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Methodology for Minimizing Power Losses in Feeders of Large Distribution Systems Using Mixed Integer Linear Programming

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Abstract. This research work presents a reconfiguration experience of a real case power distribution networks aiming to minimize the active power losses and consequently to improve the voltage profile of the overall grid. The grid is modelled as a mixed integer linear programming problem whose objective function is to minimize the active power losses subject to technical constraints, which are: the power balance in each node of the power grid, the capacity limits of the lines and the substations, maintaining the radial operation of the network. The model results are the open branches on each circuit. The technique has been successfully applied to a large power distribution networks with 2344 nodes at a 13.8kV level, located in real city resulting in an 8% and 6% losses reduction in terms of active power losses and energy respectively, and a substantial improvement in the voltage profiles regarding the current state of grid with very acceptable convergence times.

Keywords. Distribution system, Optimal Reconfiguration, Mixed-Integer Linear Programming, Optimization.

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1. Introduction

Reconfiguration is an attractive alternative for active power losses reduction in radial power distribution systems. The reconfiguration procedure consists in minimizing losses by determining the switches states open or closed till to obtain a radial and connected distribution networks topology. Nowadays the distributions grids require a constant adaptation in terms of its operation, allowing reducing the loss rates, and thus obtain energy savings that will benefit consumers and suppliers companies. In the literature, there are many methodologies for optimization of distribution systems [1]-[12] requiring large computational effort to solving large problems.

Due to vaster references number on this subject of optimal reconfiguration of distribution networks, only the works published on the last decade are considered in this paper aiming to highlight the most recent advances on this important subject.

In [1, 18] a systematic feeder reconfiguration technique that develops an optimal switching scheme is presented, maximizing the losses reduction in a distribution network. Meanwhile, in [2] an improved method based on a refined genetic algorithm to study the distribution network reconfiguration is proposed. In [3], a control strategy of open-closed status of the tie-switches is proposed. In this control strategy, the tie-switches are installed at the MV/LV substations, in this way; each line can be sectionalized at both ends, where the substations are located. Detailed features of this method can be seen in this reference. In [4] a method for feeder reconfiguration for load balancing among distribution feeders is proposed. The G-nets inference mechanism with operation rules is applied to derive the optimal switching operation decision to perform the optimal load transfer among feeders after the fault has been identified and isolated. In this method, the customer information systems and the transformers in outage management are used to determine the daily load patterns of service areas, sectionalizing switches, distribution feeders and main transformers. In [5] proposes a method that maximizes a fuzzy index using a maximum loadability index (MLI) that gives a measure of the proximity of the present state of a line in the radial distribution systems (RDS) to maximum loadability.

The MLI is computed at each bus of RDS. The value of this index, close to 1.0, indicates that the feeder is overloaded and would be unable to supply more apparent power. The overloaded buses may be identified by using this index, and adequate action may be used for improving the optimal reconfiguration scheme. Ref. [6] applied Genetic–Tabu algorithm (GTA) that is a tabu search combined with Genetic algorithm to find a global solution for optimal service restoration and reconfiguration of distribution networks. Ref. [7] presents an algorithm based on heuristic strategy that starts with the system in a meshed status with all switches closed.

The choice of the switches to be opened is based on the calculation of the minimum total network losses using a load–flow program. Ref. [8] introduces an ant colony search algorithm to solve the optimal network reconfiguration for power losses reduction. Ref. [9] proposes both a deterministic branch and bound algorithm included in the CPLEX optimization package and a genetic algorithm to solve the large scale mixed-integer-programming formulation of the distribution reconfiguration problem. Ref. [10] describes a genetic–algorithm for reconfiguration of a distribution network in order to minimize financial losses due to voltage sags.

The proposed method starts with a selected number of switches that generate various topologies. Load–flows are then performed to evaluate the feasibility of these topologies. For each of these topologies, fault analysis is performed to first calculate voltage sags at different buses and then, to compute financial losses incurred by voltage sags at buses with sensitive industrial process. The developed software-based methodology has been applied to a 295-buses generic distribution system. Ref. [11] contributes such as a technique at low–voltage and medium–voltage levels of a distribution network simultaneously with reconfiguration at both levels. This Reference introduces a heuristic method for the phase balancing/loss minimization problem. A comparison of this heuristic with the neural networks is also performed. The application in conjunction of the neural network with the heuristic method that enables different reconfiguration switches to be turned on/off and connected consumers to be switched between different phases to keep them balanced is also carried out.

Ref. [13] proposes an improved Tabu Search algorithm for loss-minimum reconfiguration in apparently large-scale distribution systems. This algorithm take advantages of the features of the network structure itself and make Tabu Search algorithm be more suitable to solve the reconfiguration problem. ITS algorithm with mutation operation and high quality candidate neighbourhood has been developed in this work. This methodology has been tested to an 11 kV distribution system with 118 sectionalizing switches and 15 tie switches.

Ref. [14] presents an application of the ant colony optimization concepts to the optimal reconfiguration of distribution systems. The considered objective is to minimize the power losses at distribution systems. The methodology has firstly been tested in a distribution network 33 nodes the Baran and Wu case, where, the obtained active power losses on the base case are 176.4 kW and after application of the methodology the obtained active power losses are 127.4 kW.

These reported value are not true at all, please see reference [15] where this example has been studied by many others researchers around the world. The values reported are 202 kW in the actual state of the network, and after reconfiguration the active power losses are 139.5 kW. The methodology has secondly been applied to a 531 nodes distribution network. The characteristics and data of this distribution networks are omitted.

Ref. [16] proposes a rule based comprehensive approach to study distribution network reconfiguration. The proposed algorithm consists of a modified heuristic solution and the rules base. The objective is minimizing the system power loss. The methodology has been tested on a small distribution system of 33 nodes.

Ref. [17] presents a (PSO) algorithm to solve the optimal reconfiguration problem minimizing the power loss. The PSO algorithm is introduced with some modifications such as using an inertia that decreases linearly during the simulation process, which allows the PSO to explore a large area at the start of simulation. This methodology bas been tested on two test distribution systems of 32 nodes and 69 respectively.

Ref. [15] presents a deterministic methodology to solve the distribution network reconfiguration problem. It is worth to mention that the formulation stated in this reference is the complete one, because it takes into consideration not only the switching status opened/closed, but also the transformer taps, the distributed generation and the capacitors bank steps. This formulation has been solved by benders decomposition technique that consists on dividing the problem in master and slave. The first one is to determine the distribution networks topology that must be sent to the slave problem for adjust the system parameters. This methodology has been tested on 201 nodes real distribution networks.

As can be seen there are widely used models dealing with the distribution reconfiguration problem. Many techniques have also been used to solve the reconfiguration problem, deterministic, evolutionary and inspired algorithms, but all the tested and published methods have a limited horizon regarding to tested distribution networks. No large distribution systems that consist of more than 600 nodes have been tested. The new contribution of this paper is the application and testingthe proposed methodology to real large distribution systems consisting of 2344 nodes, 3 substations and 10 primary distribution feeders.

The paper is organized as follows: Section 2 explains the reconfiguration problem formulation of power distribution networks. Section 3 identifies the optimization technique to solve the proposed model. Section 4 explains the analysis and validating the results. Section 5 exposes the mathematical model of the case under study. Section 6 analyses the real case study and finally Section 7 highlights the main conclusions of this research work.

2. Formulation of The Problem of Distribution Networks Reconfiguration

The problem of distribution networks reconfiguration can be formulated as an MILP type optimization problem. Thus, it is necessary to develop a type of methodology that can solve the problem under study. In order to formulate the problem, it is necessary to define a mathematical model, so the annual costs of active power losses within the network can be minimized (small investments). Active power losses have a square expression, according to the power rate which circulates through the lines. Thus, it is important to conduct approximations and use linear optimization techniques which lead to best mathematical solutions and reduced computer time calculation.

