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Distribution System Loss Reduction and Management in a Region of Mexico

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ABSTRACT Electric distribution systems are often characterized by poor performance and high losses within their circuits. These losses must be reduced with different methods well-proven in the industry such as capacitor placement, system management, and appropriate distributed generation modeling and location, helping to improve the overall electrical distribution companies' performance. For this purpose, by the use of the commercial package Synergi®, the determination of the suitable loss reduction method for different circuits of an electric distribution system in a region of Mexico is presented in this paper. Furthermore, some modifications to existing circuits are identified, evaluated, and suggested to achieve both the reduction of the technical losses and the improvement of the system´s voltage regulation. Also, it is shown how once the suggestions derived from these studies are implemented, the expected improvement in the system's performance is achieved. Finally, the important role of a distribution network operator to increase the system's capabilities and assuring their improved performance is highlighted.

KEYWORDS— Distribution system; loss reduction; capacitor placement; voltage improvement; system management.

I. INTRODUCTION

Losses in the electric distribution system have always remained an important worldwide issue to solve, either to reduce economical losses or to comply with the current performance policies. There are many different strategies to achieve these goals depending on the type of loss dealt with. The first type is the technical losses, which occur in the form of heat dissipation in different components of the distribution networks; their reduction involves not only system planning, improvement, and modeling tools; but also deploying higher-efficiency equipment, such as transformers and motors, e.g., manufacturers and researchers around the world are making efforts to minimize [1], [2] and evaluate [3] core losses of distribution transformers. The second type is the non-technical losses, which are derived from issues that occur outside the transportation of electrical energy or dissipation of power in distribution components, such as non-paying customers, past-due portfolio, bad business administration, and theft of electrical energy. Similar to technical losses, efforts are carried out to reduce non-technical losses [4]-[7].

In this context, technical losses are usually evaluated by finding the active power loss at peak load periods of the distribution system and multiplying it by the circuits loss factor [8]. This result times the considered period results in the energy losses (the commonly used periods range from monthly to yearly). It is important to mention that most SCADA systems can calculate the power losses of a distribution system, making energy loss evaluation faster and more efficient, and facilitating the engineer's job. The solutions for the two different types of losses may vary considerably, some even include staff training and the use of new ways to disseminate information to customers to learn how to efficiently use electrical energy and reduce their energy consumption [9]. In this sense, some solutions to reduce technical losses include methods such as reactive power compensation, system management, and appropriate distributed generation location [10]. However, the electricity sector deregulation has added new constraints to the distribution system operation, since the market competition forces the distribution companies to operate under new and more strict efficiency standards. Hence, some of the well-known loss reduction methods should be properly tested and evaluated as discussed in this paper.

For the aforementioned, the impact of the restructuring of the Mexican electrical system on the distribution system operation is slightly presented in this paper. Furthermore, the technical losses of an operative region of a municipality of Mexico called Patzcuaro are calculated using the commercial software Synergi® [11], which provides the power losses in different circuits throughout the system. Then, to obtain the total technical losses, energy losses are calculated using a specialized Microsoft Excel macro provided in [12]. Both computer tools facilitate the distribution system operator's losses evaluation as well as provide an efficient and fast way to plan and reduce them in the electrical distribution systems.

II. RESTRUCTURING OF THE MEXICAN ELECTRICAL SYSTEM

Most international electric distribution companies are immersed in a highly competitive global market. Their main purpose is to satisfy customers in terms of energy quality, price, service, and efficiency by using the proper technology and analysis tools. However, Fig. 1 shows that, although energy losses in the transmission and distribution systems of some developed countries are less than those of some developing countries [13], loss reduction still represents a challenge for all of them despite their economic development.

In this context, since the passing of a new Law regarding the deregulation of the electric industry in Mexico, its distribution system has new requirements to guarantee efficiency, energy quality, continuity, and security, since now the generation and energy marketing sectors are in the free market economy, i.e., non-governmental companies can now participate in the generation and sale sectors of electric energy and the Mexican State is the only responsible for operating the transmission and the distribution systems. Hence, for the importance of these systems to achieve a fair and competitive Mexican electricity market, the new Law stipulates that if the transmission and distribution systems operations do not meet a prespecified economic objective before two years, the Mexican Government may reserve the right to hire external help to carry out all the activities needed for these sectors [14]. This implies the proper modeling and analysis of all the changes that must be made to reduce technical and non-technical losses, which are some of the most important factors to improve. For example, Fig. 2 shows how the technical losses are increasing over the years, and it is prospected an increment of these up to 2021 [15]. It is worth noting in this Figure that the step increase in losses from 2009 to 2010 is because a former distribution company feeding the metropolitan area of Mexico City was declared in bankruptcy and the Federal Electricity Commission took charge of this area, accounting for the corresponding losses. Furthermore, a decrease in non-technical losses is also shown as a result of the implementation of different policies to address energy theft and the past-due portfolio can be observed.

