Chapter

Distributed Sources Optimal Sites and Sizes Search in Large Power Systems

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Abstract

The integration of renewable sources into the power system has now become an unavoidable necessity for these technical and economic advantages and for the protection of the environment. In this chapter, a study is given for the integration of the Distributed Source (DS) in an optimal way and this by looking for the best location (sites) and the best power to be injected (size). The optimization technique used is based on genetic algorithms under technical and safety constraints, with the aim of minimizing active network losses and maximizing voltage stability. These objective functions are handled as a single and multi-objective problem. This study is applied on the standard IEEE 30 bus network under the MATLAB code.

Keywords: distributed source, optimal site and size, active power losses, voltage stability improvement, genetic algorithm

1. Introduction

Non-conventional or clean production is increasing rapidly around the world, thanks to it's advantages such as reduced environmental impact, small size and it is a renewable energy [1]. The traditional power system is characterized by the unidirectional of the power flow because the energy comes from centralized sources [2]. These sources are generally based on fossil resources that are exhaustible and polluting for the environment.

The transmission power system spreads on long distances, which leads to losses in the lines by Joule effect on the one hand, and on the other hand, it requires huge investments and waste lands with long achievement times, which has led researchers to think about other solutions to face these problems [3].

Among these solutions is to have sources of electrical energy close to the consumers (local production). With the liberalization of the electricity market and the evolution of decentralized source (DS) technology in recent years, an increased trend towards their use has emerged. DS is defined as small producers based on renewable or conventional sources installed at different points in the power system, either at the transmission or distribution level [4]. The rate of DS integration tends to increase progressively in several countries [5].

In spite of the various advantages of DS, its sources present disadvantages when they are inserted into the power system, such as frequency instability caused by the intermittency of some renewable sources (e.g. photovoltaic and wind power) [6]. They also present some constraints, such as exceeding the thermal limits of power lines, increased Joule effect losses and the dysfunctioning of electrical protection devices and the exceeding of voltages at connection points. These constraints are due to the wrong choice of size (maximum power) and site of the DS, which requires the search for the best sites and adequate sizes [7].

A number of researchers have studied the problem of optimal site and size of DS to distribution networks [4, 8]. Example, in researchers [9] presented a technique a review of optimal DS placement in distribution network. DS site and size search techniques can be based on artificial intelligence techniques, metaheuristic techniques or deterministic techniques [10]. While most papers deal with this problem as a single-objective problem and some papers have focused on the problem of multi-objective optimizations [11]; these studies have considered a variety of objective functions including voltage profile improvement, losses minimization, reliability index minimization (SAIFI, SAIDI and END), fuel cost minimization, greenhouse gas emission minimization, maximization of DS penetration rate and maximization of voltage stability [12–18]. Some researchers have examined the problem of optimal sitting and size of DS to transmission networks [19–29].

Based on the literature search carried out, it was noted that the optimal integration of DS into distribution networks is largely discussed, however, there is less literature on the integration of DS into transmission networks.

The objective of this chapter is to study the problem of determining the Optimal Sites and Sizes of DS (OSSDS) in the transmission power system while taking into account the various constraints of the system (technical and security constraints). This is achieved by using a metaheuristic optimization technique such as the Genetic Algorithm (GA) technique. The objective functions considered in this work are the minimization of active power losses and the voltage stability improvement. These objective functions are treated as mono-objective and multi-objective (the objective functions are combined to a single objective function via weighting factors). This study has been applied on the IEEE 30 bus network under MATLAB code. For this reason, this chapter is organized according to the following plan: Section 2 will present the mathematical formulas of the OSSDS problem, i.e. the objective functions, the different constraints. Section 3 will present definitions on the method used (GA) and their application on OSSDS. Section 4 will give the description of the IEEE 30 node network and the limitations of the study framework. Section 5 will present the simulation, interpretation and analysis of the results obtained. Finally, the conclusion of the chapter and some perspectives.

2. Formulation of the OSSDS problem

The objective of this work is to research what is the optimal power to be injected by DS and the bus of their insertions that gives us the best performance of the power system considering the imposed constraints. To reach this objective we must define the fitness function and the constraints of equality and inequality which will be detailed in the following sections [30, 31].

2.1 Objective function (OF)

The OSSDS is formulated as a single and multi-objective problem using two objective functions.

2.1.1 First objective: minimization of active power losses

The first concern of the power system operator is to minimize active power losses in the line, this is expressed by the following equation:

$$TPLI_k = \sum_{k=1}^{N_B} r_k I_k^2 \tag{1}$$

where r_k and I_k, are the resistance and the current of the transmission line k respectively. TPLI represent the Total Power Losses Index of the network.

2.1.2 Second objective: improvement of the line voltage stability index

To assure that the operating point of the power system is far from the voltage collapse point, the voltage stability index must be improved. Among the effective indices that have been proposed in the literature is the Line Voltage Stability Index (LVSI) [32]. The LVSI of the line between bus i and jis given by the following equation:

$$LVSI_k = \frac{4X_{ij}Q_j}{\left[V_i \sin\left(\theta_{ij} - \delta_{ij}\right)\right]^2} \leq 1 \tag{2}$$

where X_{ij}, Q_j, V_i, θ_{ij}, and δ_{ij} are the line reactance, is the reactive power at receiving end, the voltage at receiving end, is the line impedance angle between bus i and j and voltage phase angle difference between bus i and busj, respectively.

The line which represents an LVSI value close to 1 will be considered, the most critical line and may lead to the network collapse.

