OPTIMAL DISTRIBUTED GENERATION PLACEMENT PROBLEM FOR RENEWABLE AND DG UNITS: AN INNOVATIVE APPROACH

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Abstract

In this paper, an innovative approach regarding the Optimal Distributed Generation Placement (ODGP) problem is presented. Loss minimization is considered as the objective, while taking into account the network's technical characteristics as constraints, i.e., node voltage and line thermal limits. Two different aspects are considered; First the installation planning of generic Distributed Generation units (DGs), and second, the installation planning of Renewable Energy Sources (RESs) exclusively. For the latter, the Capacity Factor (CF) concept is implemented and a mix of RESs is considered to be installed e.g., Solar, Wind and Hydro, simultaneously. The implemented analysis demonstrates a method of considering the geographical characteristics of the area, where the examined network is placed, the different weather conditions and the availability of RESs, all at once, by the aid of the CFs, while trying to keep complexity at minimum. Local Particle Swarm Optimization (LPSO) is utilized for solving the ODGP. The method is tested upon 16-, 33- and 69-bus systems.

1 Introduction

The penetration of DGs in Distribution Networks (DNs) has been considered as an efficient way to exploit the benefits of sustainable energy promoted by distributed energy resources. In most cases, appropriate consideration of DG installation can highly benefit the network in terms of loss reduction, voltage-profile and reliability improvement [1]. On the other hand, high penetration levels could potentially cause problems to several operational DN's characteristics, especially due to reverse power flow, leading to excessive losses, and feeder overloading [2]. Thus, optimization tools which provide both optimal locations and capacity of DG units to be installed could be highly appreciated by Distribution Network Operators (DNOs).

As presented in literature, a great amount of scientific research has been undertaken to address this problem [3-8]. However, limited efforts have been made to provide an optimal solution in terms of DG's number, location and size altogether [9], [10], nor a comprehensive study considering DG number, location, size and type simultaneously, for maximizing DG penetration has been addressed adequately [11-15].

In this paper, the ODGP problem is addressed in two aspects. On the one hand, in terms of optimal number, site and size of DGs simultaneously, reaching therefore an actual optimal solution of the ODGP and resulting in the appropriate set of DGs to be installed for loss minimization. On the other hand, the DG type term is also considered enriching in this way the value of the optimal solution regarding realistic information. This is achieved by the use of the CF concept; that is technology-, weather-, and geography-dependent, therefore influencing the installation of certain type of DGs according to its value.

In this paper, three RES technologies where considered: Photovoltaic (PV), Wind Turbines (WT) and Hydro Power Plants (HP). Since RESs have been used, this aspect is called Optimal RES placement (ORESP).

As an optimization technique, LPSO has been utilized and the problem has been applied to three-bus system.

It should be stressed, naturally, that is assumed that the penetration of new DG or RESs capacity requirements into the grid will be determined by the network operator in terms of a specific strategic plan regarding the optimum location and size for these new power units. Given that, the ODGP problem towards loss minimization in DNs, refers to the optimal siting and sizing of DGs that are expected to be installed by private stakeholders in a power system, under the condition that the DNO would provide a guideline to convey such investments in the recommended locations towards loss minimization. This guideline would in turn conform to the respective strategic plan about loss reduction under ODGP as scheduled by the DNO.

This paper is organized as follows: in Section 2, the problem formulation is presented. In Section 3 the optimization technique, namely LPSO, is developed. In Section 4 the results are analyzed and finally Section 5 is devoted to conclusions.

2 Problem Formulation

2.1 Objective Function

The objective function F_{loss} in ODGP problem describes loss minimization due to the penetration of DG units and it is expressed as follows:

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

where:

- $g_{i,j}$: the conductance of buses i and j,
- n_l : the total number of buses in the network,
- V_i, V_j : the voltage magnitudes of nodes i and j,
- θ_i, θ_j : the voltage angles of nodes i and j.

