was initially introduced in 1995 by Eberhart and Kennedy (1995), inspired by the social behaviour of bird flocking or fish schooling. Several versions have been developed since then (Shi and Eberhart 1998; Mendes, Kennedy, and Neves 2003; Hu, Shi, and Eberhart 2004) in order to adjust the methodology to different optimisation problems. In this work, the version of the local-PSO-variant (L-PSO-V) (Parsopoulos and Vrahatis 2010) has been utilised; this PSO version is differentiated with regard to the global-PSO-variant (G-PSO-V) by terms of global best particle definition. In the G-PSO-V version, each particle compares its personal best position found so far with the global best position within the swarm. In the L-PSO-V version, the global best is replaced by local bests, extracted by neighbourhoods that the particles form, thus they are actually the best positions within fictitious swarms which constitute only parts of the whole initial swarm. It should be mentioned that L-PSO-V has been chosen because, in contrast with its global counterpart, it improves the swarm's ability to avoid the local optima, due to its ability to provide a better balance between exploration and exploitation of the solution space. Thus, it could be considered more of a guarantee than global PSO, which is extensively used in papers, unlike the Local PSO. The concept of L-PSO-V is formulated as follows:

- If X_i is the ith particle of the swarm with $i = 1, \ldots, N$ then the neighbourhood (NB) of X_i is defined as $\text{NB}_i = \{X_{n1}, X_{n2}, \ldots, X_{ns}\}$, where $\{n_1, n_2, \ldots, n_s\} \subseteq \{1, 2, \ldots, N\}$ is the index set of its neighbours.
- $|NB_i|$ defines the size of the neighbourhood.
- P_{gi} indicates the best particle of neighbourhood NB_i, thus $P_{gi} = \arg\min f(P_j)$ with $j = n_1, n_2, \ldots, n_s \forall X_i \in \text{NB}_i$.

The structure of the neighbourhoods is performed under the ring topology. More specific, each neighbourhood is structured based on the particles' numbering as presented in the following expression:

$$\text{NB}_i = \{X_{i-r}, X_{i-r+1}, \ldots, X_{i-1}, X_i, X_{i+1}, \ldots, X_{i+r-1}, X_{i+r}\}. \tag{7}$$

In Equation (7), variable r defines the size of the neighbourhood and is called neighbourhood radius. The velocity and position of each particle are updated via the following expressions:

$$v_{ij}(t+1) = wv_{ij}(t) + c_1R_1(P_{ij}(t) - X_{ij}(t)) + c_2R_2(P_{gj}(t) - X_{ij}(t)), \tag{8}$$

$$X_{ij}(t+1) = X_{ij}(t) + v_{ij}(t+1), \tag{9}$$

where $i = 1, 2, \ldots, N$ and $j = 1, 2, \ldots, n$.
In Equation (8), the inertia factor w linearly decreases as follows:

$$w(t) = w_{\text{up}} - (w_{\text{up}} - w_{\text{low}})\frac{t}{T_{\max}}, \tag{10}$$

where t defines the iteration number of the algorithm implementation, w is the upper limit of inertia, w_{low} is the lower limit of inertia and $T_{\max}$ is the maximum number of iterations.

The complexity level of the L-PSO-V algorithm depends on the problem's dimensions which in turn determine the length of each particle. Each particle consists of two basic parts: (a) the number of DGs (or nodes) to be installed and (b) the demand of each node regarding the generated active power. The first part of each particle is in direct relationship with the following variables of the problem:

- the number of DG units
- the installation points

The selection of the DG units' number should determine the DoF regarding these two aforementioned variables of the problem. More specific:

- if $n_g < n_{\text{total}}$ (where n_g is the number of the candidate DG units to be installed in respective number of nodes and n_{total} is the total number of the DN's nodes) then the algorithm seeks for optimal siting and sizing of a predefined number of DG units. This is the case of penetration schemes #1, #2 and #3. That means that the highest possible DoF are equal to three. Moreover, if the installation points are also predefined, like in penetration scheme #3, then the DoF could decrease to two.
- if $n_g = n_{\text{total}}$ (proposed in this work) then the algorithm seeks for the optimal solution regarding (a) the number (since all nodes are candidate for DG installation) and (b) the installation points. Thus, in this case it is ensured that the DoF for the first two variables are also equal to two.
- if $n_g > n_{\text{total}}$ approach is redundant since the algorithm will result in the same solution as above, but through an unnecessary strain.