For multiobjective optimization, the two objectives functions are combined in a single linear function using weighting factors. Mathematically, this is given in the following form:

$$F_{MO} = \alpha_1(TPLI_k) + \alpha_2(LVSI_k) \tag{3}$$

where α_1 and α_2 represent the weighting factors of active power losses index and the line voltage stability index, respectively.

2.2 Equality constraints

Equality constraints represent power balance equations between generation and demand. For a transmission power system in presence of DS, the active and reactive power equality constraints can be expressed as follows [33]:

$$\begin{cases} \sum_{i=1}^{N_G} P_{Gi} + \sum_{i=1}^{N_{DS}} P_{DSi} - \sum_{i=1}^{N_D} P_{Di} - \sum_{i=1}^{N_B} P_{li} = 0 \\ \sum_{i=1}^{N_G} Q_{Gi} + \sum_{i=1}^{N_{DS}} Q_{DSi} - \sum_{i=1}^{N_D} Q_{Di} - \sum_{i=1}^{N_B} Q_{li} = 0 \end{cases} \tag{4}$$

where (P_G, Q_G) is the active and reactive power of the conventional generator, (P_{DS}, Q_{DS}) is the active and reactive power produced by DS. This source is capable of delivering the active and reactive power. (P_D, Q_D) represent the active and reactive power demand at the load bus, (P_l, Q_l) represent the active and reactive power losses.

2.3 Inequality constraints

These constraints represent the physical limits of the lines, conventional generators and DS as also the security limits of the voltages of the network busses. They are expressed by the following equations:

$$S_{bi} \leq S_{bimax} \text{ for } i = 1 \ldots \ldots \ldots \ldots . \ldots \ldots . N_B \tag{5}$$

$$P_{Gimin} \leq P_{Gi} \leq P_{Gimax} \text{ for } i = 1 \ldots \ldots \ldots \ldots \ldots . \ldots N_G \tag{6}$$

$$Q_{Gimin} \leq Q_{Gi} \leq Q_{Gimax} \text{ for } i = 1 \ldots \ldots \ldots \ldots \ldots . \ldots N_G \tag{7}$$

$$V_{imin} \leq V_i \leq V_{imax} \text{ for } i = 1 \ldots \ldots \ldots \ldots \ldots \ldots \ldots N \tag{8}$$

$$S_{imin}^{DS} \leq S_i^{DS} \leq S_{imax}^{DS} \text{ for } i = 1 \ldots \ldots \ldots \ldots \ldots . \ldots \ldots N_{DS} \tag{9}$$

$$\sum_{i=1}^{N_{DS}} P_{DSi} \leq \tau * \sum_{i=1}^{N_D} P_{Di} \text{ for } i = 1 \ldots \ldots N_{DS} \text{ and } i = 1 \ldots ..N_D \tag{10}$$

where S_{bi} is the apparent power that transits via the line between the nodes i and j. S_{bimax}, is the maximum limit of the line (thermal limit). P_{Gimin}, P_{Gimax}, P_{Gimin} and P_{Gimax} are the minimum and maximum active and reactive powers of the i^{th} conventional generator. S_{min}^{DS} and S_{max}^{DS} are the minimum and maximum production powers of the DS. N, N_D, N_G, N_B and N_{DS} are the number of network busses, number of load busses, the number of generators, the number of branches and the number of DS, respectively. V_{imin} and V_{imax} are minimum and maximum voltage in bus i.

For reasons of power system security, the network operator has limited the penetration rate $(\tau_{\%})$ of DS. This limit is set depending on the robustness of the network (each network has its specific). This rate is calculated by the ratio of the total active power of the DS to the total active power demanded or the total power generated by conventional sources multiplied by one hundred; this is given by the following Equation [34]:

$$\tau_{\%} = \frac{\sum_{i=1}^{N_{DS}} P_{DSi}}{\sum_{i=1}^{N_D} P_{Di}} * 100 \tag{11}$$

2.4 Constraint processing

To optimize the site and size of the DS, it is important to mention that the control variables are generated within their allowable limits using a random strategy using a metaheuristic technique. During the optimization process, it is possible to come across solutions that are unfeasible due to exceeding the voltage limit, the thermal limit of the lines or the power limit of the reference generator, in this case the OF is penalized. This OF is reformulated as follows [33]:

$$F^P = \sum_{i=1}^{n_{OF}} f_i + k_P \left(P_{slack} - P_{slack}^{lim}\right)^2 + k_V \sum_{i=1}^{NL} \left(V_{L_i} - V_{L_i}^{lim}\right)^2 + k_s \sum_{i=1}^{NB} \left(S_{b_i} - S_{b_i}^{lim}\right)^2 \tag{12}$$

where k_p, k_V and k_s are the penalty factors of the active power produced by the reference generator (slack bus), the voltage at the load nodes and the penalty constrained of the thermal limit of the lines, respectively.

The limits of the various variables are determined by the following equation:

$$T_i^{lim} = \begin{cases} T_i^{max} & \text{if} \quad T_i > T_i^{max} \\ T_i^{min} & \text{if} \quad T_i < T_i^{min} \\ T_i & \text{if} \ T_i^{min} \le T_i \le T_i^{max} \end{cases} \tag{13}$$

T, represents the variables P_{slack}, V_{L_i} and S_{b_i}.

The values of the penalty factors are determined by empirical means. After several tests it is decided that, k_V=k_s =10,000 and k_p=1000.

From the above mathematical formulation, it can be noted that the use of such a model to solve real size problems is practically not possible with a classical approach. Consequently, in order to solve practical problems, it is necessary to use metaheuristic methods, that is, the genetic algorithms method.

