MULTI-OBJECTIVE PARETO NETWORK OPTIMIZATION PROBLEM FOR TECHNICAL, ECONOMICAL AND ENVIRONMENTAL OBJECTIVES

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REZUMAT. Nevoia de a exploata cât mai eficient rețelele electrice de distribuție, luând în considerație atât problemele economice cât şi de mediu, a dus la dezvoltarea şi implemetarea unor noi tehnici de optimizare care furnizează soluții potrivite ținând cont de aceste aspecte. Lucrarea propune o problemă de optimizare multi-obiectiv pentru găsirea solutiilor optime Pareto pentru încărcarea optimă a surselor de generare distribuită combinată cu o strategie Demand Response pentru modificarea consumului de energie a unor consumatori în rețea pentru obiective tehnice, economice şi de mediu.

Cuvinte cheie: optimizare, multiobiectiv, front Pareto, rețele de distribuție.

ABSTRACT. The need for efficient operation of distribution sytems, taking also into account the environmental impact and economic climate, has led researchers to implement new optimization methods that can provide suitable solution for these aspects. This paper presents a multi-objective optimization approach that finds the Pareto-optimal solutions for the optimal loading of the distributed generation sources present in a distribution system combined with a Demand Response strategy for modifying the consumption of some consumers in the network for technical, economical and environmental objectives.

Keywords: : optimization, multi-objective, Pareto front, distribution networks

1. INTRODUCTION

The current problems regarding the depletion of fossil fuel resources, environmental pollution and low energy efficiency, led to a new trend of generating energy locally by using small-scale, low-carbon or renewable energy sources, such as fuel cells, wind power, photovoltaic panels, combined heat and power (CHP) etc. This type of generation is called distributed generation (DG) [1] and the energy sources are called distributed energy resources (DERs).

Distributed generation (DG) generates electricity from low power sources (<50MW). Because, DG is a new approach in the electricity industry there is no generally accepted definition, but many definitions exist [2,3]. For example, in [3] DG is defined more in term of connection and location than in term of generation capacity. From all existing definition was drawn the conclusion that at least the small-scale generation units should be considered as part of DG. Taking into account the issues mentioned above and considering also the last European Union (EU) climate and energy package [4], whose targets involve a reduction by 20% of greenhouse gas emissions and use of primary energy, and the requirement that 20% of EU energy consumption to come from renewable resources , many countries have adopted this new energy generation in order to minimize the greenhouse gas emissions.

In general, DERs are modular units of small capacity, due to their lower energy density. DERs are being preferred for their reduced greenhouse gases and pollutant emissions, and for improving the overall power quality and reliability. These are usually placed near the loads and are geographically widespread [5].

On the other hand, for reducing energy usage during peak power hours or for improving the reliability by reducing the energy not supplied under contingency scenarious, the Demand Response (DR) programs [6] were implemented.

In general, DR refers to different types of actions, in normal or emergency conditions, which are taken at the user side to enhance the efficiency of the distribution system operation.

Thus, considering the need for a more efficient operation of the electricity distribution systems, considering also the environmental impact and economical constraints, new optimization techniques were developed and implemented for providing the most suitable solutions for these aspects. Because these objectives must be optimized simultaneously, multi-objective evolutionary algorithms can be used for finding the optimal solutions. Among the most used optimization techniques utilized in the present day are the multi-objective meta-heuristic algorithms such as Strength Pareto Evolutionary Algorithm 2 (SPEA2) [7,8], Pareto Archived Evolution Strategy (PAES) [9,10], Non-dominated Sorting Genetic Algorithm 2 (NSGA2) [11,12], etc, which involve special methods for taking into account more than one objective and for analyzing the solution obtained.

In this paper, a multi-objective optimization problem is proposed for finding the optimal loading of the DG sources combined with a DR strategy for modifying the consumption of some important consumers in the network. The concurrent objectives are minimization of energy losses, production cost or greenhouse gas emissions and profit maximization. For this purpose the NSGA II method was implemented in Matlab. This is one of the most popular evolutionary multi-objective algorithms, and can provide suitable compromise solutions, defined as Pareto fronts or Pareto-optimal solutions, for situations in which conflicting objectives exist.