The second part of each particle directly affects the following two variables of the problem:

- the capacity of each DG unit
- the aggregated capacity of the DG to be penetrated

If any limitation is set regarding the value of either of these variables then the DoF concerning them will vary between zero and one. This is the case of penetration schemes #1 and #2. In this work, the value of the second part of each particle is not subject to any limitation, thus the DoF for the involved variable are equal to two.

In Table 3, the values of all variables included in the algorithm are summarised. All power flow analyses during the PSO implementation have been performed with the MATPOWER® software package (Zimmerman and Murillo-Sánchez 2011).

Table 3. Variable values for the proposed PSO algorithm.

Variable	Value
c1: coefficient of personal best	2.05
c2: coefficient of global best (here neighbourhood best)	2.05
w_{up}: inertia upper limit	0.9
w_{low}: inertia lower limit	0.4
p: penalty factor	10
N: number of particles in swarm	50
r: neighbourhood radius (neighbourhood size)	2
T_{max}: maximum number of iterations	1000
Convergence tolerance	10^{-7}

4. Results

4.1. *Examined DNs*

In this work, the impact of different penetration schemes to the ODGP problem is examined on two benchmark DNs. More specific, the L-PSO-V algorithm, presented in detail in Section 3, is applied on the IEEE 33 (Kashem et al. 2000) and IEEE 118 (Warkad, Khedkar, and Dhole 2009) bus systems. The selection of these two DNs is based on the following clarifications: the IEEE 33 bus system is a radial DN with no installed DG units, while the IEEE 118 bus system is a meshed network and a significant number of DG units are already installed. Therefore, the impact of the proposed penetration schemes is examined for both kinds of DNs. It should also be clarified that each penetration scheme is implemented via the presented PSO algorithm, in order

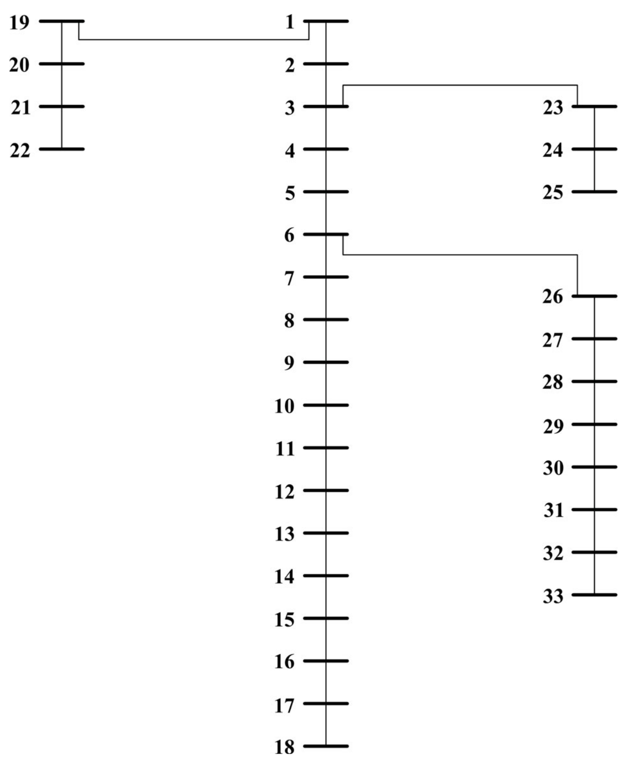

Figure 1. IEEE 33 bus system.