3. Genetic algorithm method

GA is a metaheuristic optimization technique inspired by natural selection, and genetics developed by Holland-John, who conceived and realized an idea on how to transform the characteristics of natural evolution into a computer program [35]. The algorithm is based on a set of possible solutions randomly initialized in the search space. Individuals are represented by their design variables or by chromosome coding. Some solutions from the first population are used to form a new population based on genetic operators (crossover, mutation and selection). The goal is for the new population to be better than the previous one. The solutions that will be used to form new solutions are randomly selected according to their merit represented by an objective function specific to the problem posed, which should be minimized or maximized, so the better the individual, the greater his chances of surviving and reproducing, until the stop criterion is satisfied.

3.1 Application of the GA method

The goal of the GA method is to determine the optimal site and size of the DS to be integrated into the power system while minimizing the objective function under imposed constraints. Initially the vector of state variables and the vector of control variables are expressed as below:

The vector χ^T of state variables is composed of the active generation power at the reference bus P_{G_1} the load bus voltages V_{Li}, the reactive power produced by conventional generators Q_{G_i}, the apparent power transiting through transmission lines S_{li}. This vector χ^T can be expressed by:

$$\chi^T = \left[P_{G_1}, V_{L_1} \dots V_{L_{NL}}, Q_{G_1} \dots Q_{G_{NG}}, S_{l_1} \dots S_{l_{Nl}}\right] \tag{14}$$

The vector v^T of the control variables shows the active power outputs of the DS (size) S_{DS} and the site or location of the DS L_{DS}. Hence, this vector can be represented by:

$$v^T = [S_{DS_1}, S_{DS_2} \dots \dots .S_{DS_{NDS}}, L_{DS_1}, L_{DS_2} \dots ..L_{DS_{NDS}}] \tag{15}$$

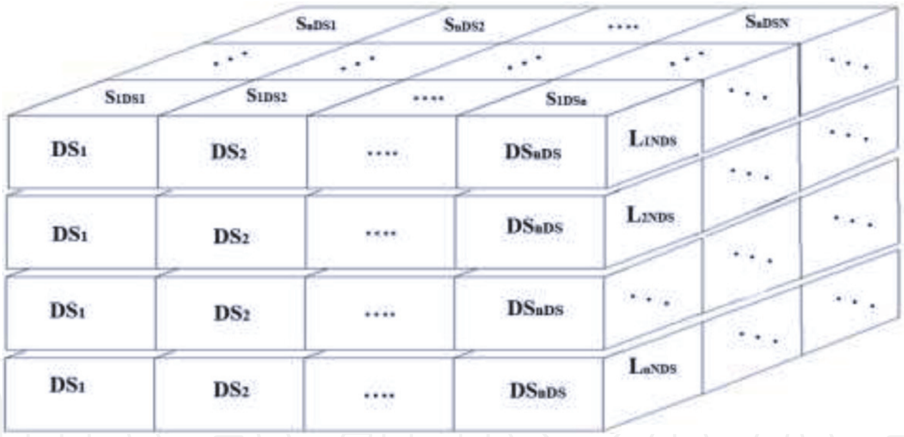

Figure 1.
Control variable vector structure.

Figure 1 indicates the chromosome structure employed in this study.

Step 1: In determining the site and size of DS, the genetic algorithm method was suggested. The main steps for researching the site and size of DS are as follows:

Step 2: Run a power flow and determine the various network parameters in the absence and presence of DS, using the Newton Raphson method.

Step 3: Select the GA parameters (number of generations, population size, crossover and mutation probability) and randomly generate the values of the sites and sizes between their limits using Eqs. E16, E17 and E18 (creation of the initial population P_0).

$$P_0 = [X_1, X_2 \ldots \ldots X_i \ldots .X_{n\ \text{population}}] \tag{16}$$

$$L_{wi} = round(2 + rand(N_{bus} - 2)) \tag{17}$$

$$S_{wi} = P_{min}^{DSi} + rand(P_{max}^{DSi} - P_{min}^{DSi}) \tag{18}$$

where $round(\bullet)$ represents the value of a number that is rounded to the next integer, and *rand* represents a random number uniformly distributed between 0 and 1 [24].

Start the iteration meter $t = 0$.

Step 4: Run the power flow in the presence of the DS and evaluate the objective function for each individual.

Step 5: Examine all network constraints using Eqs. E4 to E8. If the latter are satisfied, go to the next step. If not, penalize the OF using Eq. E12 and go to the next step.

Step 6: Generate new populations following the laws of GA (crossover, mutation and selection), increase the generation meter ($k = k + 1$) and repeat steps 4 to step 6up to the stop criteria (maximum number of generations).

Step 7: Extract the best individual and show the results (site, size and various network parameters).

Figure 2 shows the flowchart of the search for the site and size of DS to be incorporated into the power system.

4. Description of the studied network

The IEEE 30 bus network is used by power system researchers to test the effectiveness of their programs simulation. This system is composed of 30 buss, 41 transmission lines, 04 transformers, 06 conventional generators with a total generating capacity of 435 MW with a reactive capacity of −95 MVAr to 520 MVAr and 21 loads with a total power demand of 283.4 MW and 126.2 MVAr [35]. Bus No. 1 is taken as the reference (slack bus). **Figure 3** shows the single line diagram of the network studied.

