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I+D INVESTIGACIÓN Y DESARROLLO

Planning of power distribution networks in densely populated cities Through distributed generation and capacitive compensators

Planeamiento de redes eléctricas en ciudades densamente pobladas Con generación distribuida y compensación capacitiva

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Resumen

Este artículo analiza diferentes opciones para realizar planeamiento de redes eléctricas de distribución en zonas con gran densidad de población a través del uso de generación distribuida y compensación capacitiva. La metodología de planificación permite determinar el tamaño de la unidad a instalar, el nodo en que debe ser ubicada y el año en que se debe hacer la inversión, con el fin de minimizar las pérdidas de energía durante el periodo de planificación. El estudio evalúa cuatro casos que son: planificación sin compensación capacitiva (SC) y sin generación distribuida (DG), planificación usando SC, planificación usando DG, y planificación usando los dos elementos simultáneamente. Los resultados muestran que el uso simultáneo de SC y DG disminuye las pérdidas totales de energía y mejora los perfiles de tensión en los nodos de la red, con lo cual se obtienen muy buenos resultados en el planeamiento.

Palabras Clave: redes eléctricas de distribución, planeamiento, planeación multietapa, generación distribuida, compensación capacitiva, optimización.

Abstract

This paper analyses different options that can be used to solve the problem of the planning of power distribution networks by including capacitive compensation and distributed generation. The methodology for planning aims to determine the size of the units, the bus where the units have to be located, and the year in which investments should be made, in order to minimize the total energy losses on the network during the planning period. The work analyses four different cases: planning using neither capacitive compensation (SC) nor distributed generation (DG), planning using only SC, planning using only DG, and planning using reactive compensation and distributed generation simultaneously. Results show that simultaneous use of SC and DG reduce the total energy losses and improve the voltage profiles on the network, so good results for the planning are obtained.

Keywords: power distribution networks, planning, multi-stage planning, distributed generation, capacitive compensation, optimization

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1. Introduction

Modernization and expansion of power distribution networks joined with control of the operational work- conditions are important aspects that must be managed for LDC companies because of the growth of power demand. Most of distribution networks are radially configured and then affected for voltage drops and feeder overload [1], [2]. Those problems suggest challenges regarding the thermal limits of feeders and the voltage limits on buses, which should be faced [3]. For this reason, capacitive compensators are usually used to control these problems; it is not possible, however, to reach the required quality levels of services [4], [5].

There are different options to solve the planning problem, but some of these are expensive and not feasible. A common way to solve the problem in densely populated cities is to build complementary or supplementary feeders to reduce losses and voltage drops. A second way is to repower the cable feeders to increase their capacity and reduce losses. A third one is to build new substations or to connect the network through external feeders to increase the energy importations using an external power input different from the main substation. Other solution to solve the main problems is to link and to operate a second substation, but it would involve high capital investments; however, this will not be a feasible solution if there are not customers willing to pay for improving reliability and services quality. Implementing the solution proposed previously, LDC companies should invest in assets, but they should have to pay for purchases of energy to high-voltage network providers, or to pay for the energy to a neighboring distribution company.

Another option to solve the problems is to use distributed generation connected to the primary distribution network [6]–[8]. This solution is also possible and implies high capital investments, but opposite to the previous case, companies can reduce energy purchase costs because they would be owners of the DG units.

Many researchers have worked on this kind of problems for a long time by using different optimization techniques as analytic mathematical models [9]–[11], and heuristic optimization techniques [8], [12], [13], but in some cases the solutions do not meet real DG sizes and capacities available in the market. This implies that loss reductions and obtained solutions do not necessarily reach the desired loss reductions, because any minor modification in the size and characteristics of the capacitor banks and the DG units will change the final solution.

1.1. Current problems in power distribution networks

Failures in distribution networks are common because of the high complexity of the networks, the large number of elements composing the network, and by overload on feeders and transformers caused by the high power demand [3]. In addition to these problems companies and users might be affected by loss of supply, low quality of the service, and damages to assets and equipment connected to the network [14]. For this reason, LDC companies must manage and control the network under the adequate operational conditions. One of the ways to prevent these problems is to ensure that planning is done correctly; this is important because planning is one of the steps prior to the final design and specification of the elements to install on the network.