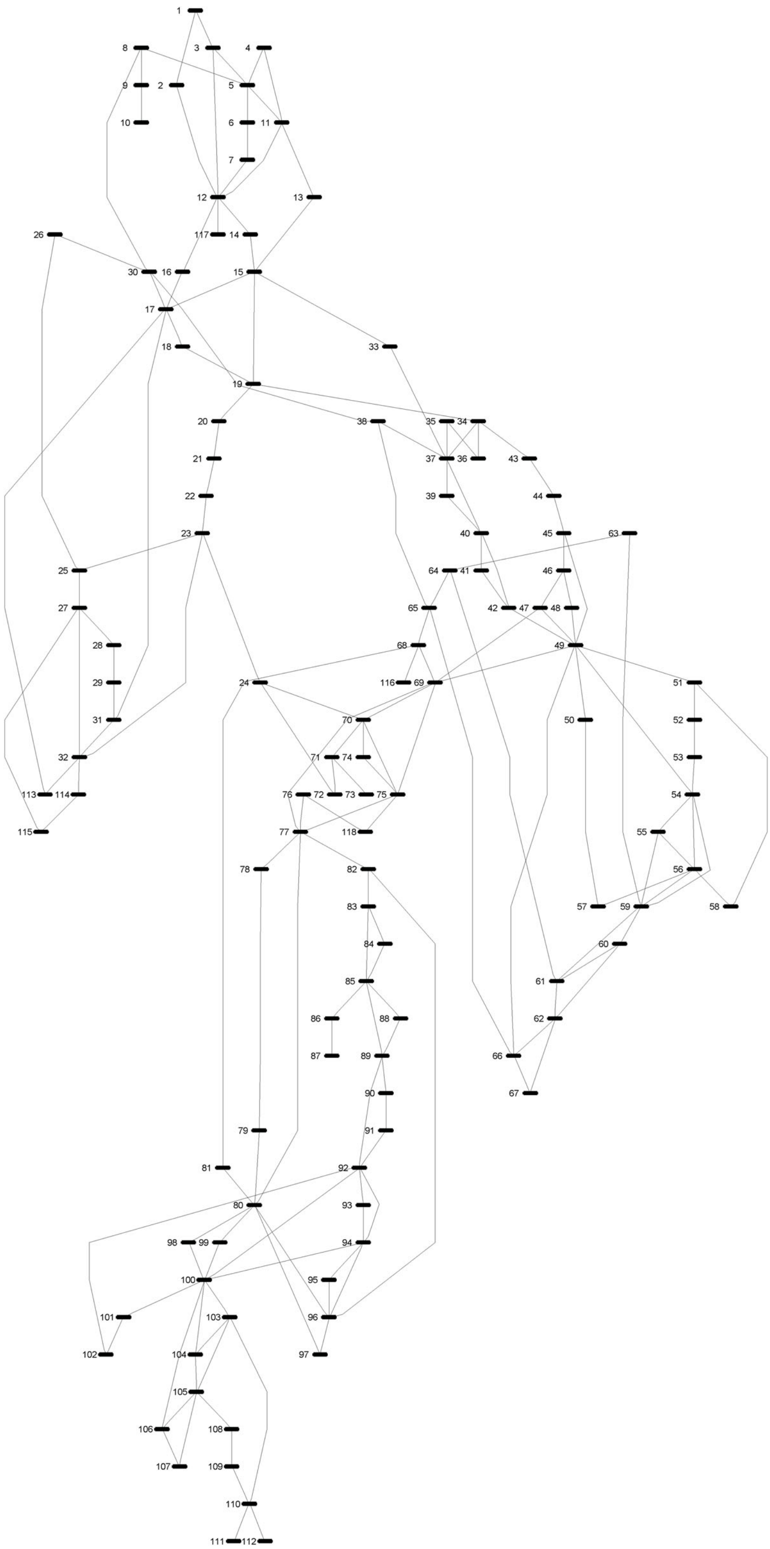

Figure 2. IEEE 118 bus system.

to ensure that the solution algorithm is common for all penetration schemes. That means that for each penetration scheme the PSO algorithm is applied under different DoF regarding the four involved variables, which in turn requires different formulations about the particles' dimensions. The layout of the two DNs is presented in Figures 1 and 2, while all the essential data about the DNs are provided in Table 4.

4.2. *Loss reduction and voltage profile for all penetration schemes*

In Table 5, the analytical results after the algorithm application for the 33 bus system regarding the five penetration schemes are presented. For schemes #1 and #2 with predefined aggregated DG capacity, the results in Table 1 refer to 50% penetration with respect to the total load of the respective DN.

The results in Table 5 show that among all penetration schemes, the proposed one in this work (i.e. scheme 5) with four DoF (all included variables in the ODGP problem are subject of

Table 4. Data for 33 and 118 bus systems.