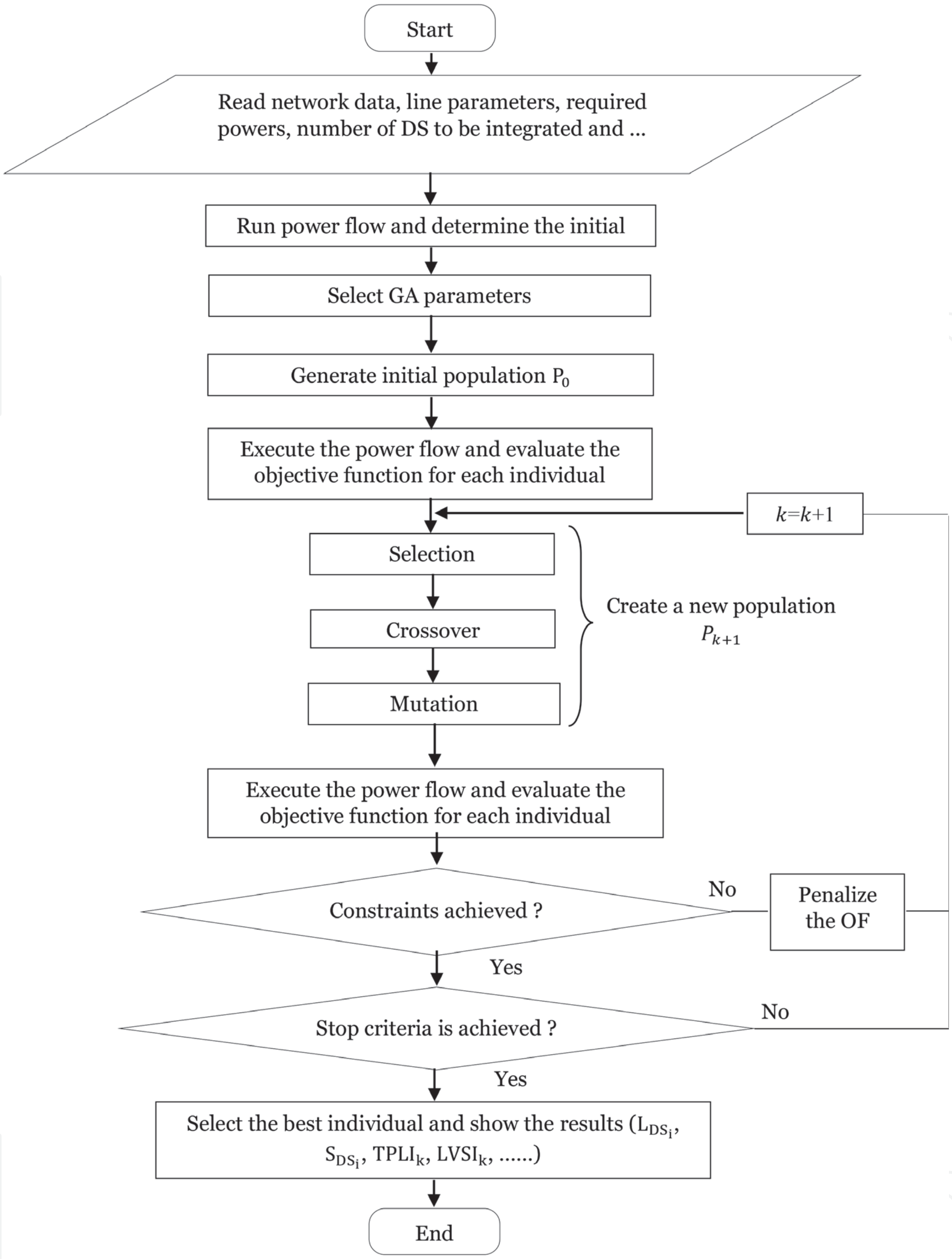

Figure 2.
DS site and size search flowchart.

4.1 Study framework

Before beginning the presentation of the simulation results, it is necessary to cite the limitations of the study framework under consideration. The Newton Raphson method is used via the MATPOWER software to calculate the power flow. For the GA method the existing Toolbox in the MATLAB library (GA function) will be used. The voltage limits of the network busses are limited between 0.95 pu- 1.1 pu. DS are considered as sources capable of delivering active and reactive power, using a power factor of 0.8. DS integration are modeled as PQ busses (negative loads). It is important to note that all load nodes are considered candidate busses for DS sites. It is important to note that the number of DS to be integrated into the network is