2.2 Constraints

The objective function in (1) is subject to the following constraints:

As equality constraints the power flow equations are used, and as inequality constraints the following expressions formulate the nodal voltage and branch currents constraints:

$$V_i^{\min} \leq V_i \leq V_i^{\max} \quad (2)$$

$$S_b \leq S_b^{\max} \quad (3)$$

where $V_i^{\min}$and $V_i^{\max}$ are voltage limits of each bus and $S_b^{\max}$ the ampacity level of each branch b by terms of apparent power.

2.3 Penalty Function

The constraints of power flow equations and of (2) and (3), are incorporated in the objective function as penalty terms, creating a generic Penalty Function, in order to minimize the computational burden and facilitate the solution process [16], [17]. The formulation is as follows:

$$PF(x) = \min(f(x) + \Omega(x)) \quad (4)$$

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

where:

- $PF(x)$: the generic Penalty function
- $f(x)$: the Objective function (F_{loss})
- $\Omega(x)$: the Penalty term
- ρ : the penalty factor
- $q(x)$: refers to the equality constraints defined by the power flow equations
- $h(x)$: refers to the inequality constraints.

2.3.1 Penalty Function for ODGP

For the ODGP problem, the specific Penalty Function could be written:

$$PF^{\text{ODGP}} = \min\left[F_{\text{loss}} + \rho_P\Omega_P + \rho_Q\Omega_Q + \rho_V\Omega_V + \rho_L\Omega_L\right] \quad (6)$$

with Ω_P and Ω_Q referring to the equality constraints and Ω_V and Ω_L to the inequality constraints, respectively, and ρ concerns their respective penalty factors.

2.3.2 Penalty Function for ORESP

The main difference between the ODGP and the ORESP problems is that in the latter, the variations regarding power outputs of RESs that are related to their technology and the natural resources' potential, have to be taken into consideration. For instance, solar irradiance, wind speed, and water availability are expected to vary among candidate installation points within a network, and these variations could have a significant impact on the optimal siting and sizing of such RES especially when a mix of different RES is examined to be penetrated. In this, paper three types of RES i.e. PV, WT, and HP units are considered to be available for installation. Thus, the problem in this case refers to the optimal determination regarding the combination of different types of RES units to be optimally placed and sized towards loss minimization.

Consequently, an additional constraint has been implemented via the consideration of the RESs' CFs. More specifically, each DN's node is assigned a specific value for each of the three CFs that correspond to each of the three technologies considered. The values of these CFs express the potential of the respective natural resources available in that node. The DN's nodes are divided into groups, representing different areas with different natural characteristics and resources, therefore different CFs. Thus, according to their positions RESs obtain their CFs. These CFs are then added up together and the sum is subtracted from the *PF* for the ORESP problem.

Thus, for the ORESP problem, the specific Penalty Function could be written:

$$PF^{\text{ORESP}} = \min\left[F_{\text{loss}} + \rho_P\Omega_P + \rho_Q\Omega_Q + \rho_V\Omega_V + \rho_L\Omega_L - \rho_{CF}\Omega_{CF}\right] \quad (7)$$

where $\Omega_{CF} = \sum_{k=1}^{k_{\max}} CF_k$, $k_{\max}$ being the number of RESs and ρ_{CF} the respective penalty factor.

The PF^{ORESP} is problem- and constraint-dependent, i.e. it cannot bear a unvocal and constraint value for the penalty factors. Therefore, for the equality/inequality constraints' penalty terms, which represent approximately the same magnitude (i.e. 0.01) the penalty factors are given a common value of 10, to familiarize with the results from the target function and be comparable, whereas, the CFs penalty factor is assigned a value of 100 reflecting the term's strict prohibition upon geography and natural resources.

Moreover, both DGs and RESs have been considered with unity power factor and been applied as PQ, instead of PV type units.

3 PSO Technique

The ODGP problem is a mixed-integer, non-linear optimization problem subject to several constraints and its dimensions could highly increase. The conventional approaches utilizing analytical methods could be complex and time-consuming in this case, or restricted to the solution of just one DG unit being placed [18]. Therefore, PSO is implemented and Local PSO or LPSO, in particular.