DN data	33 bus system	118 bus system
Number of buses	33	118
Number of branches	32	186
DN load (active power in MW)	3.72	4242
DN load (reactive power in MVAr)	2.3	1438
Number of DG units installed	#	54
System generation (active power in MW)	#	4373.4
System generation (reactive power in MVAr)	#	0
DN losses for the initial configuration (MW)	0.211	132.86

Table 5. Results regarding the five penetration schemes for the 33 bus system.

Penetration scheme/DoF	Initial losses (MW)	Final losses (MW)	Loss reduction (%)	Nodes for DG installation	DG capacity (MW)	Aggregated DG capacity (MW)
#1/1	0.211	0.0845	59.9610	7	0.6200	1.8600
				14	0.6200	
				31	0.6200	
#2/3	0.211	0.0808	61.6929	8	0.3500	1.8600
				15	0.5113	
				25	0.2476	
				30	0.4359	
				33	0.3140	
#3/2	0.211	0.0678	67.8787	8	0.6303	2.9063
				15	0.5101	
				25	0.8298	
				30	0.6225	
				33	0.3136	
#4/3	0.211	0.0663	68.5707	6	0.7988	3.2242
				10	0.3913	
				16	0.3800	
				24	0.9677	
				31	0.6864	
#5/4	0.211	0.0644	69.5012	6	0.6858	3.4992
				8	0.3643	
				14	0.5365	
				21	0.2860	
				24	0.5199	
				25	0.4284	
				31	0.6783	

simultaneous optimisation) provides the highest reduction in terms of power losses. This is due to the fact that the solution is not biased by predefining one or more of the four basic variables of the problem. Therefore, the algorithm embeds the highest possible freedom concerning the exploration of the most efficient solution without being subject to the following disadvantages:

- if the value of one variable is initially and arbitrarily set then its optimality is not ensured;
- if the optimisation of the variables is not performed simultaneously (parallel optimisation) but under a sequential form, then it is highly possible to bias the solution.

One important conclusion derived by the results in Table 5 is that the more the DoF are in the solution algorithm, the better solution is provided. The only discord concerning this observation refers to scheme #3 which yields higher loss reduction than in case of scheme #2 although its DoF are less. This is due to the fact that although the installation points in scheme #3 are predefined, this predefinition is not completely incidental but it is based on the optimised installation points provided by scheme #2. Moreover, it should be clarified that scheme #5 is not subject to 50% DG penetration since the variable concerning the aggregated DG capacity is not subject to any limitation. Despite the latter, the optimal aggregated DG capacity resulted by the algorithm is comparable with the other schemes. The results indicate that the most crucial variable in the ODGP problem is the total DG capacity to be optimally sited and sized. This means that when the problem is solved under a predefined total DG capacity, the solution refers to a specific case study rather to an ODGP optimisation problem. The results provided by schemes #4 and #5 indicate that the DG units siting also plays an important role towards the optimised solution and finally, a high distribution of the DG units (i.e. the number of nodes to host such units) could also improve the solution in comparison to the case that limited and predefined nodes are considered as the only installation points.

In Figure 3 the results concerning the application of the five penetration schemes for the 33 bus system are presented. The three values of the penetration levels (i.e. 30%, 50% and 70%) concern only schemes #1 and #2 due to the fact that for these schemes the total aggregated DG capacity is predefined and thus it is not optimally computed. The other penetration schemes, that is, schemes #3, #4 and #5, are not subject to these penetration levels since for them, the algorithm allows the optimised aggregated DG capacity to be penetrated. The bar graph in Figure 5 shows that the penetration scheme #5 (the proposed in this work) yields the minimum losses in all examined