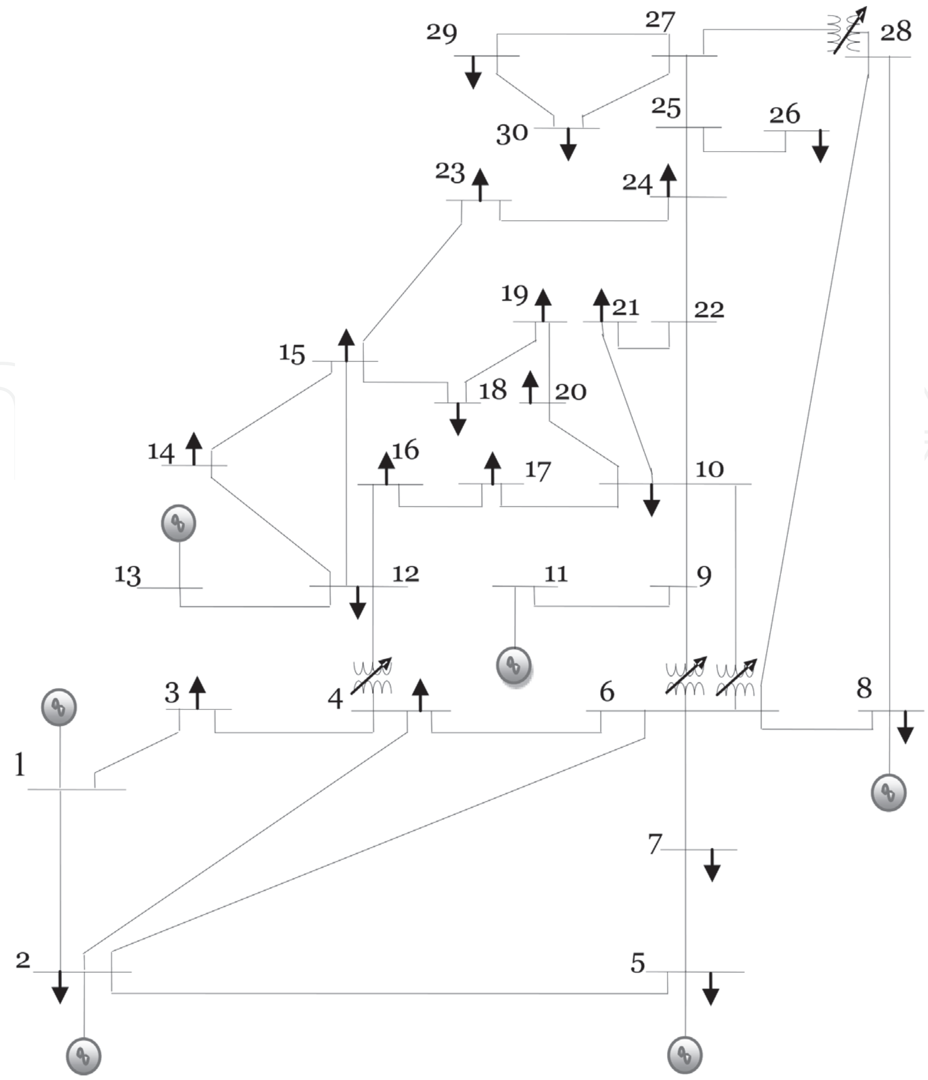

Figure 3.
Schematic diagram of the IEEE 30 bus network.

chosen in advance. After integration of a DS up to 10 DS, it is observed that, the best number from the viewpoint of improving the network parameters is 05 DS. For this reason, this study considers the insertion of five DS. The limits of the active power delivered by each DS are between 0 and 100 MW. And the penetration level limit of the total power delivered by the DS is $0.5 * \left(\sum_{i=1}^{N_D} P_{D_i}\right)$ MW that is $\sum_{i=1}^{N_{DS}} P_{DS_i} \leq 0.5 * \left(\sum_{i=1}^{N_D} P_{D_i}\right)$. After several tests on the studied network, it is noted that, the optimal parameters of the GA method are: the number of chromosomes (population size) is fixed at 100, the maximum number of generations is 50, the probability of mutation is 0.01 and the probability of crossover is 0.9. The multiobjective optimization considered in this study is based on the method of aggregate objectives through the weighting factors. It is important to note that, the choice of the values of these factors are dependent on the network operator and on the importance of the index to be improved. For this reason, the values of the weighting factors are set as follows: α_1=0.8 and α_2 =0.2. In this study four cases are considered: the first case shows the simulation results for the base case (Execute the optimal power flow without DS). Second case, presents the results of the minimization of active losses only. Third case, presents the results of the voltage stability index improvement. Fourth case, presents the simulation results of the multi-objective case, it is the minimization of the bi-objectives at the simultaneous (minimization of losses and voltage stability index improvement).

5. Simulation results and interpretations

After the execution of the elaborated program, the simulation results achieved are shown bellow. **Table 1**, represents all the simulation results obtained for the five cases studied, as also the physical power limits of conventional generators.

Parameters	Limits		Case 01	Case 02	Case 03	Case 04
	Max	Min				
P_{G1}(MW)	200	50	182.64	52.47	60.61	50.46
P_{G2}(MW)	80	20	50.58	50.58	50.58	50.58
P_{G3}(MW)	50	15	18.52	18.52	18.52	18.52
P_{G4}(MW)	35	10	18.09	18.09	18.09	18.09
P_{G5}(MW)	30	10	10.40	10.40	10.40	10.40
P_{G6}(MW)	40	10	13.26	13.26	13.26	13.26
Q_{G1}(MVAr)	200	−20	−8.56	16.94	6.16	17.97
Q_{G2}(MVAr)	100	−20	23.47	−8.88	−15.30	−8.98
Q_{G3}(MVAr)	50	−15	32.04	3.22	23.75	−5.10
Q_{G4}(MVAr)	60	−15	49.29	−5.34	−2.80	−4.82
Q_{G5}(MVAr)	50	−10	5.39	−10.00	−6.98	−7.92
Q_{G6}(MVAr)	60	−15	2.74	−14.26	−15.00	−12.29
Total Conventional Active Production	435	115	293.49	163.33	171.46	161.31
Total Conventional Reactive Production	520	−15	104.37	−18.32	−10.16	−21.14
Total Load (MW, MVAr)	(283.40, 126.20)					
DS Site(Best Location)	**	**	**	7	4	7
				9	12	17
				12	20	20
				18	23	23
				30	29	30
DS Size (MW, MVAr)			**	(46.96, 35.22)	(36.40, 27.30)	(67.52, 50.64)
				(38.58, 28.93)	(52.97, 39.73)	(27.48, 20.61)
				(5.63, 4.22)	(6.07, 4.55)	(10.36, 7.77)
				(18.09, 13.56)	(11.37, 8.52)	(4.60, 3.45)
				(13.60, 10.20)	(9.73, 7.30)	(15.05, 11.28)
TPLI (MW)			10.89	2.798	4.620	2.945
LVSI			0.181	0.158	0.067	0.149
Loading Parameter (pu)			2.1	4.4	5.7	5.2

*** without DS integration.*

Table 1.
Summary of network simulation results for the various cases.