1.2. The problem of planning

Planning of power distribution networks is a tool that can be used to determine the expansion requirements of the network based on the forecasted demand, the starting state of the network, the capacity limits of assets, the operational limits of the network, and the constraints of capital investment. This tool can be used to plan the expansion, to improve the characteristics, to modernize the facilities, and to guarantee the power capacity requirements. The optimization process involves choosing the optimization objectives, the models and characteristics of the network, the network configuration, and the models and specifications of equipment and elements to be used; it also defines the operational constraints that must be met when the network is working.

1.3. Purpose of the research

Most of the big cities like Bogota (Colombia) have old distribution networks which are about to reach their maximum capacity. Assets like transformers, feeders, and cables on some parts of the network work close to their maximum operational capacity, while voltages on buses may be under the minimum operational limits. These kinds of networks do not have large expansion requirements, but they have to support the increasing energy demand caused by apartment buildings which now days are becoming more common in neighborhoods where houses where the unique kind of constructions years before.

Reactive SC power compensators are commonly used in Colombia to reduce voltage drop problems on radial distribution networks, but it does not solve all the problems because of the feeder overheat and voltage drops due to the large length of the feeders. Although DG is not commonly used in distribution networks in Colombia, DGs can be included as one of the elements that can be connected to the distribution network for self-supply of energy and electricity retailing, according to recent policies on energy. The act 1715 of 2017 and the resolution CREG-030 of 2018 allow LDC companies to use DG units as a possible solution to improve the operational conditions of the network.

Having described the problems and having in account that implementation of this kind of technologies on the Colombian distribution networks is already allowed by the new regulation and electricity policies, then, it is necessary to know the possible solutions that can be implemented to solve these problems. Furthermore, it is also important to identify the advantages of using these technologies, to know the best way to obtain the maximum benefit when improving the operational conditions of the network, and to ensure the energy supply in the medium and long term.

2. Methodology

This paper analyzes some possibilities that can be implemented to reduce failures and to manage the overload problems and the voltage drops. To analyze and solve the described problem, a 28-bus test system which represents a radial primary distribution system is used (Figure 1). The test system is composed of a 2.5 MVA power substation, 27 branch feeders, and 28 load buses with a total peak demand of 1.64 MW and 628.8 kVAR for the first year, with a power factor equal to 0.7 in the transformer.

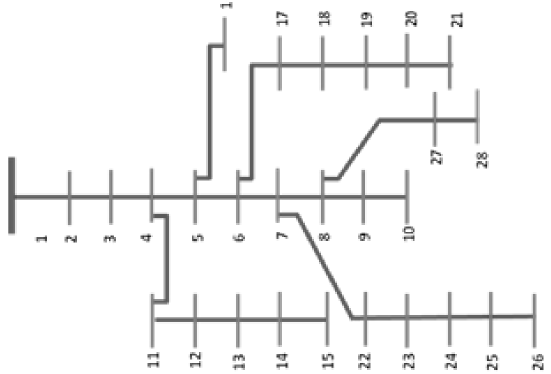


Figure 1. Twenty-eight-bus distribution test system used for the simulations.

Source: Own.

In addition to the basic elements, the distribution network includes three capacitor banks used to supply the reactive power necessary to meet the minimum voltage requirements in the starting year. These capacitor banks are located in buses 21, 24, and 28. The reactive power capacities for those banks are 2000 kVAR, 1200 kVAR, and 1600 kVAR, respectively.

2.1. Load modeling

Forecasted demand is the main parameter to start the planning because it determines the power and energy requirements year by year during the planning period [15]–[17]. That is necessary to determine the upgrading requirements for the network, which involve the adequate selection and sizing of the capacitive compensators as well as the DG units.

The rising rate of demand is 3% per year, and it is used to predict its yearly growth during the planning period. Active and reactive demands are represented by using the peak demand on each bus of the network, and forecasted demand is calculated using the rising rate of demand, starting from year one.