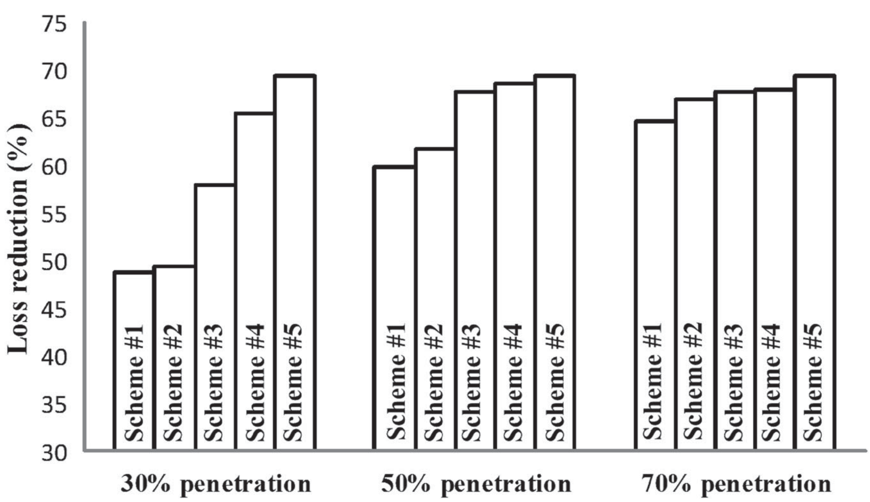

Figure 3. Loss reduction for the 33 bus system depending on penetration schemes.

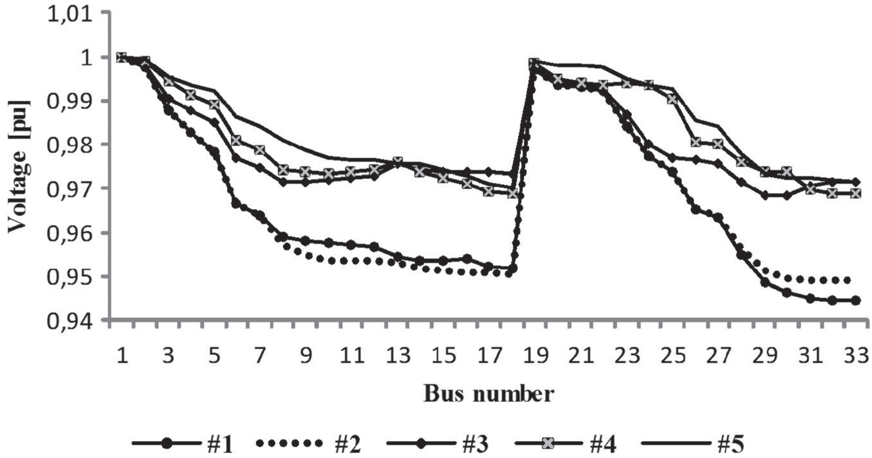

Figure 4. Voltage profile for the 33 bus system concerning the five penetration schemes.

cases. Moreover, it seems that only for high penetration levels (70% and above), penetration schemes could yield comparable loss reduction with scheme #5. But even in this latter case, the penetration scheme still provides the optimal solution since for the other four schemes at least one variable somehow predefines and the solution algorithm does not optimise its value. Thus, the optimal solution is considered the one for which all four involved variables are simultaneously optimised, as in penetration scheme #5.

In Figure 4, the voltage profile for the 33 bus system regarding the five penetration schemes is presented. It should be mentioned that for schemes #1 and #2, the aggregated DG capacity is 30% of the total load of the network. The upper line in Figure 4 corresponds to the proposed penetration scheme in this work that does not undergo any kind of limitations for the involved variables. From Figure 4 it is observed that the proposed scheme succeeds in providing the best voltage profile for the DN. It should be mentioned though that the voltage profile of the scheme #5 is not optimal for all nodes (e.g. scheme #4 yields a slightly better profile for nodes 25–28) but as illustrated in Figure 5 the voltage profile of scheme 5 is the most balanced one, the metric represents the mean value of the normalised node's voltage to the nominal voltage of the network. In Figure 5 the metric utilised to express the voltage profile of each scheme under a single value is computed by the following expression:

$$V_{\text{balanced}} = \frac{\sum_{b=1}^{z} (V_b / V_{\text{nominal}})}{z}, \tag{11}$$

where z is the total number of nodes of the network, V_b is the voltage of node b and V_{nominal} is the nominal voltage of the network.

Moreover, the bar concerning scheme #5 is the same in size for all three scenarios since DG aggregated capacity is not predefined and for higher penetration levels, networks performance in terms of losses reduction seems to be more homogeneous. However, the proposed solution (scheme #5) is always the best.

The 118 bus system presents two basic differences, with regard to the 33 bus system, which are summarised as follows:

- the network is not radial,
- the aggregated capacity of the already installed DG units is slightly higher than the total load of the network, thus the penetration of additional DG units should be implemented under special consideration in order not to overload the whole system.