Figure 4, shows the situation of apparent power transmitted via transmission lines in all the cases studied. **Figure 5** shows the voltage profile of several different cases.

From the results obtained by running the optimal power flow without DS (case 01), it is found that the total active losses are 10.89 MW, the LVSI is 0.181 and loading parameter (LP) is 2.1 pu.

In the case of the minimization the TPLI only (case 2), it can be seen that the total active losses are reduced to 2.798 MW, which represents a reduction rate of 74.3%, the LVSI has been improved with 12.7% and loading parameter represents a rate of 52.27%, that is after the integration of 05 DS with a total active power of 122.86 MW and reactive power of 92.13 MVAr distributed to the different sites (busses 7, 9, 12, 18 and 30) respecting all the constraints of the network.

When improving the LVSI only (case 3), the simulation results show that busses 4, 12, 20, 23 and 29 are selected as the best sites for DS power installations producing a total power of 116.54 MW and 87.4 MVAr. This implementation has enhanced the LVSI parameter from the value 0.181 to 0.067, which represents a rate of 62.9%, the losses are reduced to 4.62 MW, which is 57.5% and a loading parameter improvement rate of 63.15%.

The multiobjective optimization (case 04) proved that the results give a compromise between the different values of the minimized objective functions. In this case, the TPLI is improved by 72.9%, LVSI has been minimized by 17.67% and loading parameter has been increased by 59.61%. The advantage of Multi-objective

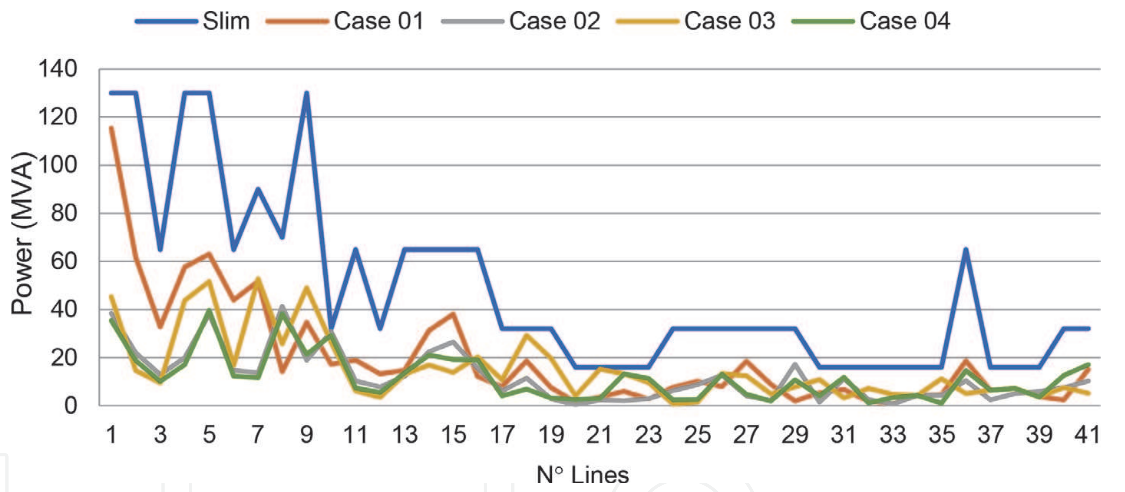

Figure 4.
Apparent power of the transmission lines for several cases.

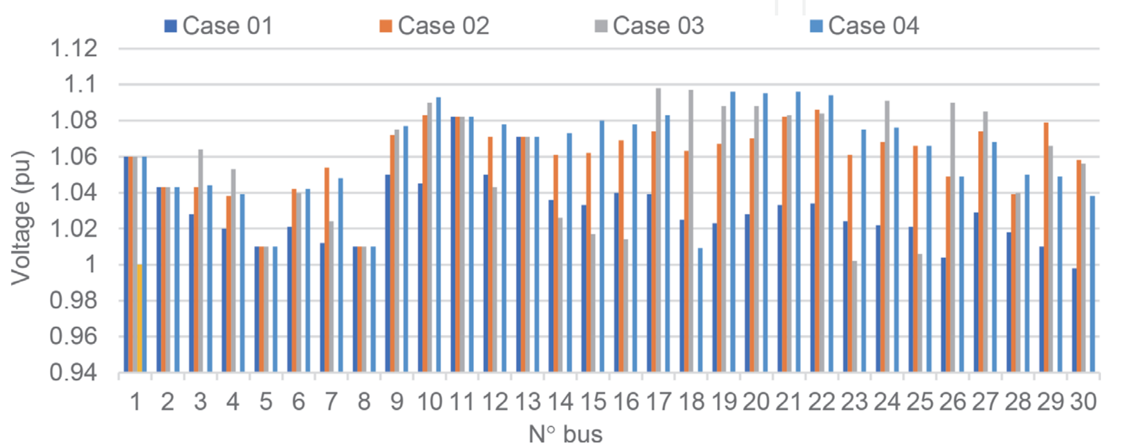

Figure 5.
Voltage values of the network bus for several cases.