2. MULTIOBJECTIVE OPTIMIZATION PROBLEM

In general, multi-objective optimization problems must be solved differently than single optimization problems. For the single objective, the goal is to find one solution, which usually is the global optimum [13]. In the case of multiple conflicting objectives, there is not only one solution, but a set of solutions considered as feasible for the entire set of analyzed objectives.

A multiobjective optimization problem [14,15] (with k objectives functions) can be defined as follows: if $f:\Re^n \rightarrow \Re^r$ is a vector of functions, a feasible solution $x^* = (x_1^*,...,x_n^*)$ is nedeed to be found, which satisfies:

- the inequality constraints:

$$g_i(x) \geq 0, \quad i = 1,\ldots,p \quad p \geq 0$$

- the equality constraints:

$$h_i(x) = 0, \quad i = 1,\ldots,q \quad q \geq 0$$

and which aims to optimize f, by minimization or maximization. Although some objective functions may require to be minimized, and some maximized, because any maximization problem can be switched in a minimization one, in this paper it will be considered that all the objective functions must be minimized.

Solving multi-objective problems involves finding a set of optimal solutions which allow the best compromise between the objective functions that are optimized. These solutions are called non-dominated solutions or Pareto-optimal solutions. The concept of Pareto-optimal was introduced by Vilfredo Pareto in 1896 [16].

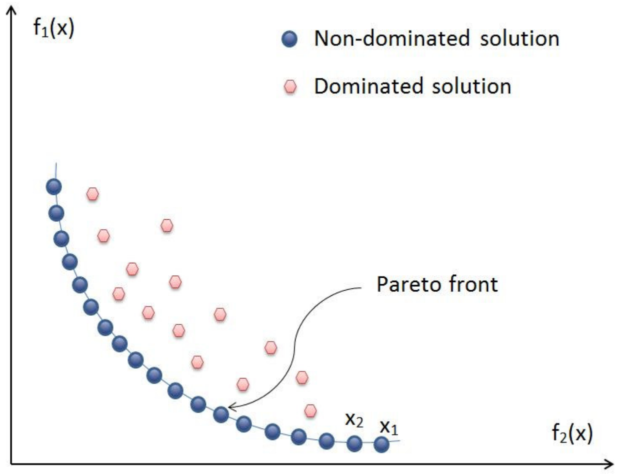

Fig. 1. Pareto-optimal front for a bi-objective problem

Most of the multi-objective optimization algorithms use the domination concept, when two solution are compared to see which one dominates the other.

A solution $x^* \in X$ is said to dominate another solution $x \in X$ if the following conditions are both true:

1. The solution $x^* \in X$ is no worse than $x \in X$ in all objectives.
2. The solution $x^* \in X$ is strictly better than $x \in X$ in at least one objective.

The Pareto-optimal solutions set, P^*, can be defined as:

$$P^* = \left\{x^* \in X \middle| \nexists y \in X : f(y) \leq f(x^*)\right\} \quad (1)$$

A solution $x^* \in X$ is a Pareto-optimal solution or a non-dominated solution, if and only if another solution $x \in X$, $f(x) \prec_{pareto} f(x^*)$ does not exist.

Thus, for a set of Pareto-optimal solutions, the Pareto front PF^* (Figure 1) is defined as:

$$PF^* = \left\{f(x^*) = (f_1(x^*),..., f_k(x^*)) \middle| x^* \in P^*\right\} \quad (2)$$

Each solution has a point on the Pareto front and represents a vector whose components are the trade-offs in the decision space. Obtaining the Pareto front is the main goal of the multi-objective optimization. Because the Pareto front can contain a large number of points, a good solution is to find a limited number of these points, which should be uniformly spread over the Pareto front and also be found as close as it can be to it. Choosing a solution over another is a matter of user decision.

3. NON DOMINATED SORTING GENETIC ALGORITHM II (NSGA II)

The Non dominated Sorting Genetic Algorithm II (NSGA II) was proposed by Deb et al. [17] and is one of the most popular evolutionary multi-objective algorithm.

The NSGA II uses:

- fast non-dominated sort strategy;
- diversity strategy;
- elite strategy.

The algorithm starts by generating a population of competing individuals, then it ranks and sorts each individual depending on its non-domination level. Thus, all individuals from the population will have assigned a rank (fitness) value depending on which front they belong to. The individuals that are situated in first front will have a fitness value of 1, the individuals from the second front will have the fitness value of 2 and so on.