2.2 Planning characteristics and models

The proposed planning problem analyzes the growth of demand for the power distribution network but not its expansion. The planning horizon is 10 years, and the problem is modeled by using mathematical modeling and the multi-stage planning technique [18], [19]. The objective function is the minimization of total energy losses during the planning period, subject to constraints in the DG and SC sizes. Additional constraints are the substation power factor, which limit the active and reactive power to supply and the operational conditions of the network. The solution to the optimization problem is obtained by using the GAMS software.

2.3 Mathematical representation of the problem

SETS

i,j	Buses of the network
h	Hour of day
y	Year of the planning

VARIABLES

$Pg_{y,h,i}$, $Qg_{y,h,i}$	Active and reactive power supplied by substation
$TLoss$	Total energy losses during the whole planning
$Vyhi$, Vyh,i	Bus voltages
$Zdg_{y,i}$, $Zsc_{y,i}$	Size of DG and SC units to install in year y on bus i.
$B,y.h.j$, B,y,h,i	Voltage angles on the buses

PARAMETERS

$MaxDGyear$	Maximum number of DG units that can be installed by year
$MaxTotal$	Maximum number of DG plus SC units that can be installed for the whole planning
$MaxNDG$	Maximum number of DG units that can be installed during the whole planning
$MaxNSC$	Maximum number of SC units that can be installed during the whole planning
$MaxNSCyear$	Maximum number of SC units that can be installed per year
$Ndg_{y,i}$ $Nsc_{y,i}$	Maximum number of DG and SC units that can be installed in a bus
$MaxNCyear$	Maximum number of DG and SC units that can be installed in a
$PredDG$, $PredSC$,	Basic size of the DG and SC unitsthat can be used in the planning
$PD_{y,h,i}$, $QD_{y,h,i}$,	Active and reactive power demand
Q_{oi}	Capacitive compensation existed in year 0
θ_{ij}	Impedance angles for the i,j feeder
θ_{PF}	Power angle for substation transformer

The optimization problem is solved on GAMS software by using the AC power flow equations, which ensure the power balance on the network and meet the basic operational constraints. The following part of the paper presents the equations used to represent the mathematical model of the problem, including models for capacitors, DG units, and constraints.

2.3.1 Objective function. Minimization of total energy losses

$$TLoss = 0.5 * \sum_{y,h,i,j} -Y_{bus} * Cos(\theta_{i,j}) * (V_{y,h,i}{}^2 + V_{y,h,j}{}^2) - 2 * (V_{y,h,i} * V_{y,h,j} * \cos(\delta_{y,h,j} - \delta_{y,h,i})) \quad (1)$$

2.3.2 Operational constraints of the problem:

Power flow equations

$$Pg_{y,h,i} + Pdg_{y,h,i} - PD_{y,h,i} = \sum_{j=1}^{n} |V_{y,h,i} V_{y,h,j} Y_{i,j}| * cos(\theta_{i,j} + \delta_{y,h,j} - \delta_{y,h,i}) \quad (2)$$

$$Qg_{y,h,i} + Qo_i + Qsc_{y,h,i} - QD_{y,h,i} = -\sum_{j=1}^{n} |V_{y,h,i} V_{y,h,j} Y_{i,j}| * sin(\theta_{i,j} + \delta_{y,h,j} - \delta_{y,h,i}) \quad (3)$$

Reactive power can be supplied for Substation

$$Qg_{y,h,i} \le Pg_{y,h,i} * tg(\theta_{PF}) \quad (4)$$

Voltage limits

$$0.95 \text{ p.u} \le V(y,ht,i) \le 1.1 \; p.u \quad (5)$$

2.3.3 DG and reactive compensation constraints

Modeling of DG units and SC compensators is performed by using predefined sizes to calculate the final size of the unit to be installed in each bus. That is calculated by multiplying the number of units to be installed in a bus and the predefined basic sizes, which are $Pred_{SC}$ for compensator units and $Pred_{DG}$ for DG units. The problem restricts the maximum number of units that can be allocated in a single bus, the maximum number of units that can be installed during a single year, and the maximum number of units that can be installed during the whole planning. Although the model specifically includes neither the capital investments nor the budget, it is possible to indirectly limit the maximum capital to be invested during a year, the maximum capital to be invested for each type of device, and the maximum capital to be invested during the full planning when limiting the maximum number of units that can be installed during a year or during the whole planning.