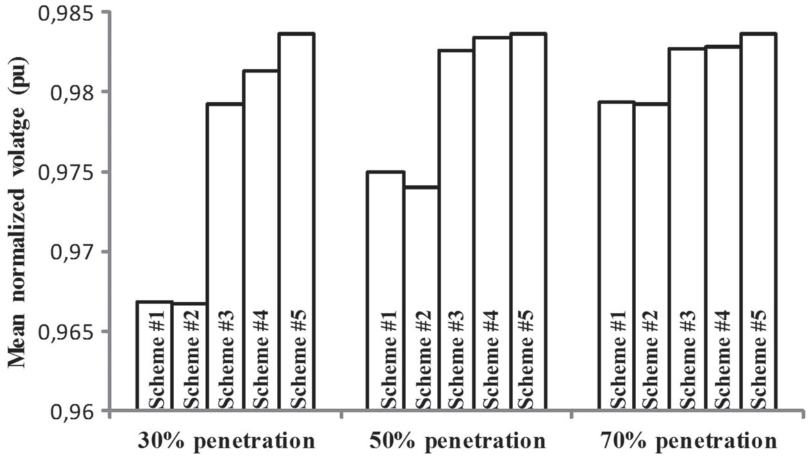

Figure 5. Balance level of the voltage profile for the 33 bus system by means of average pu voltage of all nodes.

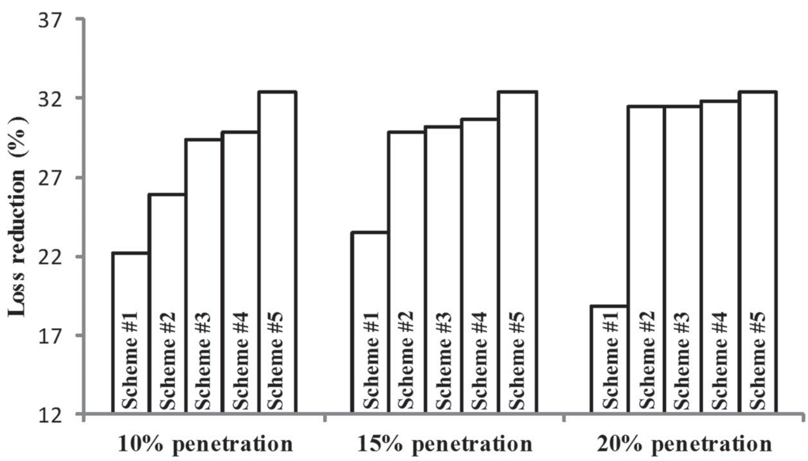

Figure 6. Loss reduction for the 118 bus system depending on examined penetration schemes.

Therefore, the examined penetration scenarios regarding schemes #1 and #2 are significantly lower and equal to 10%, 15% and 20% of additional DG with respect to the installed total load. The results after the application of the five penetration schemes are presented in Figure 6.

The results presented in Figure 5 indicate that the proposed penetration scheme yields once more the optimal solution without the need for examining various penetration scenarios, since the respective variable regarding the required optimal aggregated DG capacity is determined by the solution algorithm. In fact, for 20% penetration the total aggregated DG capacity is equal to 848.4 MW, while the optimal solution indicates an optimal aggregated capacity equal to 753.18 MW. This difference explains why the loss reduction in this case (20% penetration) for scheme #1 is so low. It is highly possible that the high DG penetration has caused congestion problems to the DN with reverse power flow and increased carrying currents to some branches (Liew and Strbac 2002; Méndez Quezada, Rivier Abbad, and Gómez San Román 2006).

The DN's voltage profile by means of the average pu voltage of all nodes is presented in Figure 7. Although the differences among the penetration schemes are relatively small, this is because the DN presents an already significant installed DG capacity, the proposed scheme #5 in this work still yields the most balanced voltage profile for the network.