In order to investigate distribution networks reconfiguration, a mathematical model is proposed to minimize annual costs of power losses on the lines. In the case the company does not want to invest on build new line sections nor new substations. The model can include many aims as per the operator/planner considerations.

Active power losses have a square expression according to the power which circulates on the lines. In this work, it is estimated that conducting approximations and using linear methods which offer almost exact mathematical solutions will be used.

The developed mathematical model has the following components:

Variables declaration: Includes two variables groups

a) Representation of the powers which circulate through early network line segments. Powers occupy the first column (L_i) on the coefficient matrix of the mathematical model's variables and are real variables:

$$X_i \geq 0;\ i = 1, \ldots, L_i \quad (1)$$

b) The variables for the decision of opening/closing the line selected, which are attached to correspondent powers, at a 1 to 1 ratio, in other words, powers which circulate through the lines if there are any. Integer variables occupy the following columns within the coefficient matrix:

$$X_i;\ i = L_i + 1, \ldots, 2L_i \quad (2)$$

These are binary variables which indicate when a certain line is opening/closing by means of a switch.

c) Integer variables which represent the need to expand or increase substations, for instance, installing *L* expansion capacities on a *p* substation, are represented by the binary variable$Y_{P,L}$. If there are N_t feeding points to expand the network and each of them must evaluate several capacities of transformers substations to select the most suitable capacity (analysing technical-economic factors), the quantity will be different for each Substation. If it is $N_c(p)$, there are $\sum_{p=1}^{N_t} N_c\,(p)$ integer variables, occupying the columns:

$$i = 2\,L_i + 1, \ldots, 2L_i + 1 + \sum_{p=1}^{N_t} N_c\,(p) \quad (3)$$

2.1 Objective function

The problem of electric power distribution networks reconfiguration can be formulated as a linear programming problem with binary variables. Its solution includes a selection of, among other possible configurations, the one which results in less active power losses and subjected to a set of constraints:

- Radial configuration of the distribution system;
- Acceptable voltage levels;
- Reliability, among others.

In this section, authors are trying to minimize the costs of energy losses by using loss curves piecewise linearization to linear functions (straight small sections). Generally, this function can be written as follows:

$$\text{Min F} = \text{Z}_1 + \text{Z}_2 + \text{Z}_3 \tag{4}$$

Objective function components are:

a) Cost of losses within the feeder braches or lines (Z_1)

In N_d load nodes, the set of lines which enter the nods coincide with the total number of paths on the initial network. Considering the linearized expression of power losses to the maximum load condition [46] the following expression was obtained:

$$Z_1 = \sum_{i=1}^{N_d} \sum_{k=IN(i,1)}^{IN[i,Kl(i)]} C \cdot [S(k)]^2 \cdot W(i,k) \tag{5}$$

where:

IN(i, k): Line reference number k which enters the i node; $\text{k} = 1, \dots, \text{Kl(i)}$

Kl(i): Quantity of lines which enter the i node

S(k): Is the apparent power which circulates through k lines (kVA); $\text{k} = 1, \dots, \text{L}_\text{i}$

C : Is the coefficient of the cost of losses due to the power which circulates through the lines [*€/(kVA.year)*]

$C = C_1$ If there is a three-phase section branch and otherwise $C = C_3$

$$C_1 = \frac{\rho \cdot J_{eco} \cdot (12 \cdot Cd + Ce \cdot Fpd \cdot 8760) \cdot FVA \cdot D_{ij}}{\sqrt{3} \cdot U_l} \tag{6}$$

$$C_3 = \frac{4 \cdot \rho \cdot J_{eco} \cdot (12 \cdot Cd + Ce \cdot Fpd \cdot 8760) \cdot FVA \cdot D_{ij}}{\sqrt{3} \cdot U_l} \tag{7}$$

$$FVA = (1 + RI)^t; \quad t = 1, \ldots, N \tag{8}$$

being:

FVA : Is the conversion factor for the current value of the losses cost, this is because the investments in several variants are made in different years. It is necessary to reduce costs in the first year [19]

ρ : Resistivity of the conductors or cable material (Ω-mm^2/km)

Cd : Contracted power rate (*€/kVA/month*); is this type of tariff is applied

Ce : Cost rate *(€/kVA.h*). It is supposed to be a uniform power factor in the network

Fpd : Loss factor

U_l: Line-to-line voltage (V)

R_l: Capital growth rate (%/ year)

N : Lifetime of the project (year)

$D_{ij} = L$: Distance between two nodes (m)

The linearization of the objective function was conducted according to the Venikov criterion [24]. This approximation supposes that the facilities lines conductors are working close to the rated current which is the economic density (J_{eco}).

$$I = J_{eco} \cdot S_{ec} \tag{9}$$

where:

J_{eco}*:* Current economic density (*A/mm^2*)

S_{ec}*:* Conductor's cross section area (*mm^2*)

The active power losses are:

$$\Delta P = k' \cdot R \cdot I^2 = k' \cdot R \cdot I \cdot I \tag{10}$$

replacing:

$$\Delta P = k' \cdot R \cdot J_{eco} \cdot S_{ec} \cdot I \tag{11}$$

and therefore:

$$I = k'' \cdot \frac{S}{U_l}; \qquad R = \frac{\rho \cdot L}{S_{ec}} \tag{12}$$

Where:

k' and k'' are constants which depend on the type of service (single-phase or three-phase).

S : Load power (kVA)

R : Conductor's resistance (Ω/km)

I : Current passing through the conductor (A)

Substituting:

$$\Delta P = \frac{k \cdot \rho \cdot L \cdot J_{eco}}{U_l} \cdot S \tag{13}$$

It is a linear expression is function of the apparent power.

b) Investment cost on the network lines (Z_2) in the case of expanding the network

The expression used to this end was:

$$Z_2 = \sum_{i=1}^{N_d} \sum_{k=IN(i,1)}^{IN[i,Kl(i)]} K_{el} \cdot W_{(i,k)} \tag{14}$$

Using the formula:

$$K_{el} = (E_n + N_{el}) \cdot K_{il} \tag{15}$$

where:

E_n: Economic effectiveness ratio (1/year).

$$N_{el} = (N_{al} + N_{oe}) \quad (16)$$

N_{el}: Scanning the lines rule or utility norm (1/year)

N_{al}: Amortizing the lines rule or amortizing norm according to Company Standards (1/year)

N_{oe}: Company's fixed costs rule according to Company Standards (1/year)

K_{il}: Line investment costs (€/km)

$W_{(i,k)}$: Integer of installing a line from the *k* to the *i* node

c) Transformers investment cost (Z_3)

There are N_t feeding points with $N_c(p)$ evaluated capacities in each point.

$$P = 1, \dots, N_t$$

then:

$$Z_3 = \sum_{p=1}^{N_t} \sum_{l=1}^{N_c(p)} K_{et} \cdot Y_{(p,l)} \quad (17)$$

The K_{et} parameter includes a capital inflation rate, a fixed exploration costs rule and costs that come from iron losses in the transformers.

where:

$$K_{et} = (E_n + N_{et}) \cdot K_{it} + K_{\Delta Fe} \quad (18)$$

where:

K_{it}: Total investment cost in the transformers (€)

$$N_{et} = (N_{at} + N_{oe}) \tag{19}$$

N_{et}: Fixed exploration costs rule or exploration norm according to Company Standards (1/year)

N_{at}: Transformers amortization rule or amortizing norm for transformer according to Company Standards (1/year)

$K_{\Delta Fe}$: Cost that come from iron losses in the transformers (€/year)

$Y_{(\text{p,L})}$: Binary variable for the decision of installing a L capacity on point P

The objective function includes copper loss costs in the transformers, taking another author [19] into consideration. Indicating the reasons for this cost:

- Load losses are expressed considering the square function.

$$\Delta P = P_k \cdot (S/S_n)^2 \tag{20}$$

where:

Δp : Copper losses in the transformers (kW)

P_k: Power losses with loads (kW)

S : Apparent load power (kVA)

S_n: Apparent transformer nominal/rated power

In the objective function it is necessary to linearize the copper's loss expression, introducing small errors into the final results.