A new parameter named crowding distance (CD) is introduced in addition to the fitness value, to measure how close an individual is to its neighbors. The CD has the role of keeping the diversity of the solution set and helps tha algorithm to explore the fitness ladscape. In this way the solution are spread along the Pareto front.

The next step is to create a new offspring pool by applying genetic operators (simulated binary crossover and polynomial mutation). After the offspring are created, the algorithm combines the old population with the current one obtaining a new pool which will be sorted again based on non-domination and only the best N individual, will be selected which passes to the next generation. The procedure of NSGA II is shown in Figure 2.

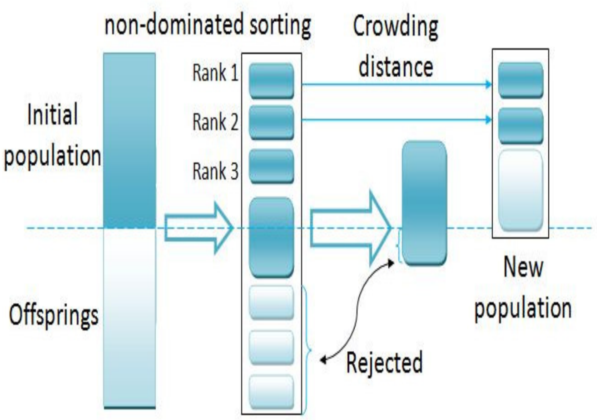

Fig. 2. NSGA II procedure

4. PROBLEM FORMULATION

This paper proposes a multi-objective optimization approach for finding the optimal loading of the distributed generation sources combined with a DR strategy for modifying the consumption of some important consumers in the network, taking into account the following objective functions:

- energy losses minimization:

$$\min\left\{ f_l(x) = \sum_{h=1}^{H} \sum_{b\in B} R_b \cdot I_{bh}^2 \right\} \tag{3}$$

where R_b is the resistance of branch b and I_{bh} is the current flowing through branch b at hour h.
H- the time frame of the optimization problem;
B- number of branches in the considered network.

- minimization of production cost for the energy supplied by local generators:

$$\min\left\{ f_C(x) = \sum_{t=1}^{T} (C_{Dg}(t) + C_{FC}(t) + C_{CPP}(t)) \right\} \tag{4}$$

where:

- production costs for the Diesel generator (C_{Dg}):

$$C_{Dg}(t) = \sum_{i=1}^{N} e_i \cdot P_{Dg,i}(t)$$

where:

e_i - Diesel fuel price; e_i =2□/kWh;

$P_{Dg,i}(t)$ – the output power (kW) of Diesel generator *i*, at interval *t*.

N – number of Diesel generators;

- production costs for Fuel Cells (C_{FC}):

$$C_{FC}(t) = \frac{C_{ng}}{C_p} \cdot \frac{P_t}{\eta_t}$$

where:

C_{ng} –the natural gas price; C_{ng} =1.5 □/kWh;

P_t –electrical power produced at interval *t;*

η_t – the cell efficiency at interval *t* (η_t =20-30%);

C_p – caloric capacity (C_p =10.462 kWh/m^3)

- production costs for coal power plant

$$C_{CPP}(t) = C_c \cdot P_t$$

where:

C_c – coal price; C_c =2.4 □/kWh;

P_t – power produced at interval *t;*

- greenhouse gas emissions minimization (GHG):

$$\min\left\{ f_{GHG}(x) = \sum_{t=1}^{T} \begin{pmatrix} E_{Dg} \cdot P_{Dg}(t) + E_{FC} \cdot P_{FC}(t) \\ + E_{CPP} \cdot P_{CPP}(t) \end{pmatrix} \right\} \quad (5)$$

where:

$P_{Dg}(t)$, $P_{FC}(t)$, $P_{CPP}(t)$ – the power produced by the Diesel generator, Fuel Cell and the coal power plant at interval *t*;

E_{Dg}, E_{FC}, E_{CPP} – emissions produced by the Diesel generator, Fuel Cell and the coal power plant at interval *t;*

- maximizing the profit of the owner of the DG sources:

$$\max\left\{ f_{\Pr}(x) = \sum_{t=1}^{T} (P_{cons,t} - P_{sys,t}) \cdot c \right\} \quad (6)$$

where:

$P_{cons,t}$ – power consumption of consumers at interval *t*;

$P_{sys,t}$ – power imported in the analyzed system at interval *t*;

c- price of energy sold by the owner of the DR souces to the local consumers; $c = 4$ □/kWh ;

Specific greenhouse gas emissions (GHG) considered for this study case are shown in Table 1.