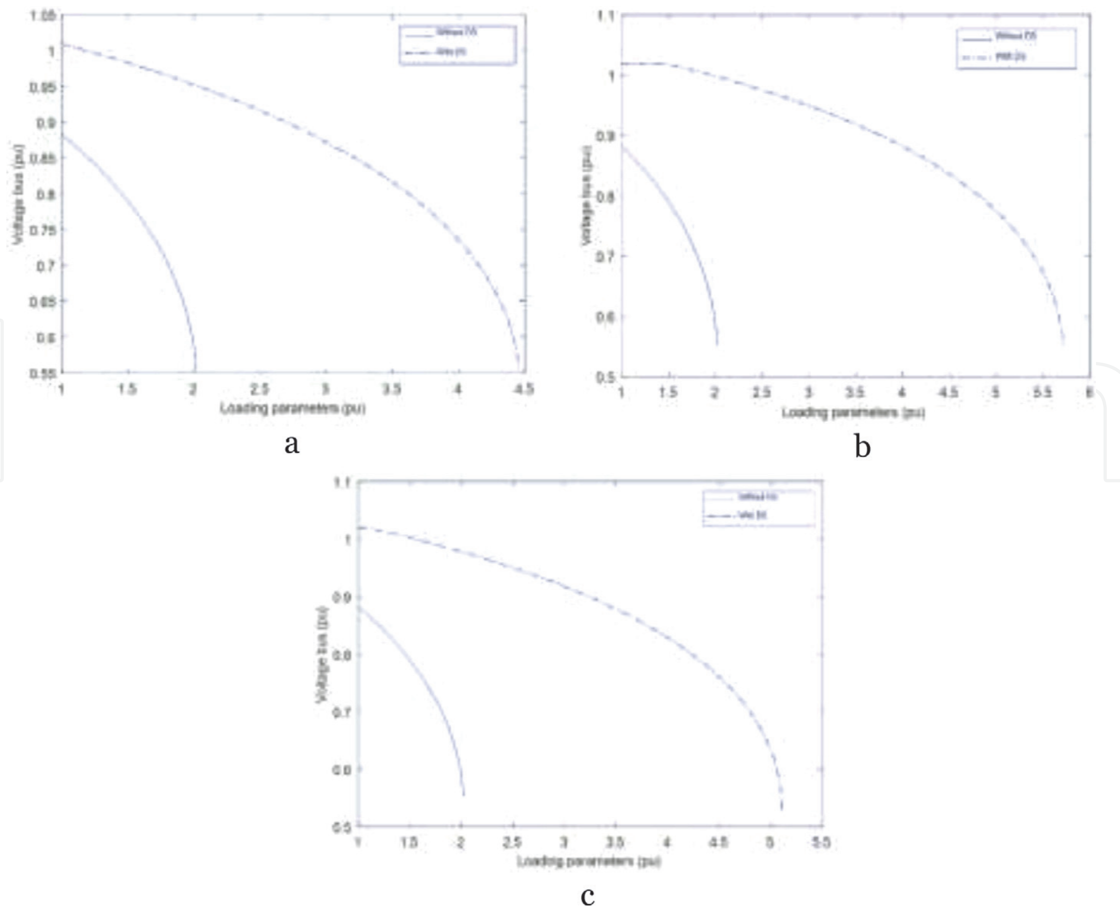

Figure 6.
(a) LP in case 2, (b) LP in case 3 (c) LP in case 4.

optimization consists in improving several parameters of the electrical network and having the best compromise.

Figure 4 shows that all line powers are below the thermal limit power, which demonstrates the consideration of line stresses.

Figure 5 shows that all the bus voltages are included between the limits 0.95 pu and 1.1 pu. **Figure 6** illustrates the PV curves before and after the integration of the DS for the three cases.

Figure 6 shows the positive influence of DS integration on the voltage stability margin of the IEEE 30 bus network. This figure also shows that case 3 represents the best value of LM, because the objective function only maximizes the voltage stability.

6. Conclusion

This chapter solves the problem of searching for the optimal location and size of DS in the transmission power system considering the required constraints, using the GA technique. In this work, various objective functions are targeted, minimizing active losses and voltage stability improvement. The last ones are treated as a mono and multi objective problem. The simulations carried out have shown that the results are dependent on the minimized objective function. The results achieved show the efficiency of the GA method. The perspective of this study is to include the constraint related to the transient stability of the rotor angles of conventional generators, in order to maintain the stability of the system during DS disconnection.

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Appendix

The data (lines, consumptions, generators) of the IEEE 30 bus network used in this study are shown below [36]. **Table 2** shows the bus data of the IEEE network studied. **Table 3** represents the line data. **Table 4** shows the data of the conventional generators.

Bus i	Type	P_d(MW)	Q_d(MVAr)	G_s	B_s	Area	V_m	V_a	BaseKV	Zone	V_{max}	V_{min}
1*	3	0	0	0	0	1	1.06	0	132	1	1.1	0.95
2	2	21.7	12.7	0	0	1	1.043	−5.48	132	1	1.1	0.95
3	1	2.4	1.2	0	0	1	1.021	−7.96	132	1	1.1	0.95
4	1	7.6	1.6	0	0	1	1.012	−9.62	132	1	1.1	0.95
5	2	94.2	19	0	0	1	1.01	−14.37	132	1	1.1	0.95
6	1	0	0	0	0	1	1.01	−11.34	132	1	1.1	0.95
7	1	22.8	10.9	0	0	1	1.002	−13.12	132	1	1.1	0.95
8	2	30	30	0	0	1	1.01	−12.1	132	1	1.1	0.95
9	1	0	0	0	0	1	1.051	−14.38	1	1	1.1	0.95
10	1	5.8	2	0	19	1	1.045	−15.97	33	1	1.1	0.95
11	2	0	0	0	0	1	1.082	−14.39	11	1	1.1	0.95
12	1	11.2	7.5	0	0	1	1.057	−15.24	33	1	1.1	0.95
13	2	0	0	0	0	1	1.071	−15.24	11	1	1.1	0.95
14	1	6.2	1.6	0	0	1	1.042	−16.13	33	1	1.1	0.95
15	1	8.2	2.5	0	0	1	1.038	−16.22	33	1	1.1	0.95
16	1	3.5	1.8	0	0	1	1.045	−15.83	33	1	1.1	0.95
17	1	9	5.8	0	0	1	1.04	−16.14	33	1	1.1	0.95
18	1	3.2	0.9	0	0	1	1.028	−16.82	33	1	1.1	0.95
19	1	9.5	3.4	0	0	1	1.026	−17	33	1	1.1	0.95
20	1	2.2	0.7	0	0	1	1.03	−16.8	33	1	1.1	0.95
21	1	17.5	11.2	0	1	1	1.033	−16.42	33	1	1.1	0.95
22	1	0	0	0	0	1	1.033	−16.41	33	1	1.1	0.95
23	1	3.2	1.6	0	0	1	1.027	−16.61	33	1	1.1	0.95
24	1	8.7	6.7	0	4.3	1	1.021	−16.78	33	1	1.1	0.95
25	1	0	0	0	0	1	1.017	−16.35	33	1	1.1	0.95
26	1	3.5	2.3	0	0	1	1	−16.77	33	1	1.1	0.95
27	1	0	0	0	0	1	1.023	−15.82	33	1	1.1	0.95
28	1	0	0	0	0	1	1.007	−11.97	132	1	1.1	0.95