Transformers are limited to work between a maximum and minimum apparent power interval S (kVA), $S_{min}(l) \leq S \leq S_{max}(l)$ which is usually between the transformer's 70% and 100% rated or nominal capacity.

where:

l : Capacity of the installed transformer in each substation (kVA)

Total loss costs have a square variation, and so the variable cost component can be used both in nominal capacity $S \leq S_n$ and smaller loads. This is a small component when compared to the fixed cost, concluding that:

$$(S/S_n)^2 < (S/S_n) < 1 \tag{21}$$

and so, acceptable intervals to work on the variable cost difference, comparing several capacities, are small. When despised, there are no serious mistakes.

2.2 Technical constraints

a) Power balance in the nodes *(Kirchhoff's First Law for apparent power):*

Includes all load nodes and is expressed according to the apparent power in (kVA), supposing that there is a single power factor to the network.

$$\sum_{k=1}^{K_1(i)} S[IN(i,k)] - \sum_{k=1}^{K_2(i)} S[IT(i,k)] = S(i); \quad i = 1, \dots N_d; \quad k = 1, \dots, K_2(i) \quad (22)$$

where:

$IT_{(i,k)}$: Reference number for lines leaving the i node

S : Apparent power circulating through the line (kVA)

$K_2(i)$: Quantity of line leaving the i node

$K_1(i)$: Quantity of line entering the i node

$S(i)$: Apparent load power of the i node (kVA)

b) Capacity selection in each substation:

In each *p* substation point, only one transformer already existent on the initial network will be installed (if necessary, in case of expansion) through the following expression:

$$\sum_{i=1}^{N_c(p)} Y(p,l) \leq 1; \quad p = 1, \dots, N_t; \quad l = 1, \dots, N_c(p) \quad (23)$$

c) Eliminating minimum load or underutilized substations:

This restriction helps eliminating disabled substations

$$\sum_{k=1}^{K_2(p)} S[IT(i,k)] \geq S_{min}(l) \cdot Y(p,l); \quad p = 1, \dots, N_t; \quad l = 1, \dots, N_c(p) \quad (24)$$

where:

$S_{min}(l)$: Minimum acceptable load limit imposed by the rules of related institutions (kVA) or electricity company utility.

d) Maximum load limitation or overload in substations:

This constraint enables a maximum load limitation in each substation, this avoiding their overload.

$$\sum_{k=1}^{K_2(p)} S[s, IT(i,k)] \leq S_{max}(l) \cdot Y(p,l); \quad p = 1, \dots, N_t; \quad l = 1, \dots, N_c(p) \quad (25)$$

where:

$S_{max}(l)$: Maximum acceptable load limit (kVA). This value is usually defined by the electric utility.

e) Thermal limit in lines:

Power circulating in each line cannot exceed the maximum limit imposed by itself.

$$S(k) \leq SL(k)_{max} \cdot W(i,k); \quad k = IN(i,k), \dots, IN[i, K_1(i)]; \quad l = 1, \dots, N_d \quad (26)$$

where:

SL_{max}: Maximum apparent power allowed by the line capacity (kVA)

$W(i,k)$: Binary variable of line decision

f) Radial configuration condition:

Each load node receives energy from one single line.

$$\sum_{k=IN(i,1)}^{IN[i,K_1(i)]} W(i,k) = 1; \quad i = 1, \dots, N_d \quad (27)$$

g) General load power limitation according to the capacities of substations or electric power generation unities. General power balance of the distribution system.

The total load power at a given substation point must be lower or equal to the sum of the maximum capacity of each substation.

$$\sum_{k=IT(p,1)}^{IT[p,K_2(p)]} S(k) \leq S_{max}\,[N_c(p)] \cdot Y[p, N_c(p)]; \qquad p = 1, \dots, N_t \quad (28)$$

where:

$S(k)$: Apparent power sent in each output line capacity (kVA)

h) Eliminating two-way power flow directions on the lines:

The line should have one way only.

If the $lk = IT\ (i,k)$; $k < K_1(i)$ and $K_1 = IN(i,k)$; $k < K_2(i)$ then:

$$W(i, lk) + W(i, kl) \leq 1; \quad j = 1, \dots, N_d \quad (29)$$

where:

i : Node references

kl : Line references

The constraint on the maximum voltage drop is not directly established in this model. Initially, the network's configuration is not known, such as, for instance, the number of network branch lines. A branch line is a section that starts from the transformer rand finishes on the last connected load. It should be pointed out that when network losses rise, voltage drops rise, and so the cost of power losses in the objective function demands a punishment in the cost minimization process [20-23].

One way of confirming the demands of voltage drops is when the network is relatively large, is through the power flow which circulates through the radial system after finishing the optimization process. According to the results of the power flow, it is possible to confirm that the values have violated the capacity of line sections. Constraints f and h might be considered redundant, but in practice it is possible to observe that they help increasing the speed while searching for an optimal solution. The quantity of variables considers slack and artificial variables through the following expression:

$$QV = 2 \cdot L_i + \sum_{p=1}^{N_t} N_c(p) \tag{30}$$

where QV : Quantity of mathematical model variables.

This quantity depends on the total number of lines (L_i), the quantity of substation points (N_t) and suggested capacities in each point [$N_c(p)$].

Amount of expressed restrictions:

$$QR = L_i + 2 \cdot N_d + 2 \cdot N_t + NE + 2 \cdot \sum_{p=1}^{N_t} N_c(p) \tag{31}$$

where:

QR: Quantity of restrictions on the mathematical model

NE: Number of equations resulting from two-way flow lines

3. Identification of Optimization Techniques to Solve The Proposed Model

The problem of the distribution networks reconfiguration can be formulated as a MILP type problem to which the solution would be the optimal topology of the network. All technical constraints must be satisfied, such as the power balance in all the nodes and the feeders, minimum and maximum substations load limits, thermal limit in the lines and the radial configuration condition of resulting networks. This is a combinatorial optimization programming problem and has two types of variables: binary or complicated variable, as they are usually called which are integer and continuous variables and represent the powers circulating through the branches of the network, and integer variables of the substations which may be installed into the substations points. When the number of these binary variables is increased, execution time becomes exponential function according to the time of computer calculation.

This type of problem is difficult to handle because of its combinatory nature, in addition to the difficulty in creating a mathematical formulation of certain constraints such as the radial configuration of resulting networks. There is also the problem with integer and continuous variables, which makes it a MILP problem even more difficult to solve.

The network on Fig. (1) has 4 load nodes and 2 nods as substation points. The network is made of two branch lines which are represented, in the figure, with thick lines. The dotted lines are open lines in normal operation conditions and their switches are represented on figure (1). The conductor parameters and technical data are shown on Table (1). Each circuit is fed through a 100 kVA transformer. Loads are shown in Fig. (1).