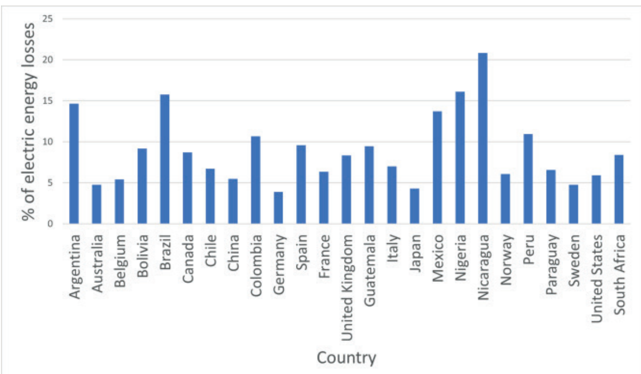

Fig. 1. Technical and non-technical transmission and distribution systems' energy losses in some countries in 2014.

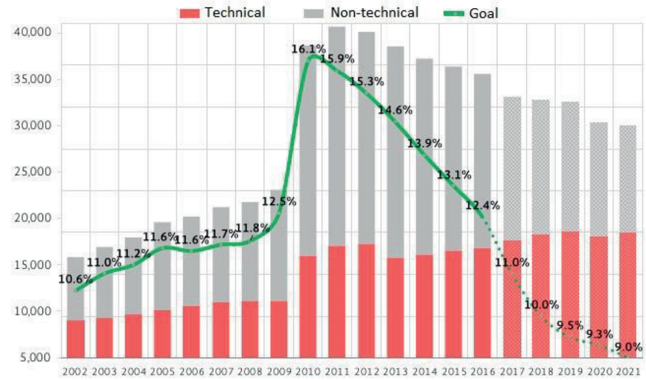

Fig. 2. Energy losses (GWh) of the Mexico distribution sector 2002-2021. Source: PRODESEN 2017-2031 (page 121), Secretaría de Energía.

Based on the aforementioned, the Mexican distribution sector must be a competitive business, i.e., it must keep trying to reduce its energy losses. For that purpose, three of the main methods of loss reduction are considered to have the major impact owing to the Mexican electrical distribution system characteristics, such as reactive power compensation, system management, and distributed generation. For instance. the simplest way to improve the power factor (PF) is the installation of capacitor banks since the reactive power compensation in a certain part of the grid provides significant benefits to the overall system. On the other hand, optimum system management helps to reduce technical losses, e.g., new service requirements increase losses, and proper loads management and the associated new infrastructure requirements may reduce their impacts on the system. The final approach considered in this paper for energy loss reduction is the appropriate location and analysis of distributed generation, which is defined as generators connected to the distribution system with a generation of less than 0.5 MW each, according to [14]. The effectiveness of distributed generation varies according to various aspects such as the proximity to loads, level of consumption of the nearby loads, and spillage of excess generation to another network with different voltage ratings. Some of the new cases of distributed generation involve renewable energies and previously installed small generators that have not been properly modeled in circuits when analyzing the grid by commonly used computational tools for the solution of power flow studies.

These are some of the new opportunities for improvement in the Mexican electrical distribution system, meaning not only a large amount of work but also many benefits. One important aspect of remodeling the system is taking into consideration the advantages Smart Grids (SG) bring to the system [16], i.e., another way to begin the improvement of the distribution networks functionality is through the implementation of the SG. One important aspect of their creation is the proper modeling of the different resources in the system, such as renewable generation, energy storage, and demand response. The cornerstone of the SG is the full deployment of the advanced metering infrastructure together with high-speed communication infrastructure for metering and control purposes. This integration of new technology can lead to better distribution system planning and operation. Nonetheless, a key component of SG would be the modeling of distributed generation, allowing the evaluation of voltage regulation, voltage fluctuations, harmonics, and transformer configurations.