PSO was initially introduced by Kennedy and Eberhart [19] inspired by the social behavior of bird flocking, or fish schooling. Two fundamental versions have been commonly used: Global and Local PSO, whereas other versions are virtually based on the one or the other. Over the years the most common version of PSO, Global PSO showed promising results in the area due to its implementation convenience and fast convergence [16]. However, it is susceptible to local minima entrapment, because its fast convergence does not allow it to better explore the solution space. Therefore, there has been a lot of effort in order to improve it [20], [21]. One approach considers the concept of neighborhoods within the swarm, thus creating the LPSO, [9], [10], which leads to better solutions due to is inherent ability of avoiding local minima entrapment by increasing its exploration capability of the solution space and addressing the issue fundamentally. The neighborhood formulation is described in detail in [17], [22]. In this paper the ring topology of neighborhoods is used due to its adequate simplicity and efficiency.

PSO is a population-based algorithm. A swarm of particles is designated to explore the solution space. The particles' position changes depending on their personal experience (personal best - pbest), their social experience, by exchanging information with the neighbor-particles (social best), and finally their previously obtained velocity, as shown in Figure 1.

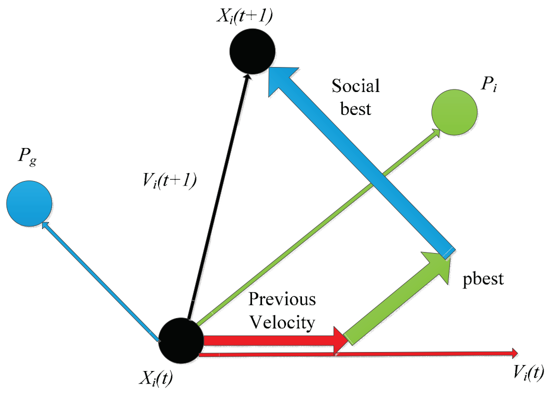

Figure 1 Vector diagram of a particle's movement

$$v_i(t+1) = wv_i(t) + c_1R_1(P_i(t) - X_i(t)) + c_2R_2(P_g(t) - X_i(t)) \quad (8)$$

$$X_i(t+1) = X_i(t) + v_i(t+1) \quad (9)$$

where $i = 1,2,\dots,N_p$, and N_p the number of particles,

$X_i(t)$: the current position of particle *i*,
$X_i(t+1)$: its future position,
$v_i(t)$: its current velocity,
$v_i(t+1)$: its future velocity,
$P_i(t)$: its personal best,
$P_g(t)$: its social best,
c_i : weighting factors, also called cognitive and social parameters,
R_i : random variables uniformly distributed within [0,1]
w : inertia weight coefficient, linearly decreasing over time, as:

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

where:

w_{up} : the upper inertia limit
w_{low} : the lower inertia limit
t : the current iteration
$T_{\max}$: the maximum number of iterations.

Furthermore, both the maximum iteration number and the convergence tolerance criteria must be met, in order for the algorithm to terminate, allowing a relatively wide investigation of the solution space under the requirement of an efficient solution.

Regarding the solution space dimensions, or more specifically the particles' dimensions, in respect to the ODGP problem, they are formulated as follows:

$$X^{\text{ODGP}} = [m, \dots, N_{\text{DG}}, P_m, \dots, P_{N_{\text{DG}}}] \quad (11)$$

where:

m : the DGs position, i.e. the bus number where it would be placed.
N_{DG} : the number of DGs to be installed.
P_i : the DGs active power output.

In respect to the ORESP problem:

$$X^{\text{ODGP}} = [m_{\text{PV}}, \dots, N_{\text{PV}}, P_{m_{\text{PV}}}, \dots, P_{N_{\text{PV}}}, m_{\text{WT}}, \dots, N_{\text{WT}}, P_{m_{\text{WT}}}, \dots, P_{N_{\text{WT}}}, m_{\text{HP}}, \dots, N_{\text{HP}}, P_{m_{\text{HP}}}, \dots, P_{N_{\text{HP}}}] \quad (12)$$

As it is evident in (12), in the ORESP aspect the particles' dimensions, and thus the solution space, consists of three parts, and each part describes the optimal siting and sizing of each RES type. Although the dimensions have highly increased, this formulation ensures that all available RES types are examined simultaneously for installation in the DN. Therefore, the solution achieved is optimal in terms of not only siting, sizing and number but also of optimal mix of RES types, thus the solution will not be biased like in cases where different RES types are installed with one RES type examined at a time [11].