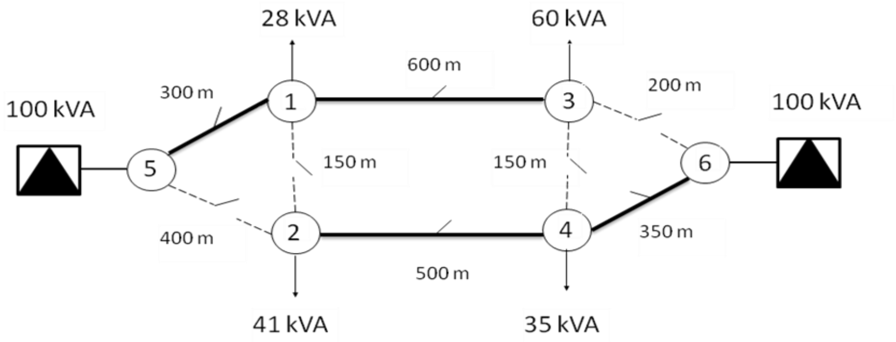

Fig. (1). Current state distribution network.

It is necessary to know the current state of the network and, in order to obtain that information, a power flow for radial distribution networks is executed. In this case, it is very simple to know the power loss values. These values are shown on table (2) and, when they are analyzed, it is possible to deduce that this network is not operating in an optimal condition. In order to determine the state of the optimal operation of this network, it is necessary to formulate the optimization problem.

Table (1). Network data.

Branch	Initial Node	Final Node	Distance (m)	Conductor				
				Section (mm^2)	R (Ω/km)	X (Ω/km)	I_{MAX} (A)	J_{ECO} (A/mm^2)
1	5	1	300	3x400 AL	0.102	0.096	515	0.5114
2	5	2	400	3x400 AL	0.102	0.096	515	0.5114
3	2	1	150	3x150 AL	0.265	0.101	285	0.8631
4	1	2	150	3x150 AL	0.265	0.101	285	0.8631
5	3	1	600	3x150 AL	0.265	0.101	285	0.8631
6	1	3	600	3x150 AL	0.265	0.101	285	0.8631

Continu table (1)

Branch	Initial Node	Final Node	Distance (m)	Conductor				
				Section (mm^2)	R (Ω/km)	X (Ω/km)	I_{MAX} (A)	J_{ECO} (A/mm^2)
7	4	2	500	3x150 AL	0.265	0.101	285	0.8631
8	2	4	500	3x150 AL	0.265	0.101	285	0.8631
9	3	4	150	3x150 AL	0.265	0.101	285	0.8631
10	4	3	150	3x150 AL	0.265	0.101	285	0.8631
11	6	3	200	3x400 AL	0.102	0.096	515	0.5114
12	6	4	350	3x400 AL	0.102	0.096	515	0.5114

Table (2). Current state network losses.

Current state of the network		
Branch	Power losses (kW)	Power losses (kVA)
5-1	1.48	1.69
1-3	3.58	3.89
2-4	1.39	2.22
4-6	1.29	1.70
Total	7.74	9.50

4. Analyzing and Validating The Results

The optimization problem is based on the initial network shown on Fig. (2). In this figure, a single power flow sense is shown when there is no doubt about its sense, for instance, between nodes 5-1, 5-2 and 6-3 and 6-4. Logically, power circulates from the source nodes until loading nodes where these powers will be consumed. When flow senses are not obvious, then they are represented with double opposite senses in order to give node 1 the possibility to, for instance, receive energy from the node 5 transformer or any other way through node 6 which represent another power source.

In order to formulate the optimization problem, powers are represented by the letter *S* and directions are represented by the numbers of involved nodes respectively. For instance, S_{51} means that the apparent power circulates from node 5 to node 1. This power is apparent and its unit is kVA.

In order to find the optimal operational configuration of the radial network, it is necessary to minimize power losses in this case, because circuits are built and so, the investment cost is null, and it is not necessary to build new branches.

The network in figure (2) has 12 lines and 2 transformers installed in nodes 5 and 6 respectively. Our aim is to minimize power losses which are the square function of the apparent power. It is necessary to calculate objective function coefficients. These values are shown in table (3).

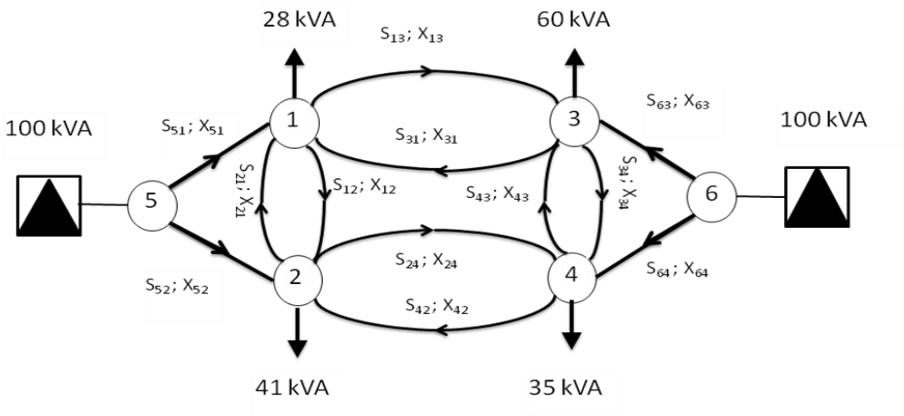

Fig. (2). Initial considered network

Table (3). Technical features of the conductors.

Branch	Initial Node	Final Node	Conductor		
			Section (mm^2)	Thermal capacity per phase (kVA)	Loss coefficient * 10^{-3} (kVA)
1	5	1	3x400 AL	118.45	19.21
2	5	2	3x400 AL	118.45	25.61
3	2	1	3x150 AL	65.55	16.21
4	1	2	3x150 AL	65.55	16.21
5	3	1	3x150 AL	65.55	64.85
6	1	3	3x150 AL	65.55	64.85
7	4	2	3x150 AL	65.55	54.04
8	2	4	3x150 AL	65.55	54.04

Continu table (3).

Branch	Initial Node	Final Node	Conductor		
			Section (mm^2)	Thermal capacity per phase (kVA)	Loss coefficient * 10^{-3} (kVA)
9	3	4	3x150 AL	65.55	16.21
10	4	3	3x150 AL	65.55	16.21
11	6	3	3x400 AL	118.45	12.81
12	6	4	3x400 AL	118.45	22.41

5. Mathematical Model of The Case Under Study

5.1 Objective function of the case under study

In order to formulate the objective function to minimize line power losses, it is necessary to know how many lines are there in Fig. (2). When observing this, it is possible to confirm that it has 12 lines and so, the objective function will have 12 terms as it is possible to confirm on the following equation:

$$\text{MIN } F = 10^{-3} * (19.21 * S_{51} + 25.61 * S_{52} + 16.21 * S_{21} + 16.21 * S_{12} + 64.85 * S_{31} + 64.85 * S_{13} + 54.04 * S_{42} + 54.04 * S_{24} + 16.21 * S_{34} + 16.21 * S_{43} + 12.81 * S_{63} + 22.41 * S_{64}); \quad (32)$$

5.2 Technical constraints of the case study

1. Power balance in the nodes (Kirchhoff's First Law):

It includes all loading nodes and is expressed according to the apparent power in (kVA), assuming a single power factor to the network. In this network, there are 4 loading nodes, which lead to the following 4 equations:

$$S_{31} + S_{21} + S_{51} - S_{13} - S_{12} = 28;$$
$$S_{52} + S_{12} + S_{42} - S_{21} - S_{24} = 41;$$
$$S_{63} + S_{13} + S_{43} - S_{31} - S_{34} = 60;$$
$$S_{64} + S_{34} + S_{24} - S_{42} - S_{43} = 35; \quad (33)$$

2. Selection of the capacity of each substation.

In this network there are 2 nodes with existing substation points, so the binary variables are fixed with the optimization process.