III. ANALYSIS OF POWER LOSSES IN THE DISTRIBUTION SYSTEM OF THE PATZCUARO REGION

The single-line diagram of the distribution system under study corresponding to the area of the Municipality of Patzcuaro is shown in Fig. 3, and the length of its feeders is shown in Fig. 4. Simulations were carried out using the software Synergi®, by first modeling the system components in the software´s *Warehouse* Module and then evaluating the system losses using the *Power Loss Analysis* module.

The *Power Loss Analysis* module of Synergi® is simple to use: first, it is assumed that the system has balanced loads by considering the peak demands of the feeder and allocating the loads along the circuits; second, a load flow analysis is performed; this results in an overview of the whole circuit power losses and the voltage regulation of the system. The resulting information is given in the format previously established in Synergi® and then is exported to Excel. To facilitate the handling of the resulting large amount of information, an Excel macro provided in [12] is used to evaluate the energy losses and to identify the location of the worst voltage regulation in the system. One of the objectives is to determine whether the circuits are within specified boundaries of losses and at the correct voltage levels.

Throughout the region, technical losses varied greatly due to the amount and type of loads connected to certain feeders. Synergi® allows double-checking the demand levels used for the study, PF, power losses in the circuit, and the total distributed generation if any. Also, determines the worst voltage regulation in the whole system on a per-phase basis, to ensure the voltage supplied to the users is within the permissible range, guaranteeing reliability and continuity in service. As an example, Tables I and II show the results of the load flow studies obtained with Synergi®.

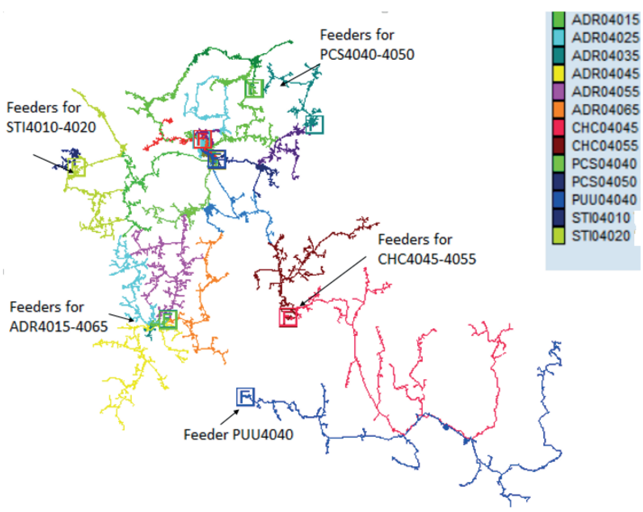

Fig. 3. Distribution system single-line diagram of the Patzcuaro area. Source: Federal Electricity Commission, Patzcuaro area.

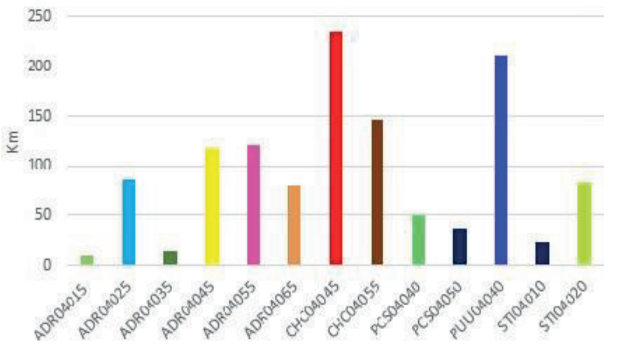

Fig. 4. Patzcuaro area feeders' length. Source: Federal Electricity Commission, Patzcuaro area.

In Table I the total power losses of the circuits ADR-4015 to ADR-4065 for May 2016 are shown; this allows the analysis of the circuits' power losses in certain sections of the zone to determine whether losses are adequate. The length of these circuits, the number of users connected, the voltage level used in the simulations (at the initial node of the circuits), the worst voltage regulation, and the corresponding name of the node are shown in Table II. It can be noticed from these results how the circuit ADR-4015 of 9.49 km with 1,757 users connected has a maximum demand of 1,060 kW and 284 kVAR; a PF of 0.97; and 4.1 kW of power losses. The worst percentage of voltage regulation of -10.125 is located at node OH-413294 (which is not shown in Fig. 3 owing to the size of the system).