4 Results

4.1 Examined DNs

The proposed methodology for both ODGP and ORESP aspects has been implemented on 16, 33 and 69 bus systems [23-25]. These DNs are radial with no kind of generation already installed on them. Their characteristics are shown in Table 1.

Table 1 Data for the 16-, 33- and 69-bus systems

Bus system	16	33	69
Number of buses	14	33	70
Number of branches	16	37	74
Active load (MW)	28.7	3.72	3.8
Reactive load (MVAr)	17.5	2.31	2.7
Initial losses (MW)	0.602	0.211	0.230

In order to assign potential for the local natural resources at each node, the under study DNs have been divided into three areas. In all DN areas, each node is assigned with three CF values for the examined technologies, i.e. PV, WT, and HP. Assuming that each area is relatively small, it is evident that the nodes within that area share the same value of the CFs of their respective technologies. Figures 2-4 present the DNs examined and how they are divided into the three areas.

For the evaluation and demonstration of the proposed methodology, two scenarios for the ORESP aspect have been chosen, reflecting two different CFs settings.

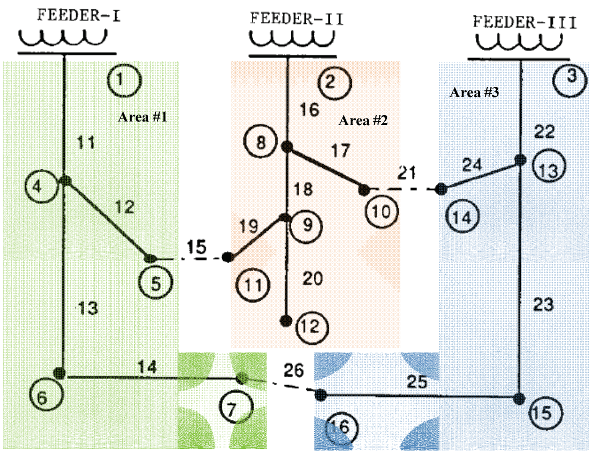

Figure 2 The 16-bus system divided in three areas

In Table 2 and Table 3, the selected area-specific CFs are given. These values represent typical values of their respective technologies [26-28]. For HP units the possible values for the respective CF are either zero, i.e. no water availability, or 0.42 and 0.45. Furthermore, in scenario #1 the CFs were assigned at each area, so that each resource would be dominant in each one of them, whereas in scenario #2 WT, and HP are competing in Area #1.