The goal of this paper is to find pairs of conflicting objective functions, for which the NSGA II method can be applied to obtain Pareto optimal solutions

5. STUDY CASE

For the study case, a test radial distribution network with N = 44 nodes, B = 47 branches, S = 4 supply nodes and Q = 7 open branches was considered [18].In order to simplify the computation, the supply nodes are considered as a single slack bus.

Several local generators are considered connected to the network as follows:

- two wind turbines with a rated constant power of 50 kW, one placed at node 10 and one at node 23;
- a 50 kW photovoltaic system (PV) at node 17;
- a Diesel generator at node 16 with capacity of 90 kW;
- a Fuel Cell at node 20 with capacity of 70 kW;
- a coal power plant at node 24 with capacity of 80 kW.

For the wind turbines and PV system a forecast was received for the analyzed time interval (4 hours), so during the optimization process their loading will not be modified. The load for the rest of local generators (Diesel generator, Fuel Cell and coal power plant) will change for finding the best solution which optimizes the objective functions mentioned above, but will be limited in order to prevent reversed power flow (export) from the analyzed system. Thus, the allowed power generation of the Diesel generator, Fuel Cell and coal power plant, which satisfy this constraint, for the time interval analysed, are presented in Table 2.

Four different types of consumers are considered in this network: commercial, residential, services, and industrial. The consumers which participate in DR programs are considered to be the industrial consumers and are placed in the nodes 10, 21, and 30. The DR consumers can modify their load at each hour, but the total load for the analyzed time interval must remain the same.

Before the technical, economical and environmental multi-objective optimization, the optimal configuration of the analyzed system was determined first, based on the average consumption and the average production of the distributed generated sources, for the last trimester of the year. The reconfiguration problem was solved by

Table 1

Specific greenhouse gas emissions (GHG)

	Diesel generator	**Fuel Cell**	**Coal Power Plant**	**System**
NOx [kg/kWh]	0.0021	0.000004	0.00254	0.00204
SO_2 [kg/kWh]	0.0002	0.00000226	0.006168	0.00444
CO_2 [kg/kWh]	0.64954	0.4309124	0.95934	0.7339

Table 2

Power generation of the local sources

Sources	**Generated power at hour h1**	**Generated power at hour h2**	**Generated power at hour h3**	**Generated power at hour h4**
Diesel Generator [kW]	74	75	71	65
Fuel Cell [kW]	55	57	54	49
CPP [kW]	56	55	53	50

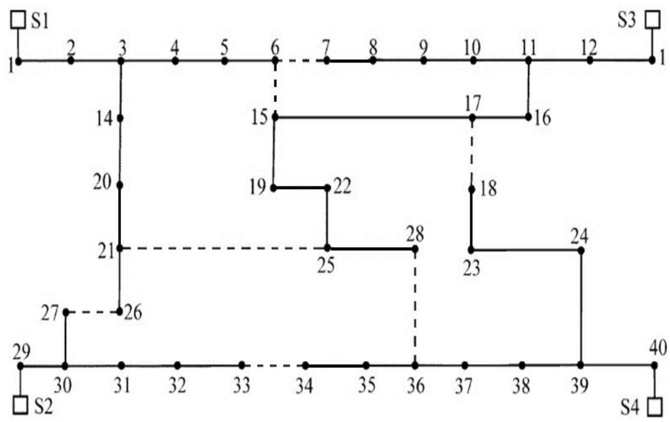

Fig. 3. New network configuration

applying the branch-exchange method for energy losses minimization, which was implemented also in Matlab. The optimal configuration radial configuration obtained with this method is shown in Figure 3.

In order to choose the objectives which will be paired for finding their Pareto front using NSGA II method, a metaheuristic algorithm, the Differential Algorithm (DE), was used for running each objective function, for a population with 100 individuals and for 100 generations. Each time, all the objective functions were computed even if the optimization was made for a single objective. For example, if energy losses were optimized in the sense of minimization, also the production cost, the emissions and the profit were computed. The results of these tests are presented in Table 3. It can be seen that when, for example, the costs are optimized in the sense of minimization, the emission decrease also, but the energy losses and the profit increase.