The results of all the feeders are then placed into the Excel macro which calculates the energy losses using the load and loss factors of the circuit. The load factor is the customer or circuit ratio of the average demand to the maximum demand. The loss factor is obtained yearly from the distribution system operator [8].

TABLE I. SIMULATED POWER LOSSES IN THE PATZCUARO REGION.

Circuit	Max. demand (kW)	Max. demand (kVAR)	PF	Power losses (kW)
ADR-4015	1,060	284	0.97	4.1
ADR-4025	1,292	392	0.96	57.582
ADR-4035	929	292	0.95	8.045
ADR-4045	1,444	333	0.97	61.051
ADR-4055	869	36	1	12.187
ADR-4065	624	70	0.99	9.006

TABLE II. VOLTAGE REGULATION IN THE PATZCUARO REGION.

Circuit	km	Users	Simulated voltage (kV)	Worst voltage regulation (%)	Node name
ADR-4015	9.49	1,757	13.92	-0.84	SV_1228
ADR-4025	85.27	1,335	13.9	-6.25	OH_328080
ADR-4035	13.99	2,494	13.9	-1.108	OH_418731
ADR-4045	117.45	2,527	13.9	-10.125	OH_413294
ADR-4055	120.03	1,820	13.9	-3.08	OH_417695
ADR-4065	79.96	2,099	14.08	0	CB_11095

IV. LOSS REDUCTION APPROACHES

The approaches for power loss reduction in the distribution system vary depending on the specific characteristics presented in a circuit. Hence, depending on the section analyzed, a power loss reduction approach may be more or less efficient; for instance, if a circuit has low PF, capacitor placement may be needed to reduce the power losses. On the other hand, proper system management will prevent future problems due to a considerable loss increment owing to a new service, whereas the connection of distributed generation in sections with a high concentration of loads will help to reduce the system losses. The application of all these approaches for energy loss reduction to the distribution system of the Patzcuaro area is presented next.

A. CAPACITOR PLACEMENT

To determine the optimal location for capacitor banks it is necessary to first obtain the maximum and minimum demands of the circuits under study from the database of the distribution company. For this purpose, an annual graph is generated showing the minimum, average, and maximum active and reactive power demand throughout the year. The circuit analyzed was PUU-4030 of the feeder PUU-4040 shown in Fig. 3; this section presents a maximum demand of 1,415.07 kW and 544.701 kVAR with an original PF of 0.93.

This first study is to compare the results to analyze how the system will be affected by the installation of switchable or fixed capacitor banks. As a starting point, a load flow study is carried out, and then the *Capacitor Placement* option of Synergi® is used. Studies with minimum kVAR determine the rating of fixed capacitor banks, whereas studies with maximum kVAR determine switchable banks. Also, a preset on the maximum permissible reactive power of the system can be set in the software. Once setting the initial parameters, a running of the option *Update Recommended List* is carried out and the program will show a set of banks organized by the highest loss reduction the installation would provide.

After running the same analysis with the maximum demand to find possible placements for switchable banks, the software recommends a capacitor injecting 300 kVAR into the system to improve the PF to 0.98. A comparison between the base case (with no capacitors installed) and the final load flow with capacitors installed at the suggested location is shown in Table III. It is important to realize that with switchable banks the PF could reach 0.98 while the power losses will be reduced from 10.4275 kW to 9.7769 kW. While this sounds like a necessary improvement, must be evaluated the cost-effectiveness of the bank's installation, since the cost of installation may be too elevated compared to the benefits of capacitor banks in the system. Other options provided by the software are shown in Table IV. In this Table, the base case and the results with capacitors connected at the suggested locations are presented. As demonstrated, some circuits such as CHC-4015, CHC-4055, PCS-4040, and STI-4030 do not need capacitor banks installed due to their already acceptable PFs. While the other circuits either needed fixed banks, switchable capacitors, or both to improve their PF. Installation of capacitors not only increases the PF of the circuits but also decreases the energy loss while bringing about several other benefits to the circuits. It should be pointed out that a ferroresonance study should be carried out before the cost-effectiveness evaluation of the capacitor banks installation, however, owing to the scope of this paper, no such study was carried out.