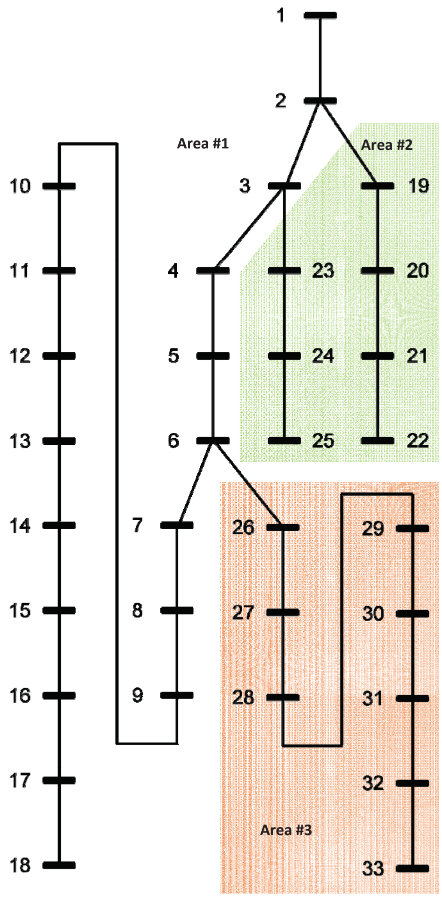

Figure 3 33-bus system divided in three areas

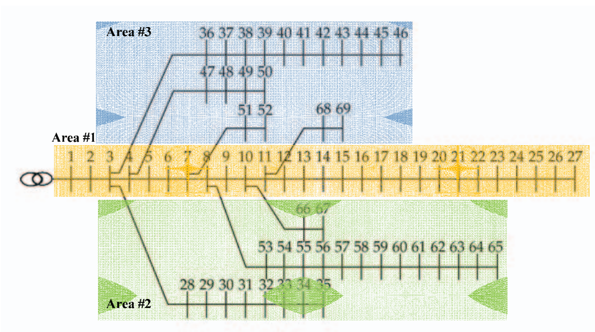

Figure 4 69-bus system divided in three areas

Table 2 CFs values - Scenario #1

Area	RES type		
	PV	WT	HP
#1	0.10	0.00	0.42
#2	0.10	0.25	0.00
#3	0.15	0.12	0.00

Table 3 CFs values - Scenario #2

Area	RES type		
	PV	WT	HP
#1	0.10	0.28	0.45
#2	0.15	0.00	0.00
#3	0.10	0.14	0.00

4.2 Results

Table 4a 16-bus system results

16-bus system results – overall			
	Initial losses (kW)	Minimum losses (kW)	Loss reduction (%)
ODGP	602.2	148.4	75.36
ORESP #1	602.2	169.4	71.87
ORESP #2	602.2	152.5	74.68

Table 4b 16-bus system results

16-bus system results – detail							
ODGP		ORESP #1			ORESP #2		
Bus No	P (MW)	type	Bus No	P (MW)	type	Bus No	P (MW)
2	2.05	PV	3	3.0	PV	2	3.06
3	3.45		11	1.36		8	2.20
4	2.0		14	3.72		9	2.62
5	1.5	WT	2	3.73		10	4.5
6	4.06		8	3.76		14	3.32
7	5.18		9	2.72	WT	4	2.00
8	1.0		10	7.37		5	1.5
10	4.5	HP	6	3.45		6	4.07
11	1.36					7	5.01
12	1.0				HP	-	-
14	2.77						
Total No	Total P (MW)		Total No	Total P (MW)		Total No	Total P (MW)
11	28.89		8	29.10		11	28.29

The results of both aspects discussed in this paper are presented in Tables 4-6. Firstly, for the ORESP aspect, different CFs for the nodes among the three network areas modify, apparently, the solution, since the algorithm is set to promote a compromise between the prioritization of the candidate nodes to host units and their power production potentials defined by the assigned CFs. Secondly, it is evident that both aspects yield almost same loss reduction, with the ODGP, as expected, resulting in slightly better solution. Thirdly, the majority of nodes revealed in the ODGP, appear again in both ORESP scenarios, therefore, emerging as critical nodes for DG installation towards loss reduction. And finally, the algorithm promotes the installation of the most appropriate mix of RESs, relying on the one hand on the CFs values, but on the other not necessarily to the highest ones, as long as better solution is available. For example, in Table 5b, in ORESP #2 for 33-bus system, no HP units are suggested for the installation planning, and WTs are preferred instead, in spite of the fact that HP units have higher CF value in the same region (see Table 3). In Table 6b, though, in ORESP #2 for 69-bus system, a larger HP unit is recommended, compared to the WT unit also suggested in the same area. Thus, the algorithm achieves a truly genuine optimal mix of RESs, in every case examined. The analysis, of this work proposes an efficient method overall, by both a suitable mathematical formulation and adjustment of the solution space.