Number of units to be installed in bus i during year y

$$0 \leq Ndg_{y,i} \leq 4 \tag{6}$$

$$0 \leq Nsc_{y,i} \leq 10 \tag{7}$$

Size of the DG and SC to be installed during year y on bus i

$$Zdg_{y,i} = Pred_{DG} * (Ndg_{y,i}) \tag{8}$$

$$Zsc_{y,i} = Pred_{SC} * (Nsc_{y,i}) \tag{9}$$

Active and reactive power supplied by the DG and RCC units

$$0 \leq Pdg_{y,h,i} \leq Zdg_{y,i} \tag{10}$$

$$0 \leq Qsc_{y,h,i} \leq Zsc_{y,i} \tag{11}$$

Total number of units that can be installed during a year

$$\sum_{i}^{b} Ndg_{y,i} \leq Max_{DGyear} \tag{12}$$

$$\sum_{i}^{b} Nsc_{y,i} \leq Max_{SCyear} \tag{13}$$

Maximum number of units that can be installed during the planning by type of device

$$\sum_{y}^{n} \sum_{i}^{b} Ndg_{y,i} \leq Max_{NDG} \tag{14}$$

$$\sum_{y}^{n} \sum_{i}^{b} Nsc_{y,i} \leq Max_{NSC} \tag{15}$$

Maximum number of mixed units that can be installed during the planning process

$$10 * \sum_{y}^{n} \sum_{i}^{b} Ndg_{y,i} + \sum_{y}^{n} \sum_{i}^{b} Nsc_{y,i} \leq MaxTotal \tag{16}$$

As indicated above, the maximum capacity to be installed is determined by the integer variables $Ndg_{y,i}$ and $Nsc_{y,i}$ which represent a number of units that could be installed in any bus during any year. Active and reactive powers supplied for the units are limited by the DG and SC power capacity installed on each bus.

3. Cases of study

This paper proposes and analyzes four possible cases of study to obtain different possible solutions that can be employed to minimize the total energy losses during the planning period. Each case considers using different elements for the planning and also assumes that feeders and branches have enough capacity to support the growth of demand during the planning period. The first case runs the planning by using neither capacitors nor DG units during the planning, and it is used to identify the problems appearing by increasing demand. The second case solves the planning problem by using exclusively capacitive compensators SC to reduce the network problems. The third one solves the problem by using exclusively DG units connected to the distribution network. Finally, the last case solves the problem by using both SC and DG units to solve the planning problem.

The cases of study are defined as follow: Case 1. Planning including neither DG nor RC; Case 2. Planning including only RC; Case 3. Planning including only DG; Case 4. Planning including DG and RC simultaneously.

Overall input settings for all cases: Planning period = 10 years, demand rising rate = 3%, $Pred_{SC}$ = 20kVAR, $Pred_{DG}$ = 10kW. CASE 2 setting: Max_{NSC}= 100 $units$, Max_{SCyear} = 40 $units$. CASE 3 setting: Max_{NDG} = 40 $units$, Max_{DGyear} = 8 $units$. CASE 4 setting: Max_{NSC} = 100 $units$, $Max_{NDG} = 40\ units$, $Max_{DGyear} = 8\ units$, $MaxTotal = 100$

4. Simulation and results

This section of the paper shows the results obtained for each simulation indicating the number of units to be installed, the bus where the units should be located, their active and reactive power capacity, and the year in which the units should be installed to minimize the total energy losses, based on the budget restrictions.