B. SYSTEM MANAGEMENT

Spot loads and seasonal loads create new problems for the distribution system operator, they should be adequately modeled to accurately evaluate the energy losses. Both cases are described in this Section. In the Patzcuaro area, a request for a new connection of a 3,000 kW load with a PF of 0.9 was made. To analyze the effect of this new load connected at the circuit CHC-4055, and to evaluate the technical feasibility to supply this load, it is necessary to realize a field inspection and to actualize the circuit model in Synergi® to evaluate whether the circuit is in optimal operating conditions to respond to the new service request and to determine whether new infrastructure is needed to provide adequate service to this new load. The power flow results of the base case (without the new load connected) show that the voltage drop in the circuit is 6.84% and the power losses are 104.42 kW. After considering the new load, the results show that the power losses increase considerably from 104.42 kW to 739.42 kW. This indicates that it is necessary to realize a system modification to maintain the circuit operating near its original values of voltage regulation and power losses.

TABLE III. RESULTS OF THE BASE CASE AND CASE WITH CAPACITORS INSTALLED AT NODE PUU-4030.

Node PUU-4030	Demand (kW)	Demand (kVAR)	PF	Power losses (kW)
Base case	1 415.07	544.701	0.93	10.427
Capacitor installed	1 415.07	248	0.98	9.776

TABLE IV. RESULTS OF THE BASE CASE AND CAPACITORS INSTALLED.

Circuit	PF	Power losses (kW)	Final PF	Final Power Losses (kW)	Fixed capacitor banks (kVAR)	Switchable capacitor banks (kVAR)
ADR4045	0.93	14.72	0.99	13.3	None	150
CHC4015	1	1.97	1	1.97	None	None
CHC4055	0.99	21.54	0.99	21.54	None	None
PCS4040	0.9	18.11	0.9	18.11	None	None
PCS4070	0.97	23.122	0.99	22.29	75	None
PUU4010	0.89	27.22	0.97	22.402	None	225
PUU4030	0.93	10.427	0.98	9.776	None	300
STI40110	0.9	2.279	0.97	2.03	75	75
STI4030	0.97	10.03	0.97	10.03	None	None

The proposals to achieve this are either to recalibrate the line feeding the new service or to construct a new line. After several studies. the best results are obtained by replacing the conductor from ASCR 3/0 to ASCR 336, reducing the series resistance and as a result the conductor losses. With this new recalibration, the voltage drop is 11.72% while the power losses are reduced to 349.07 kW. The length of the recalibration of the primary line is 12 km. The other option was the construction of a new line supplying the load directly from the feeder; results from simulations show a resulting voltage drop of 4.57% and power losses of 99.45 kW. This new circuit requires 11 km of ASCR 266 conductor. The total investment for the recalibration of the 12 km segment would be USD 262,000 approximately. While the total investment for the construction of the new circuit would be approximately the same amount. The similarity in prices is due to the cost difference between ASCR 336 and ASCR 266, and the infrastructure improvements to support heavier conductors.

A new factor derived from the Mexican electricity sector deregulation plays an important role at this point: since the distribution sector has the pressure to be competitive, the attention has been directed to the reduction of the technical and non-technical energy losses only, and new investments in system expansion and/or modification are restricted by the Mexican Government, especially when they show a low rate of return on investment as these two cases analyzed. For the aforementioned, the construction of a new line is suggested by the Federal Electricity Commission, since brings more overall benefits to the grid. However, the cost of the construction will be covered by the new customer to meet the criteria of return on investment imposed by the Mexican Government. As mentioned before, this was the best solution to maintain efficiency, reliability, and continuity in the service to other customers.

For the case regarding seasonal loads, a spot load connected in the circuit CHC-4065 with a rated demand of 150 kW is considered. This seasonal load does not consume electric energy constantly throughout the year because of consists of a set of pumps used for agriculture purposes mainly active during the dry season. However, for reasons of simplifying the typically performed studies, this load has been considered constantly connected to the system when yearly energy loss evaluations are performed. As obviously, the system load flows will vary considering the seasonality of the load. During May, June, and July this load operates with a demand of approximately 140 kW with a PF of 0.85, while in the other months, this load does not consume any power. As previously mentioned, while this is a key factor in load flow studies, this has not been modeled yet in Synergi®. For this reason, the model implemented in Synergi® is updated including the changes in demand of the spot load located at the mentioned location. The results demonstrate a lowering of power losses in this circuit, as expected.