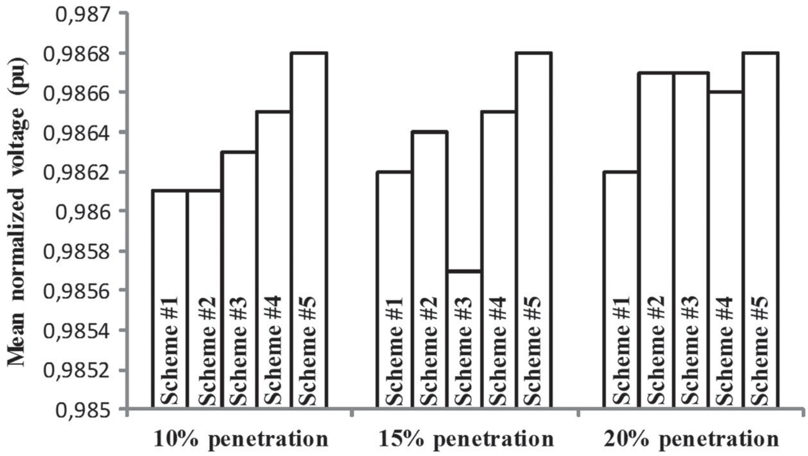

Figure 7. Balance level of the voltage profile for the 118 bus system by means of average pu voltage of all nodes.

Table 6. Proposed methodology vs. approaches with DoF < 4 regarding the 33 bus system.

	ODGP methodology				
	DoF < 4				DoF = 4
Results	Acharya, Mahat, and Mithulananthan (2006)	Abu Mouti and El-Hawary (2011a)	Shukla et al. (2010)	Moradi and Abedini (2012)	Proposed
Loss reduction (%)	47.31	47.14	47.1	42.48	69.50
Number of DG units	1	1	1	3	7
Node position for DG installation	6	6	6	11, 16, 32	6, 8, 14, 21, 24, 25, 31
Aggregated DG capacity (MW)	2.49	2.4	2.38	2.99	3.49

In Table 6, the solution resulting from penetration scheme #5 (i.e. the proposed scheme in this work with four DoF) is compared with other published methodologies that embed DoF between 1 and 3. It should be mentioned that the results of Table 6 refer to the 33 bus system.

The results in Table 6 show that the proposed methodology with the highest possible number of DoF, that is, four DoF, yields the optimal solution by performing the optimal siting and sizing of DG units.

5. Conclusions and discussion

In this paper, the impact of different penetration schemes in the ODGP problem is examined. In particular, the problem is analysed on the basis of the four crucial variables that have to be optimised in order to ensure loss minimisation under the optimal siting and sizing of the DG units. These variables refer to the number of DG units to be installed, to their allocation, to the capacity of each DG unit and finally to the aggregated DG capacity that is considered to be penetrated. As seen through the literature survey, the vast majority of the proposed methodologies regarding the ODGP problem for loss minimisation constitute mostly test cases about the optimisation of some of the aforementioned variables either under a sequential or parallel approach. Therefore, in this work a concept based on DoF is introduced in order to highlight the importance of none of these variables to undergo any kind of limitation during the optimisation process. Since four variables are considered during the solution of the ODGP problem, the maximum of the DoF is four as well. By that sense, four penetration schemes are formed in correspondence to methodologies from the literature, aiming to examine the solution's efficiency for cases with less DoF. Moreover, a fifth penetration scheme is proposed in this work, in order to prove that the optimal solution is subject to four DoF that should be optimised simultaneously towards a not biased solution.

The five penetration schemes are applied to the benchmark IEEE 33 and IEEE 118 bus systems, while the solution algorithm is common for all of them and relies on a L-PSO-V algorithm. Results indicate that the more the DoF considered in the problem are, the most efficient the solution is. By that sense, the optimal solution in terms of loss minimisation is provided by the fifth penetration scheme having four DoF for which none of the variables is subject to any limitation, while all variables are optimised simultaneously in order to avoid a biased solution. Since the fifth penetration scheme provides better energy efficiency performance and allows increased aggregated DG capacity usually applied by RESs, it serves directly the objectives of sustainable energy concept in both 'twin pillars' (Prindle and Eldridge 2007); therefore, it is proposed by the authors as a means of promoting the sustainable energy. Moreover, it is shown that the proposed penetration scheme yields the most balanced voltage profile for the examined DN since the deviation by the nominal voltage is the lowest possible for the majority of the network's nodes.

The analysis in this work aims to establish the proper context regarding the ODGP problem in order to ensure that both the problem formulation and the solution algorithm are not subject to any constraints that could bias the solution. Thus, the optimal solution could be evaluated based on the efficiency of the proposed solution algorithm.

Disclosure statement

No potential conflict of interest was reported by the authors.

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