$Y_1 = 1;$

$Y_2 = 1;$

(34)

3. Eliminating minimum load or underused substations.

In the example there are 2 nodes with substation points, so there will be 2 equations:

$S_{51} + S_{52} - 50 * Y_1 >= 0;$

$S_{63} + S_{64} - 50 * Y_2 >= 0;$

(35)

4. Maximum load limitation or overload in substations:

In the example there are 2 substation nodes, so there will be two equations:

S51 + S52 - 95 * Y1<= 0;

S63 + S64 - 95 * Y2 <= 0;

(36)

5. Thermal limit in lines.

The network has 12 lines, so there will be 12 equations.

```
S51 – 118.45   * X51 <= 0;
S52 – 118.45   * X52 <= 0;
S21 –   65.55   * X21 <= 0;
S12 –   65.55   * X12 <= 0;
S31 –   65.55   * X31 <= 0;
S13 –   65.55   * X13 <= 0;
S42 –   65.55   * X42 <= 0;
S24 –   65.55   * X24 <= 0;
S34 –   65.55   * X34 <= 0;
S43 –   65.55   * X43 <= 0;
S63 – 118.45   * X63 <= 0;
S64 – 118.45   * X64 <= 0;
```

(36)

6. Radial condition of operation of the network.

In this example the network has 4 load nodes, so there will be 4 equations:

```
X51 + X21 + X31 = 1;
X52 + X12 + X42 = 1;
X13 + X63 + X43 = 1;
X34 + X24 + X64 = 1;
```

(37)

7. General power limitation according to the capacities of substations or electric power generation unites. General power balance of the distribution system. All the loads must be covered by the available generated power plus the power losses.

Each example has 1 general network power balance equation:

```
S51 + S52 + S64 + S63 - 95 * Y1 - 95 * Y2 <= 0;
```

(38)

8. Eliminating two-sense power flow on the lines. Between both paths there should be only one sense.

In this example there are 4 two-sense arches, so there will be 4 equations:

$$X31 + X13 \le 1;$$
$$X24 + X42 \le 1;$$
$$X21 + X12 \le 1;$$
$$X34 + X43 \le 1; \quad (39)$$

Binary variables are: X_{51}, X_{52}, X_{21}, X_{12}, X_{31}, X_{13}, X_{24}, X_{42}, X_{34}, X_{43}, X_{63}, X_{64}, Y_1, Y_2.

The necessary format to be executed in general optimization software LINGO is that shown in figure (3).

```
! Objective function of the 4 load nodes, substation  nodes and twelve lines network;
 MIN = (19.21 * S51 + 25.61 * S52 +
 16.21 * S21 + 16.21 * S12 + 64.85 *
 S31 + 64.85 * S13 + 54.04 * S42 + 54.04
 * S24 + 16.21 * S34 + 16.21 * S43 +
 12.81 * S63 + 22.41 * S64) * 10^-3 + 0 * y1 + 0 * y2;
! Restrictions;
! 1.        Power balance in the nodes: Kirchhoff's First Law;
 S31 + S21 + S51 - S13 - S12 = 28;
 S52 + S12 + S42 - S21 - S24 = 41;
 S63 + S13 + S43 - S31 - S34 = 60;
 S64 + S34 + S24 - S42 - S43 = 35;
! 2. Capacity selection in each substation;
 y1 = 1;
 y2 = 1;
! 3. Eliminating minimum loaded substation or underused substations;
 S51 + S52 - 50 * y1 >= 0;
 S63 + S64 - 50 * y2 >= 0;
! 4. Maximum loaded substation limitation or overused substations;
 S51 + S52 - 95 * y1 <= 0;
 S63 + S64 - 95 * y2 <= 0;
```

```
! Thermal limit of  the lines;
 S51 - 118.45 * X51 <= 0;
 S52 - 118.45 * X52 <= 0;
 S21 - 65.55 * X21 <= 0;
 S12 - 65.55 * X12 <= 0;
 S31 - 65.55 * X31 <= 0;
 S13 - 65.55 * X13 <= 0;
 S42 - 65.55 * X42 <= 0;
 S24 - 65.55 * X24 <= 0;
 S34 - 65.55 * X34 <= 0;
 S43 - 65.55 * X43 <= 0;
 S63 - 118.45 * X63 <= 0;
 S64 - 118.45 * X64 <= 0;
! Radial conditions of the final distribution network configuration;
 X51 + X21 + X31 = 1;
 X52 + X12 + X42 = 1;
 X13 + X63 + x43 = 1;
 X34 + X24 + X64 = 1;
! General load power limitation according to the capacities of substations or electric power generation
unities. General power balance of the distribution system;
 S51 + S52 + S64 + S63 - 95 * y1 - 95 * y2 <= 0;
! Eliminating two-way power flow on the lines. Between both paths there should be only one way!;
 X31 + X13 <= 1;
 X24 + X42 <= 1;
 x21 + X12 <= 1;
 X34 + x43 <= 1;
! Defining the binary variables or the complexity variables;
@BIN( X51);
@BIN( X52);
@BIN( X21);
@BIN( X12);
@BIN( X31);
@BIN( X13);
@BIN( X24);
@BIN( X42);
@BIN( X34);
```

```
@BIN( X43);
@BIN( X63);
@BIN( X64);
@BIN( y1);
@BIN( y2);
!;
```

Fig. (3). Problem formulation code in LINGO software format.

Software results (LINGO) just as they can be seen in figure (4).

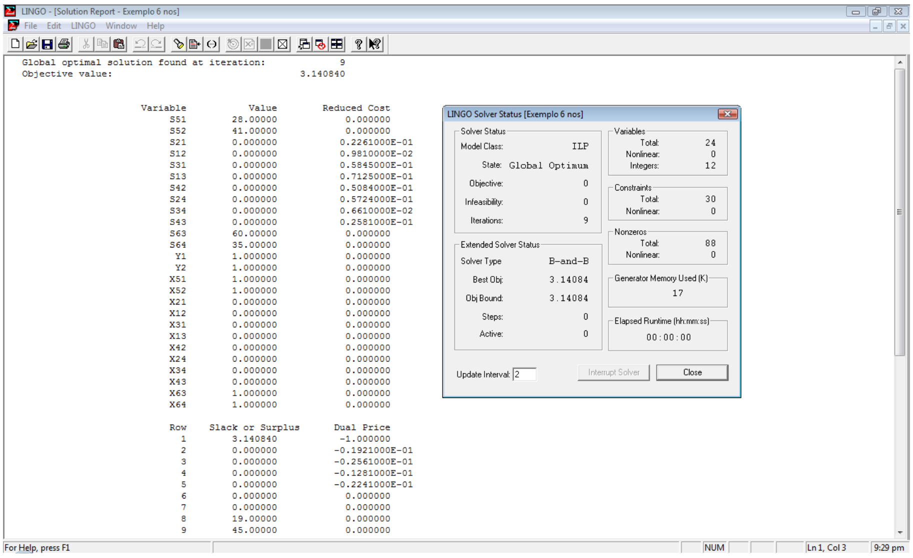

Fig. (4). Execution of the mathematical model on LINGO Software.

LINGO software results can be seen in table (4).