Thus, considering the results from Table 3, three different bi-objective optimization problems were considered for finding the non-dominated solutions set (Pareto front):
- case I: minimization of energy losses and minimization of production costs;
- case II: minimization of energy losses and minimization of greenhouse gas emissions;
- case III: minimization of greenhouse gas emissions and profit maximization.

For solving the objective functions described in (3), (4), (5) and (6) using NSGA II algorithm, it is required to represent the possible solutions using chromosome chains. The chromosome structure for the optimization multi-objective problem is presented in Figure 4.

Each bi-objective optimization problem was run for 500 generations and for a population of 300 individuals. The optimization time interval is set to 4 hours, (10, 11, 12 and 13 from the analyzed day). Thus, the chromosome will have 24 gene (Figure 4):
- genes 1 – 12 represent the power generated by the Diesel generator, Fuel Cell and coal power plant at the analyzed time interval;
- genes 13 - 24 represent the consumption of the three DR consumers in the network, for the analyzed time interval.

In tables 4, 5 and 6 are given examples of optimal solutions found by the NSGA II method for cases I, II and III described above. It can be seen that, when production costs are minimal, the energy losses increase, and vice versa. The same happens when the energy losses and the greenhouse gas emissions are optimized. In this case,it can be observed that it is preffered not to generate power from de coal power plant because the greenhouse gas emissions are very high. Thus, the other DR sources are loaded at maximum and the rest of the needed power is imported. In 3rd case, the same thing is observed when minimizing greenhouse gas emissions. When the profit is needed to be maximized, because the energy imported from outside the system must be minimal (see (6)), the energy is generated mostly by the local production sources, and because the coal power plant has the higher greenhouse gas emissions (Table 1), the emissions also increase.

In Figure 5, 6 and 7 the Pareto front for the cases I, II and III considered for optimization are presented.

Because, in the absence of any further information, it cannot be said that any Pareto solution is better than another, a decision maker is needed for choosing an optimal solution depending on his own prioritary objective.

Table 3

Comparation between objective functions in the case when only one is beeing optimized

Optimization	Costs	Emissions	Profit	Energy losses
Costs	**decrease**	decrease	increase	increase
Emissions	decrease	**decrease**	increase	increase
Profit	decrease	decrease	**increase**	increase
Energy losses	increase	increase	decrease	**decrease**

$g1 \cdots g4$	$g5 \cdots g8$	$g9 \cdots g12$	$g13 \cdots g16$	$g17 \cdots g20$	$g21 \cdots g24$
$Pg_{Dg,h}$	$Pg_{FC,h}$	$Pg_{CPP,h}$	$Pc_{DR1,h}$	$Pc_{DR1,h}$	$Pc_{DR1,h}$

Fig. 4. Chromosome structure used for implementing NSGA II method

Table 5

Optimal solutions founded for case I

Optimal solution obtained using NSGA II method																							
Power generation of Diesel Generator				Power generation of Fuel Cell				Power generation of coal power plant				Consumption for DR1				Consumption for DR2				Consumption for DR3				Energy losses [kWh]	Production cost [¢/kWh]
63	73	70	65	55	56	53	49	24	46	22	26	13	23	26	17	22	14	28	5	23	17	24	10	0,1032	1209
17	15	6	2	54	42	36	36	32	31	30	29	21	20	22	17	24	19	14	11	19	16	20	18	0,0669	1431

Table 6

Optimal solutions founded for case II

Optimal solution obtained using NSGA II method																									
Power generation of Diesel Generator				Power generation of Fuel Cell				Power generation of coal power plant				Consumption for DR1				Consumption for DR2				Consumption for DR3				Energy losses [kWh]	GHG [kg]
69	75	70	65	56	56	53	49	4	5	7	2	27	28	12	13	17	17	20	15	15	22	7	30	0,1124	440
15	14	6	3	39	37	37	48	30	31	31	30	18	20	23	19	17	14	15	23	20	19	16	18	0,0667	505

Table 7

Optimal solutions founded for case III

Optimal solution obtained using NSGA II method																									
Power generation of Diesel Generator				Power generation of Fuel Cell				Power generation of coal power plant				Consumption for DR1				Consumption for DR2				Consumption for DR3				Profit [cent]	GHG [kg]
65	75	69	62	56	56	53	49	1	2	1	1	20	23	11	26	17	10	12	30	20	9	22	23	3139.	440
64	73	71	66	55	55	53	49	55	56	48	49	19	14	32	15	9	29	14	17	24	23	7	20	3969	487