Case one is used as the reference case and to identify the voltage and losses problems which are on the system when there are not upgrades for the network, but the demand increases continuously year by year. In all cases it is assumed that feeders have enough capacity to support the growth of demand during the planning period, so it is not necessary to upgrade or to repower the feeders. The results for cases two, three, and four show the solutions that solve the problems identified in case one, ensuring the compliance of minimum operational voltages and the minimization of the total energy losses.

4.1 Case 1

The results show voltage problems when there are not network upgrades during the planning time, so the buses at the end of the network have voltages drop. Therefore, case 1 does not meet the minimum operational-voltages required for the network. Simulations show that voltages drop to 2.7% under the minimum operational voltage when there is neither DG nor additional SC connected to the network. Additionally, the total energy losses in year 10 increase since 5.02% up to 7.3% compared with year 1.

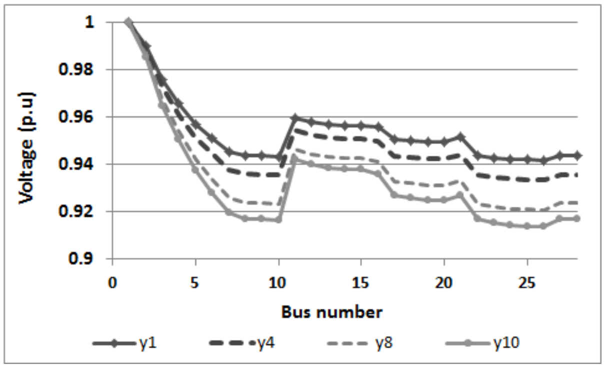


Figure 2. Voltage profile of the network during the starting point. This shows the voltage in each bus in order to identify those buses with the lowest voltages. Source: Own

Figure 2 shows that some buses have voltages under the minimum 0.95 p.u allowed voltage, and that is happening during the whole planning period.

4.2 Case 2

Case 2 solves the problems identified in case 1 by exclusively using SC units; then, the solution shows that SC units should be located in 17 out of the 28 possible busses as shown in Figure 3.a. The solution proposes the location of 30 SC units distributed in the 17 buses, as shown in Figure 3.a. Those SC units should be installed during the first 5 years of the planning and should not overpass the maximum number of units defined in the constraints. Having obtained the results, it is possible to identify the more sensitive buses, which need more reactive compensation such as buses 7, 8, 9, 19, 26, and 27.

	4	7	8	9	10	11	12	13	14
y1	2	2	3	10	1	5		1	
y2		10	10				1		
y3	3	3			2		3		2
y4					2				

y5	15	16	17	19	22	25	26	27	28
y1	1	1		5		1	8		
y2			1	8				10	
y3					1				
y4			3						
y5									

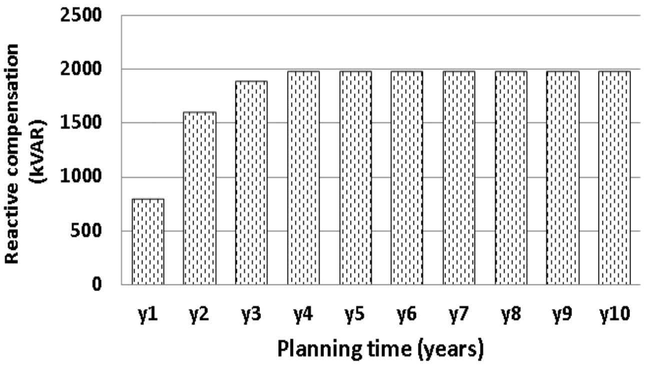


Figure 3. **a. Years and buses in which SC units** should be installed in case 2. b) Cumulative SC reactive capacity installed during the planning. Source: Own.

Based on Figure 3.a., it is also possible to find that bus 7 demands the higher investment because 15 units in total are necessary during the planning. Considering the same Table it is also possible to find no investments since five to ten year because of budget constraints, which limit the total number of units to be installed. The budget limit is included indirectly when limiting the maximum number of SC units that can be installed during the planning.