Table (4). Results of the general optimization program.

```
Global optimal solution found at iteration: 9

                          Objective value:    3.140840

      Variable            Value           Reduced Cost
```

S51	28.00000	0.000000
S52	41.00000	0.000000
S21	0.000000	0.2261000E-01
S12	0.000000	0.9810000E-02
S31	0.000000	0.5845000E-01
S13	0.000000	0.7125000E-01
S42	0.000000	0.5084000E-01
S24	0.000000	0.5724000E-01
S34	0.000000	0.6610000E-02
S43	0.000000	0.2581000E-01
S63	60.00000	0.000000
S64	35.00000	0.000000
Y1	1.000000	0.000000
Y2	1.000000	0.000000
X51	1.000000	0.000000
X52	1.000000	0.000000
X21	0.000000	0.000000
X12	0.000000	0.000000
X31	0.000000	0.000000
X13	0.000000	0.000000
X42	0.000000	0.000000
X24	0.000000	0.000000
X34	0.000000	0.000000
X43	0.000000	0.000000
X63	1.000000	0.000000
X64	1.000000	0.000000

Row	Slack or Surplus	Dual Price
1	3.140840	-1.000000
2	0.000000	-0.1921000E-01
3	0.000000	-0.2561000E-01
4	0.000000	-0.1281000E-01
5	0.000000	-0.2241000E-01
6	0.000000	0.000000
7	0.000000	0.000000
8	19.00000	0.000000

9	45.00000	0.000000
10	26.00000	0.000000
11	0.000000	0.000000
12	90.45000	0.000000
13	77.45000	0.000000
14	0.000000	0.000000
15	0.000000	0.000000
16	0.000000	0.000000
17	0.000000	0.000000
18	0.000000	0.000000
19	0.000000	0.000000
20	0.000000	0.000000
21	0.000000	0.000000
22	58.45000	0.000000
23	83.45000	0.000000
24	0.000000	0.000000
25	0.000000	0.000000
26	0.000000	0.000000
27	0.000000	0.000000
28	26.00000	0.000000
29	1.000000	0.000000
30	1.000000	0.000000
31	1.000000	0.000000
32	1.000000	0.000000

5.3 Interpretation of the results of the case under study

The values to be interpreted are in table (5) and the meaning of each of the variables is shown in figure (5). In this figure, there are 2 branch lines with different configurations from the current state because of the result of the optimization process. These branch lines have fewer power losses as shown in table (6).

In order to compare the optimization results, it is necessary to calculate branch lines power losses or circuits arising from the optimization, so that this might be accessed. As this is a simple network, then it is very simple to know how many power losses there are. These values are shown in table (6).

Table (5). LINGO software results.

Global optimal solution found at iteration: 9

Objective value: 3.140840

Variable	Value	Reduced Cost
S51	28.00000	0.000000
S52	41.00000	0.000000
S63	60.00000	0.000000
S64	35.00000	0.000000
Y1	1.000000	0.000000
Y2	1.000000	0.000000
X51	1.000000	0.000000
X52	1.000000	0.000000
X63	1.000000	0.000000
X64	1.000000	0.000000

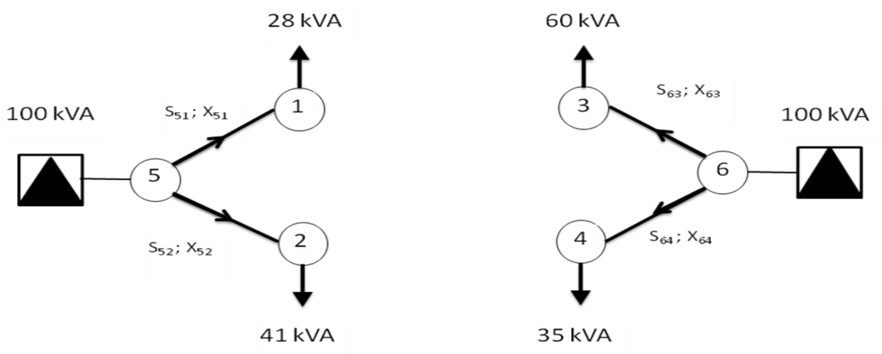

Fig. (5). Network topology after reconfiguration.

Table (6). Network power losses after the reconfiguration.

Branch		After reconfiguration	
Initial Node	Final Node	Losses (kW)	Losses (kVA)
5	1	0.15	0.54
5	2	0.43	1.05
6	3	0.46	0.77
6	4	0.27	0.78
Total		1.31	3.14

Comparing the results from the point of view of network power losses before reconfiguration and after this process, which are shown in table (7) (it contains losses values of apparent power in kVA and active power in kW), that is, of the current network state and the reconfiguration state. To sum up, network reconfiguration allows us to conclude that this method has many benefits, saving almost 66% of apparent power, allowing us to conclude that this method has great advantages when applied in distribution networks.

Table (7). Comparing losses in the current state and after reconfiguration.

Branch	Current State		Reconfiguration	
	Losses (kW)	Losses (kVA)	Losses (kW)	Losses (kVA)
5-1	1.48	1.69	0.15	0.54
1-3	3.58	3.89	-	-
2-4	1.39	2.22	-	-
4-6	1.29	1.70	0.27	0.78
5-2	-	-	0.43	1.05
6-3	-	-	0.46	0.77
Total	7.74	9.50	1.31	3.14
Reduction	-	-	83.1 %	66.9%

6. Real Study Case

This real case study consists of 3 substations. The general data is shown in tables (8, 9 and 10).

Table (8). General Substation Data I (S/E).

Circuit	Length (m)	Transformers number	Installed kVA
1	14181.1	243	11157.5
2	15401.7	376	17732.5
3	10026.7	258	13574
4	11505.0	307	16164
5	16008.2	179	10062.5
6	30021.7	352	15042.6
7	7361.0	12	197.5
8	2393.8	5	85

Substation 1 has an installed capacity in power transformers of 84.02 MVA, 8 circuits at 13.8 kV and has a total length of 95.4 km.

Table (9). General Substation Data II.

Circuit	Length (m)	Transformers	Installed kVA
9	12829.2	169	9980
10	10376.1	105	8836.5
11	15245.33	226	8902.5
12	10386.9	230	9100
13	15895.34	104	9692.5

Substation II has an installed capacity in power transformers of 46.5 MVA, 5 circuits at 13.8 kV, and has a total length of 64.7 km.

Table (10). General Substation Data III.

Circuit	Length (m)	Transformers	Installed kVA
14	20926	169	4902.5
15	3683	6	117.5
16	3712	13	600

Substation III has an installed capacity in power transformers of 5.6 MVA, 3 circuits at 13.8 kV, and has a total length of 28.3 km.

A database was created from these plants in which necessary values and parameters are as follows: 2799 nodes for the 14 circuits in 13.8 kV with the following data:

1. Nominal or rated voltage level in kV;
2. Average measured voltage level in kV;
3. Installed kvar in each circuit;
4. Type of dominating pole;
5. Load curve in each circuit in kVA and kW;
6. Sending node and ending node in each branch section after defining the nodes;
7. Length of each section in meters;
8. Conductor cross section area in each section;
9. Phase number;
10. Total number of kVA installed in each node.

The process of defining nodes was conducted through the plants provided in a digital format and in which the following points of interest were considered:

1. Transformers banks;
2. Conductor’s cross section area or size;
3. Switches and isolators;
4. Taps, transformers or capacitor banks;
5. Any other interest point in the circuit.

Measurements were also conducted in each circuit, more precisely on substations outputs, at the start of each circuit so that it would be possible to calculate the factors which define each of them.

Figure (6) represents an example of a load curve:

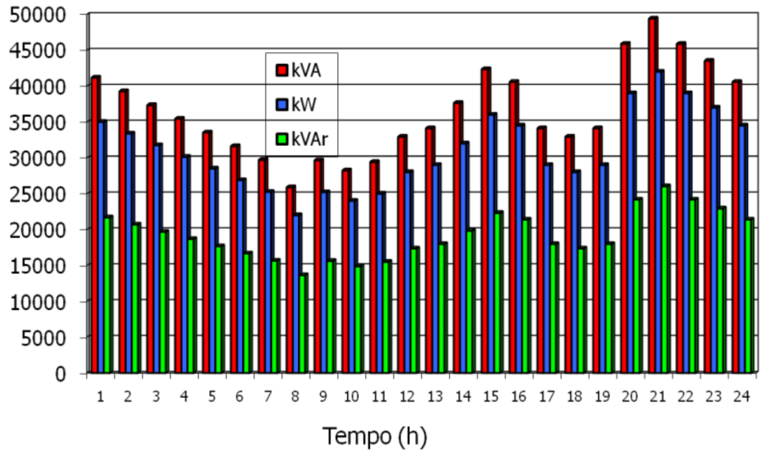

Fig. (6). Typical load curve in a circuit.