Bus i	Type	P_d(MW)	Q_d(MVAr)	G_s	B_s	Area	V_m	V_a	BaseKV	Zone	V_{max}	V_{min}
29	1	2.4	0.9	0	0	1	1.003	−17.06	33	1	1.1	0.95
30	1	10.6	1.9	0	0	1	0.992	−17.94	33	1	1.1	0.95

Base MVA = 100

Table 2.
Bus data of IEEE 30 bus power system.

Bus_i	Bus_j	R(pu)	x(pu)	b(pu)	RateA (S_{lim} MVA)	RateB	RateC	Ratio	Angle	Status
1	2	0.0192	0.0575	0.0528	130	0	0	0	0	1
1	3	0.0452	0.1652	0.0408	130	0	0	0	0	1
2	4	0.057	0.1737	0.0368	65	0	0	0	0	1
3	4	0.0132	0.0379	0.0084	130	0	0	0	0	1
2	5	0.0472	0.1983	0.0418	130	0	0	0	0	1
2	6	0.0581	0.1763	0.0374	65	0	0	0	0	1
4	6	0.0119	0.0414	0.009	90	0	0	0	0	1
5	7	0.046	0.116	0.0204	70	0	0	0	0	1
6	7	0.0267	0.082	0.017	130	0	0	0	0	1
6	8	0.012	0.042	0.009	32	0	0	0	0	1
6	9	0	0.208	0	65	0	0	0.978	0	1
6	10	0	0.556	0	32	0	0	0.969	0	1
9	11	0	0.208	0	65	0	0	0	0	1
9	10	0	0.11	0	65	0	0	0	0	1
4	12	0	0.256	0	65	0	0	0.932	0	1
12	13	0	0.14	0	65	0	0	0	0	1
12	14	0.1231	0.2559	0	32	0	0	0	0	1
12	15	0.0662	0.1304	0	32	0	0	0	0	1
12	16	0.0945	0.1987	0	32	0	0	0	0	1
14	15	0.221	0.1997	0	16	0	0	0	0	1
16	17	0.0524	0.1923	0	16	0	0	0	0	1
15	18	0.1073	0.2185	0	16	0	0	0	0	1
18	19	0.0639	0.1292	0	16	0	0	0	0	1
19	20	0.034	0.068	0	32	0	0	0	0	1
10	20	0.0936	0.209	0	32	0	0	0	0	1
10	17	0.0324	0.0845	0	32	0	0	0	0	1
10	21	0.0348	0.0749	0	32	0	0	0	0	1
10	22	0.0727	0.1499	0	32	0	0	0	0	1
21	22	0.0116	0.0236	0	32	0	0	0	0	1
15	23	0.1	0.202	0	16	0	0	0	0	1
22	24	0.115	0.179	0	16	0	0	0	0	1
23	24	0.132	0.27	0	16	0	0	0	0	1

Bus_i	Bus_j	R(pu)	x(pu)	b(pu)	RateA (S_{lim} MVA)	RateB	RateC	Ratio	Angle	Status
24	25	0.1885	0.3292	0	16	0	0	0	0	1
25	26	0.2544	0.38	0	16	0	0	0	0	1
25	27	0.1093	0.2087	0	16	0	0	0	0	1
28	27	0	0.396	0	65	0	0	0.968	0	1
27	29	0.2198	0.4153	0	16	0	0	0	0	1
27	30	0.3202	0.6027	0	16	0	0	0	0	1
29	30	0.2399	0.4533	0	16	0	0	0	0	1
8	28	0.0636	0.2	0.0428	32	0	0	0	0	1
6	28	0.0169	0.0599	0.013	32	0	0	0	0	1

Table 3.
Line data of IEEE 30 bus power system.

Bus	P_g (MW)	Q_g (MVAr)	Q_{max} (MVAr)	Q_{min} (MVAr)	V_g	S_{Base}	Status	P_{max} (MW)	P_{min} (MW)
1	0	0	200	−20	1.06	100	1	200	50
2	50.5846	0	100	−20	1.045	100	1	80	20
5	18.5227	0	50	−15	1.02	100	1	50	15
8	18.0865	0	60	−15	1.029	100	1	35	10
11	10.4038	0	50	−10	1.06	100	1	30	10
13	13.2553	0	60	−15	1.06	100	1	40	12

Table 4.
Generator data of IEEE 30 bus power system.

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