Table V shows the demand of the spot load in the circuit for the year 2016 and the corresponding losses in this circuit. It can be noticed how the losses decrease due to the consideration of the load's seasonality. This final example shows the importance of having an accurate system model and load information to have an accurate energy loss evaluation. This plays an important role in the future planning of the system or circuits affected.

C. DISTRIBUTED GENERATION

Synergi® offers an easy way to model this new type of generation through a previously created model in the *Warehouse* module. This offers the ability to specify the generators' data and to have an exact power flow study to effectively analyze the effects that these generators would have on the system. In the circuit CHC-4065, there is a clear example of the importance of modeling distributed generation in the system. The circuit has a total of 750 kW of power generated by small hydroelectric plants connected at different nodes. The first case was to model one of these plants of 350 kW. Hence, it is possible to analyze how the modeling and consideration of these generators affect the overall loss evaluation. Due to the low energy consumption of the circuit, monthly power losses increased when this small generating plant was considered.

Table VI shows the simulation for a year assuming the same maximum demands used in previous studies. Based on the results obtained, it is expected that the energy losses will show an increase when the total of the distributed generation is considered. This highlights the importance of having a comprehensive framework for multi-year planning to determine upgrades and changes that must be made such as recommended in [17] and [18].

TABLE V. RESULTS CONSIDERING THE SEASONAL SPOT LOAD.

Year 2016	Demand (kW)	PF	Original losses (kW)	Final losses (kW)
Jan.	0	0	1.2	1
Feb.	0	0	1.1	1
Mar.	0	0	1.41	0.96
Apr.	0	0	1.73	1.51
May.	142	0.85	4.49	5.38
Jun.	143	0.85	1.15	1.45
Jul.	139	0.85	1.07	1.2
Aug.	0	0	1.22	0.72
Sep.	0	0	2.26	1.74
Oct.	0	0	1.78	1.21
Nov.	0	0	2.11	1.84
Dec.	0	0	1.68	1.38
		Total	21.2	19.39

TABLE VI. LOAD FLOW RESULTS FOR THE BASE CASE AND THE CASE WITH DISTRIBUTED GENERATION.

Node	Max. demand (kW)	Max. demand (kVAR)	Losses (kW)	New losses (kW)
Jan.	255	-127	1.2	1.5601
Feb.	138	-235	1.1	1.2846
Mar.	264	-188	1.41	1.7548
Apr.	137	-383	1.73	2.0347
May.	189	-674	4.489	4.9118
Jun.	269	-116	1.152	1.6281
Jul.	261	-96	1.07	1.5513
Aug.	280	-6	1.22	1.6388
Sep.	382	-209	2.26	2.6674
Oct.	359	42	1.78	2.2486
Nov.	189	-407	2.11	2.4155
Dec.	182	-343	1.68	1.9789
		Total	20	26

V. CONCLUSIONS

The importance of loss reduction in the distribution systems was discussed in this paper, particularly regarding the changes imposed by the new Mexican electrical industry Law. It has been discussed how the distribution system operator needs to propose and implement approaches to reduce energy losses and improve voltage regulation to maintain the quality, reliability, continuity, and security of the network. Three approaches were tested using the commercial software Synergi®: capacitor placement, system management, and proper modeling of distributed generation. The first method discussed was capacitor placement, which improves the PF and reduces losses. From the results obtained, it was shown how some circuits do not need capacitor banks while others need either fixed banks, switchable capacitors, or both. On the other hand, as a distribution system operator, it is important to take into consideration system management. Managing large loads strategically in a circuit by either limiting the demand or evaluating the expansion and/or modification of the grid allows an optimal operation of the system and the correct evaluation of power losses in the system.

Furthermore, it was shown how investments made into the system to supply energy to a large customer sometimes are not justified and the end user must pay for the improvements needed, otherwise, its energy demand must be limited. Including suitable models of distributed generation may help a proper evaluation of the energy losses; even is possible to suggest the correct circuit for its deployment which could be closer to larger loads. Finally, it was shown how when distributed generation is in circuits with lower consumption the power losses increase considerably. This must be considered to take full advantage of the energy produced by renewable resources. Of course, many other aspects of the system can be improved, but these three approaches are essential and provide more benefits to the system. To create a new Mexican distribution system these factors must be considered to analyze the benefits and problems regarding the inclusion of the different components of the network, as well as their economic impact on the overall system operation.

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