6.1 Evaluation of the current state in each circuit

In order to know the state of each circuit, it is necessary to carry out a power flow to radial distribution networks. The power factor was measured in each substation and the average value is 0.85. After evaluating the current state in each circuit, power flow results and operation features in each circuit are shown in tables 11, 12, 13, 14, 15, 16, 17 and 18:

Table (11). Maximum load in S/E I circuits.

Circuit	Installed kVA	Max kW	Capacity Factor
1	11157.5	9911	1.00
2	17732.5	15073	1.00
3	13574	11506	1.00
4	16164	13739	1.00
5	10062.5	8553.1	1.00
6	15042.6	12786	1.00
7	197.5	167.9	1.00
8	85	72.3	1.00

Table (12). Active power losses in S/E I circuits.

Circuit	Line Losses		Transformer Losses		Total Losses	
	kW	In %	kW	In %	kW	In %
1	691.66	6.98	168.626	1.70	860.286	8.68
2	879.86	5.84	255.465	1.69	1135.325	7.53
3	616.17	5.36	175.857	1.53	792.027	6.89
4	618.70	4.50	231.628	1.69	850.328	6.19
5	540.98	6.32	147.796	1.73	688.776	8.05
6	724.83	5.67	221.189	1.73	946.019	7.40
7	0.21	0.12	3.311	1.97	3.521	2.09
8	0.01	0.01	1.405	1.94	1.415	1.95

Table (13). Voltage drop in S/E I circuits.

Circuit	Length (m)	Worst Node	U (kV)	ΔU (%)
1	14181.1	187	11.65	11.71
2	15401.7	231	11.56	12.42
3	10026.7	212	11.72	11.22
4	11505 .0	155	12.10	8.33
5	16008.2	155	11.79	10.68
6	30021.7	198	11.57	12.37
7	7361.0	7	13.17	0.22
8	2393.8	9	13.20	0.03

Table (14). Energy losses in S/E I circuits.

Circuit	Line Losses		Transformer Losses		Total Losses	
	MWh/year	In %	MWh/year	In %	MWh/year	In %
1	3535.84	5.52	862.03	1.35	4397.87	6.87
2	4497.67	4.61	1305.89	1.34	5803.55	5.95
3	3149.92	4.23	899.00	1.21	4048.92	5.44

Continu table (14).

Circuit	Line Losses		Transformer Losses		Total Losses	
	MWh/year	In %	MWh/year	In %	MWh/year	In %
4	3163.04	3.56	1184.17	1.33	4347.22	4.89
5	2765.54	5.00	755.55	1.37	3521.09	6.37
6	3705.48	4.48	1130.76	1.37	4836.24	5.85
7	1.07	0.10	16.92	1.58	17.99	1.68
8	0.05	0.01	7.17	1.41	7.22	1.42

Table (15). Maximum load in S/E II and III circuits.

Circuit	Installed kVA	max kW	Capacity Factor
9	9980	7144.3	1.00
10	8836.5	7457.9	1.00
11	8902.5	6795.8	1.00
12	9100	7586.3	1.00
13	9692.5	8174.5	1.00
14	4902.5	4081.7	1.00
15	117.5	99.87	1.00
16	600	510	1.00

Table (16). Active losses in S/E II and III circuits.

Circuit	Line Losses		Transformer Losses		Total Losses	
	kW	In %	kW	In %	kW	In %
9	282.32	3.95	119.218	1.67	401.538	5.62
10	308.13	4.13	98.639	1.32	406.769	5.45
11	138.39	2.04	134.234	1.98	272.624	4.02
12	156.22	2.06	130.573	1.72	286.793	3.78
13	743.35	9.09	136.392	1.67	879.742	10.76
14	54.95	1.35	73.275	1.80	128.225	3.15

Continu table (16).

Circuit	Line Losses		Transformer Losses		Total Losses	
	kW	In %	kW	In %	kW	In %
15	0.04	0.04	2.257	2.26	2.297	2.30
16	0.31	0.06	8.842	1.73	9.152	1.79

Table (17). Voltage drops in S/E II and III circuits.

Circuit	Length (m)	Worst Node	U (kV)	ΔU (%)
9	12829.2	136	12.33	6.56
10	10376.1	128	12.29	6.91
11	15245.33	171	12.67	4.01
12	10386.9	169	12.65	4.14
13	15895.34	84	11.21	15.06
14	20926	137	12.78	3.16
15	3683	4	13.19	0.06
16	3712	17	13.18	0.15

Table (18). Energy Losses in S/E II and III circuits.

Circuit	Line Losses		Transformer Losses		Total Losses	
	MWh/year	%	MWh/year	%	MWh/year	%
9	23867.95	3.52	5818.98	0.86	29686.93	4.38
10	30080.86	3.67	8733.90	1.07	38814.75	4.74
11	21273.63	1.82	6071.57	0.52	27345.20	2.34
12	21362.55	1.84	7997.68	0.69	29360.23	2.53
13	18667.70	8.11	5100.02	2.22	23767.72	10.33
14	24812.61	1.2	7571.81	0.37	32384.42	1.57
15	7.25	0.04	114.27	0.63	121.51	0.67
16	0.34	0.05	48.44	7.03	48.78	7.08

6.2 Network reconfiguration

The model which should be used in the network reconfiguration includes the following circuits:

1. Circuit 1;
2. Circuit 2;
3. Circuit 3;
4. Circuit 4;
5. Circuit 5;
6. Circuito 6;
7. Circuit 9;
8. Circuito 10;
9. Circuit 11;
10. Circuito 12.

Other circuits were not included in the reconfiguration study because they didn't have any connection or were close to other circuits/substations and had a low loss rate.

In order to carry out modification works in the network, a meeting with operators from the electric company was conducted in order to define possible connections or positions (opening/closing) of switches and a shorter connection distance of 55 meters was established because of the companies' economic restrictions. The file of possible connections is shown in table (19).

Table (19). Archive of possible connections agreed with the electric company.

Sending Node	Ending Node	Length (m)	Conductor size	Initial Circuit	Final Circuit
35	143	1	4/0	1	2
56	181	44	2	1	2
66	249	1	1/0	1	2
77	146	43	4	1	2
136	151	1	2/0	1	9
139	195	24	2/0	1	2
213	124	1	1/0	2	10
217	98	34	2	2	12
231	104	39	4	2	3
244	153	1	4/0	2	10
29	8	35	1/0	3	4
42	53	43	2	3	4
55	98	41	4	3	4

Continu table (19).

Sending Node	Ending Node	Length (m)	Conductor size	Initial Circuit	Final Circuit
40	83	1	4/0	1	3
90	132	37	4	3	4
70	97	1	2/0	1	3
113	74	45	2/0	3	12
118	10	1	2/0	3	11
119	68	1	2/0	3	12
133	121	1	2/0	3	10
140	110	1	2/0	3	10
146	105	5	2	3	10
191	97	1	4	3	10
210	131	1	2/0	3	10
24	128	1	2/0	4	5
40	123	23	4	4	5
186	95	1	4/0	4	12
189	84	1	1/0	4	12
202	134	1	2	4	11
199	130	43	2	4	11
13	37	13	1/0	5	6
176	196	1	2	5	11
10	263	1	1/0	5	6
25	38	1	4/0	9	10
27	22	10	1/0	9	10
40	26	1	1/0	9	10
60	72	26	1/0	9	10
80	83	10	1/0	9	10
106	87	41	2	9	10
112	146	26	4	11	11
135	138	52	2	11	12

After creating a database (2344 circuit nodes were included in the reconfiguration process), an optimization program was executed of which the results are that the switches and sectionalizing should be open. These results are shown in table (20).