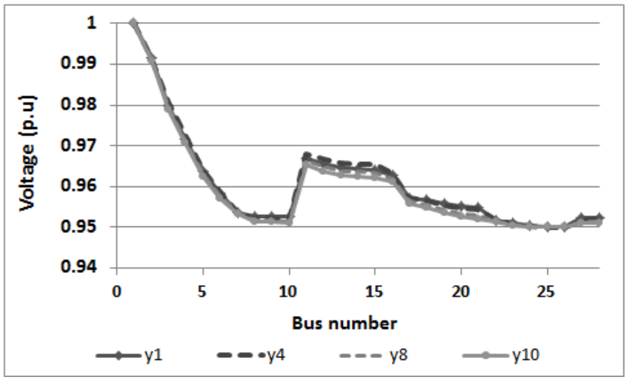
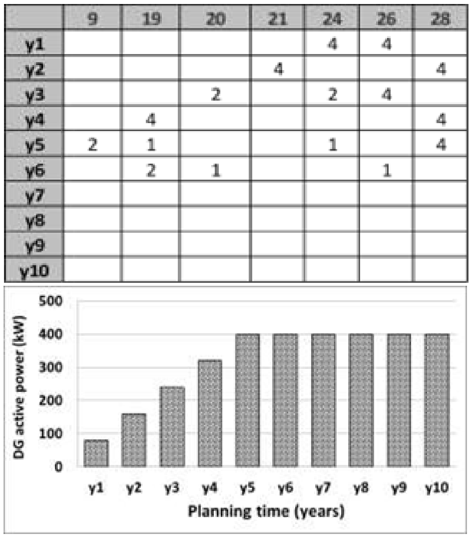


Figure 4. Voltage profile on the buses once the planning solution in case 2 is obtained. Source: Own.

Results also confirm that solutions meet the budget limits, which are represented in term of the maximum number of units to be installed year by year and the maximum number of units that can be installed during the whole planning. Figure 4 shows the voltage profile of the network during the 10-year planning period year by year; bus voltages would be between the required operational limits (0.95 p.u. and 1.1 p.u.).

4.3 Case 3

In this case, the planning solution proposes installing the 40 available DG units during the 6 initial years of the planning. The buses 19, 24, 26 and 28 require installing more DG capacity, and are located close to the end of the feeders, helping to increase the voltage levels at these parts of the network and reducing the total energy losses (Figure 5.a)



	9	19	20	21	24	26	28
y1					4	4	
y2				4			4
y3			2		2	4	
y4		4					4
y5	2	1			1		4
y6		2	1			1	
y7							
y8							
y9							
y10							

Figure 5. a. Years and buses in which DG units should be installed for case 3. b. Cumulative DG-power installed during the planning. Source: Own..

The active power installed on DGs starts with about 50 kW in year one and increases up to 400 kW in year 5 (Figure 5.b). In this way, the LDC Company reduces the whole planning losses in about 43.79% compared with the base case, and reduces the total energy importations in around 28.03 GWh during the whole planning period. In addition to the total loss reductions, the LDC obtains benefits by reducing the energy purchases from external suppliers (Figure 6).

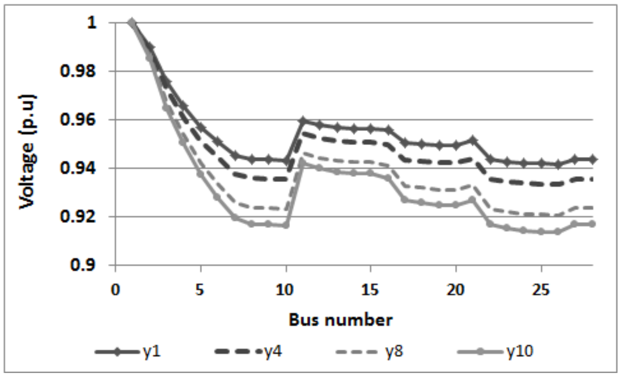
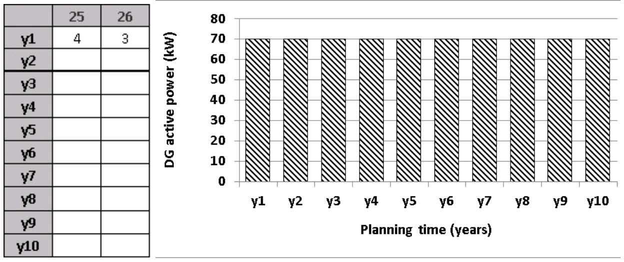