Table 5a 33-bus system results

33-bus system results – overall			
	Initial losses (kW)	Minimum losses (kW)	Loss reduction (%)
ODGP	211	64.0	69.67
ORESP #1	211	65.0	69.19
ORESP #2	211	75.9	64.03

Table 5b 33-bus system results

33-bus system results – detail							
ODGP		ORESP #1			ORESP #2		
Bus No	P (kW)	type	Bus No	P (kW)	type	Bus No	P (kW)
3	348.7	PV	14	659.1	PV	21	196.3
6	720.0		26	712.3		22	73.4
10	390.8		28	12.9		24	490.2
16	380.3		30	378.6		25	412.4
21	267.4		32	385.2	WT	4	286.9
24	451.6	WT	21	276.2		6	1,265.4
25	420.2		23	306.3		8	246.7
31	686.4		24	432.0		10	196.7
			25	393.8		14	284.4
		HP	3	76.7		18	170.5
					HP	12	277.4
Total No	Total P (kW)		Total No	Total P (kW)		Total No	Total P (kW)
8	3,665.4		10	3,633.3		11	3,900.5

Table 6a 69-bus system results

69-bus system results – overall			
	Initial losses (kW)	Minimum losses (kW)	Loss reduction (%)
ODGP	602.2	148.4	75.36
ORESP #1	602.2	169.4	71.87
ORESP #2	602.2	152.5	74.68

Table 6b 69-bus system results

69-bus system results – detail							
ODGP		ORESP #1			ORESP #2		
Bus No	P (kW)	type	Bus No	P (kW)	type	Bus No	P (kW)
12	503.2	PV	20	420.3	PV	12	534.4
19	376.0		61	23.0		40	736.7
40	718.5	WT	40	723.2		53	1,354.2
53	1,718.8		45	580.8	WT	19	385.0
61	29.48		53	1,458.1	HP	23	753.8
			56	226.0			
			59	57.7			
		HP	12	283.5			
Total No	Total P (kW)		Total No	Total P (kW)		Total No	Total P (kW)
5	3,346.5		8	3,778.2		5	3,764.2

In Figures 5-7 the voltage profiles of all test-systems for the three cases, ODGP, ORESP #1, and ORESP #2 are given.

Figure 5 Voltage profile of 16-bus system

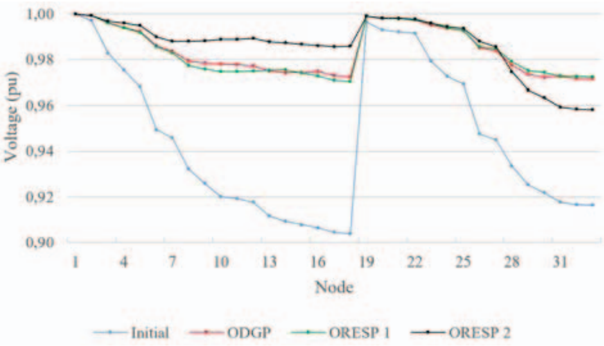

Figure 6 Voltage profile of 33-bus system

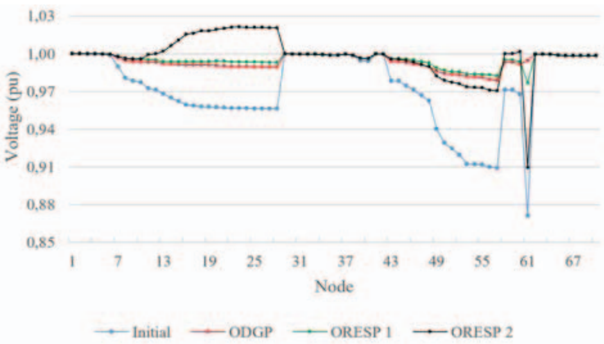

Figure 7 Voltage Profile of 69-bus system

5 Conclusions

In this paper, an innovative approach regarding the ODGP problem has been presented. Two different aspects are considered: the first refers to DG installation planning while the other concerns RES one. For both aspects, a LPSO algorithm is proposed with a suitable particle formulation that guarantees a non-biased solution. The implemented analysis demonstrates a method that takes into account the geographical characteristics, where the examined network is placed, the different weather conditions and the availability of RES, all at once, by the aid of the CFs, while trying to keep complexity at minimum. This aspect, called ORESP, achieves an optimal solution in terms of number, siting, sizing and type of RESs.

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