Table (20). Circuits should be open.

Nodes	Circuit	Nodes	Circuit
348	4	91	5
143	4	168	11
260	5	259	6
32	9	33	10
31	9	28	10
37	9	38	9
98	10	99	11
114	11	118	11
35	1	143	2
41	4	122	4
189	12	84	12
60	9	72	10

After the reconfiguration, the circuit database was changed mainly in order to study these circuits which are a result of the optimization process. In order to know the features and parameters of optimized circuits, a power flow was executed in radial networks to calculate losses in branches and voltage drops in busbars. The results of the configured network are shown in tables (21-23).

Table (21). Active power losses in reconfigured circuits.

Total losses				
Circuit	Current State		Reconfigured State	
	kW	In %	kW	In %
1	860.286	8.68	503.22	6.48
2	1135.325	7.53	658.00	5.47
3	792.027	6.89	785.00	5.63
4	850.328	6.19	556.91	5.33

Continu table (21).

Total losses				
Circuit	Current State		Reconfigured State	
	kW	In %	kW	In %
5	688.776	8.05	358.84	5.55
6	946.019	7.40	571.49	6.08
9	401.538	5.62	353.53	4.95
10	406.769	5.45	408.75	5.48
11	272.624	4.02	402.91	5.92
12	286.793	3.78	345.12	4.55

Table (22). Energy losses in reconfigured circuits.

Total losses				
Circuit	Current State		Reconfigured State	
	In MWh/year	In %	MWh/year	In %
1	4397.87	6.87	2572.48	5.13
2	5803.55	5.95	3363.70	4.33
3	4048.92	5.44	4012.76	4.45
4	4347.22	4.89	2846.85	4.21
5	3521.09	6.37	1834.38	4.38
6	4836.24	5.85	2921.46	4.81
9	2710.50	5.01	2750.24	4.63
10	2720.51	4.84	1926.24	4.52
11	1841.22	3.59	6383.39	5.12
12	1936.94	3.38	3781.12	4.54

In order to evaluate operational features in the circuits after its reconfiguration and to quantify power and energy saving, as well as the improvement on voltages, it is necessary to compare the values before and after the reconfiguration. Results concerning power and energy saving are shown in tables (24& 25).

Table (23). Voltage drops in reconfigured circuits.

Voltage Drop						
Circuit	Current State		Reconfigured State		Reduction	
	U (kV) in the worst node	%	U (kV) in the worst node	In %	U (kV)	In %
1	11.65	11.71	12.25	7.16	0.60	4.55
2	11.56	12.42	11.92	9.70	0.36	2.72
3	11.72	11.22	12.26	7.10	0.54	4.12
4	12.10	8.33	12.35	6.46	0.25	1.87
5	11.79	10.68	12.34	6.50	0.55	4.18
6	11.57	12.37	11.9	9.86	0.33	2.51
9	12.33	6.56	12.39	6.17	0.06	0.39
10	12.29	6.91	12.38	6.18	0.09	0.73
11	12.67	4.01	12.68	3.96	0.01	0.05
12	12.65	4.14	12.6	4.52	-0.05	-0.38

It is necessary to explain that during the reconfiguration process, some circuits with heavier load will lose some of it. This load will be transferred to other circuits with a lighter load. Thus, it is possible to conclude that the first case, circuits will decrease its losses and, consequently, voltage in busbars will improve. On the second case, circuits will increase its losses and its voltage will worsen. Generally, total losses will lessen and voltage will comply with the equipment's acceptable limits.

Table (24). Power saving.

Reduction of power losses		
Circuit	Total Reduction	
	In kW	In %
1	-357.062	-2.20
2	-477.325	-2.06
3	-7.028	-1.26
4	-293.421	-0.86
5	-329.937	-2.50
6	-374.528	-1.32
9	-48.004	-0.67

Continu table (24).

Reduction of power losses		
Circuit	Total Reduction	
	In kW	In %
10	+1.983	+0.03
11	+130.287	+1.90
12	+58.324	+0.77
Total	-1696.711	-8.17

Table (25). Energy saving.

s		
Circuit	Total Reduction	
	MWh/year	In %
1	-1825.387	-1.74
2	-2439.858	-1.62
3	-36.163	-0.99
4	-1500.364	-0.68
5	-1686.707	-1.99
6	-1914.776	-1.04
9	+39.740	-0.38
10	-794.268	-0.32
11	+4542.167	+1.53
12	+1844.173	+1.16
Total	-3771.444	-6.07

In tables (24 and 25), the signs (+) and (-) mean increase and decrease respectively. In these tables it is possible to confirm that, generally, reconfiguration leads to an approximately 6% to 8% saving in energy and power respectively without investment.

7. Conclusions

The main conclusions to be taken from this work are:

- Application of the formulation in real cases of electric power distribution networks, controlling all variables through a MILP type optimization model. Its solution is based on the Branch and Bound method. It may also be applied in other systems such as gas, water and communication systems;
- Introduction of mathematical simplifications on a non-linear problem in order to linearize it, so that linear optimization techniques can be applied;
- This model can be used by the distribution system operator, in the SCADA system to solve the system overload or to isolate the fault. Also it can be used by the SCADA and with the automated switches to take intelligent decision in the SCADA making the distribution networks more intelligent, acting as a smart network.
- The advantages of applying suggested methodology in the real case were an energy saving of about 3771.444 MWh/year, allowing a significant economic saving which is obtained by only opening/closing switches devices without any investments.

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منهجية مثلى لتقليل مفاقيد القدرة في مغذيات نظم التوزيع الكبيرة باستخدام خليط البرمجة الخطية الصحيحة

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ملخص البحث. يقدم هذا البحث طريقة جديدة لإعادة التشكيل لشبكات نظم توزيع القوى الكهربائية التي تتعرض لها في الحقيقية وذلك بغرض الحفاظ على الأداء الأمثل لشبكة التوزيع من خلال تقليل تكلفة مفاقيد القدرة مع الحفاظ على الحدود المقبولة لجهود قضبان التوزيع و تحسين جودة القدرة.

هذه المشكلة تم صيغتها في هذا البحث باستخدام نموذج مختلط صحيح خطي عن طريق اختيار دالة هدف تعمل على تصغير تكلفة القدرة الفعالة المفقودة آخذا في الاعتبار القيود الفنية مثل التوازن الضروري للقوي المنتجة والمستهلكة عند كل نقطة في الشبكة وسعة خطوط التغذية وقدرات محطات المحولات و الحفاظ على الاتصال الشعاعي للشكبة الكهربائية أثناء التشغيل. وقد تم تطبيق المنهجية المقترحة على شبكة توزيع عالمية حقيقية كبيرة تتكون من ٢٣٤٤ نقطة عند مستوى جهد ١٣,٨ كيلو فولت تقع في مدينة حقيقية و التي أثبتت كفاءتها و فاعليتها للوصول للحل الأمثل في زمن مقبول حيث أن الحل الأمثل أدى إلى تقليل مفاقيد القدرة بنسبة ٨٪ و الطاقة الكهربية بنسبة ٦٪ و تحسن ملحوظ في جهود قضبان التوزيع.