Figure 6. Voltage profile on the buses once the planning solution in case 3 is obtained.
Source: Own

4.4. Case 4

In this case SC and DG units are used simultaneously, based on the constraints described in section 3 for the case four, so, the number of SC and DG units is restricted for year and for the whole planning, but there is an additional constraint that limits the mixed total number of SC and DG units during the planning as show in equation 16. In this case, each DG unit has an equivalent of 10 SC units in the equation constraint (Figure 7).



	25	26
y1	4	3
y2		
y3		
y4		
y5		
y6		
y7		
y8		
y9		
y10		

Figure 7. a. Years and buses in which DG units should be installed for case 4. b. Cumulative DG-power installed during the planning.
Source: Own.

This solution proposes installing 7 DG units and 30 SC units during the planning time, so the capital is invested in the first two years of planning. Furthermore, SC installed capacity reaches up to 600 kVAR, while the DG installed capacity reaches 70 kW and remains constant during the ten years of planning (Figure 8 and 9).

	10	15	23	26	27
y1	2	10	4		6
y2		5		3	
y3					
y4					
y5					
y6					
y7					
y8					
y9					
y10					

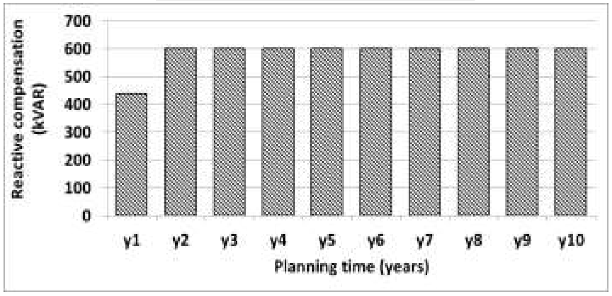


Figure 8. a. Years and buses in which the RCC units should be installed for case 4. b. Cumulative SC reactive power installed during the planning.
Source: Own.

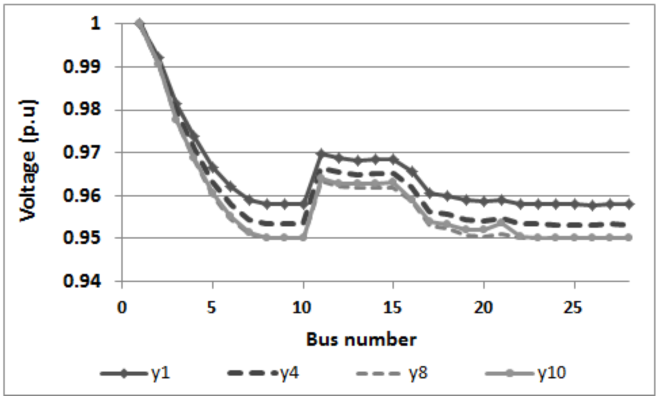


Figure 9. Voltage profile on the network for the starting point. It shows the voltage in each bus and can be used to identify those buses with the lowest voltages.
Source: Own.

Although these cases are not comparable, it is worth noting that these cases allow the voltage levels to increase within the required operational limits and to reduce the total losses with respect to case 1.
The total energy losses reach high importation reductions compared with the other cases, but it involves larger investment in the early years of the planning. This is, however, the best planning solution that can be obtained when proposing minimization of total energy losses as the main objective function.

4. Discussion and results

It is possible to identify some differences in annual energy purchases and annual energy losses and then find the best planning solution.