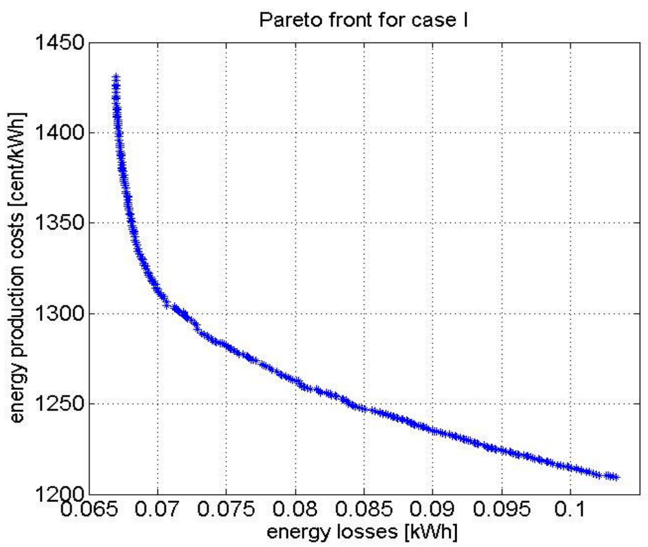

Fig. 5. Pareto-optimal solution for case I

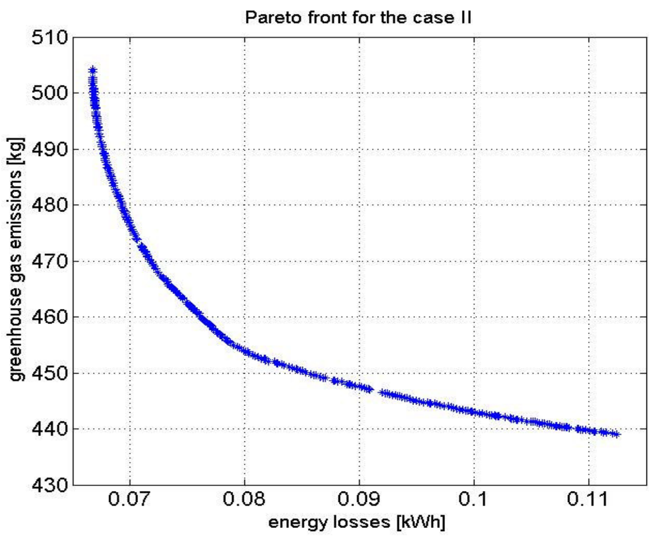

Fig. 6. Pareto-optimal solution for case II

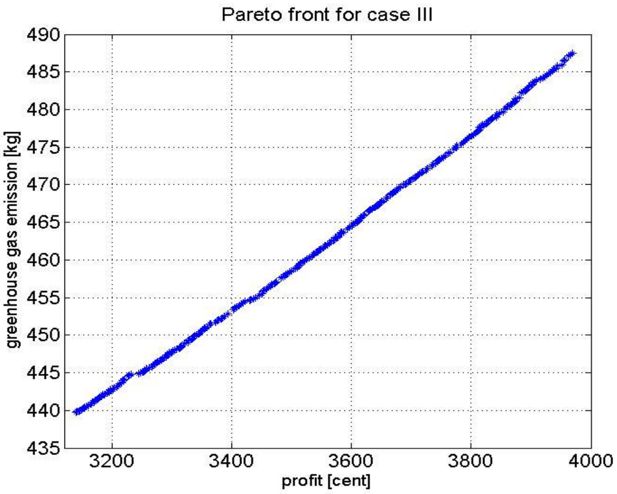

Fig. 7. Pareto-optimal solution for case III

6. CONCLUSIONS

This paper presents a study case regarding multi-objective optimization solved using a evolutionary metaheuristic algorithm.

In order to solve the optimization problem a 44-node distribution network with 6 DG units was used.

The NSGA II method was utilized for the study case and implemented in Matlab. This technique aims to find the optimal loading of the DG sources combined with a DR strategy for optimizing technical, economical and environmental objectives with the aim of obtaining the most suitable compromise solutions, defined as Pareto fronts, so the decision-maker could have more options to choose from.

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