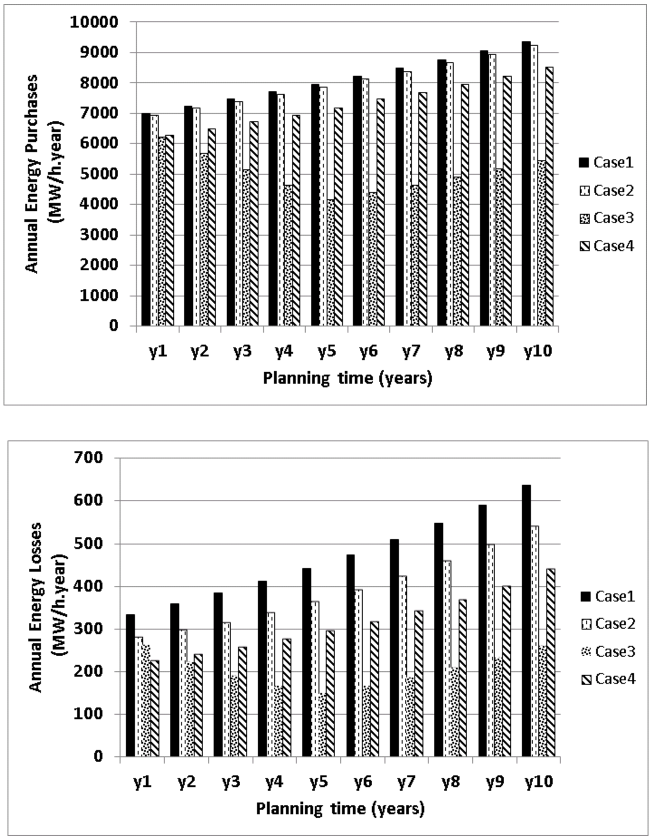


Figure 10. a. Comparison of results for the four cases. b) Annual energy importations through main substation. b) Annual energy losses for the four cases of study.
Source: Own.

Figure 10.a shows the annual energy importation for the four cases; case two has pretty low purchase reductions compared with case 1, while cases 3 and 4 have large purchase reductions because of the use of DG units.
Regarding the losses, Figure 10.b shows high losses reduction when using case 3 compared with the other cases. The solution in case 3 shows important losses reduction during the first five years of the planning; after this time losses increase because of the increasing demand, but its solution is much better compared with the other cases.

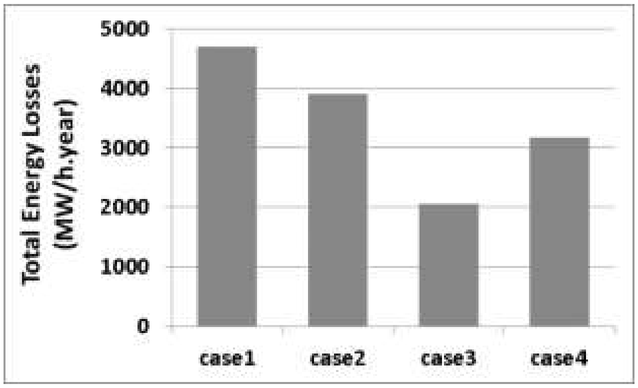


Figure 11. Total energy losses for the proposed cases during the total planning time.
Source: Own.

Having compared the total energy losses during the planning horizon, it is easy to identify the differences and benefits of using SC and DG units during the planning. According to Figure 11, cases three and four have better solutions than the other cases because of the use of DGs. The solution to case 3 has 2000 MWh of losses during the whole planning, while other solutions have more than 3000MWh of losses for the whole planning. Loss reduction obtained with the third and fourth possible solutions is better than the one obtained with the other solutions.

5. Conclusions

Results reveal that simultaneous use of DR and SC devices makes it possible to improve the voltage profiles and also to reduce the total energy losses, so significant energy losses reduction are reached. This loss reduction could result in economic benefits for Local Distribution Companies (LDCs).
Although the solution in case two improves the voltage profiles, it does not produce additional benefits as those obtained for cases 3 and 4, which produces more reductions due to energy importations and increases the economic benefits.
This kind of solutions can be performed in populated cities like Bogota, for industrial or residential areas where it is not easy to obtain enough space to upgrade or to build more substations and facilities.

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