# Expansion of Electrical Networks Considering Power Quality Aspects by Applying a Multi-Objective Tabu Search Technique

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Abstract— This paper proposes an optimization algorithm to expand electrical networks based on the application of a multiobjective Tabu Search technique. The proposed methodology finds Pareto efficient solutions to the formulated problem by searching the topology that minimizes the voltage sag/year number in the electrical system and at the same time that minimizes real power losses. The algorithm performance is tested on two systems taking into account a static transmission expansion planning in order to demonstrate the application of the developed methodology.

Keywords— Voltage sags, power quality, network expansion, tabu search.

## I. INTRODUCTION

Transmission network expansion planning, in regulated electricity markets, basically consists of minimizing the investment costs in new transmission lines while maintaining a certain level of reliability, subject to operational constraints in order to meet the system requirements according to the growing demand for electricity [1]. Currently, the transmission expansion problem has become even more challenging because the integration of renewable energy into power systems often requires new transmission lines to be built [1].

Hence, expansion of electrical networks must be done in an efficient and reliable way taking into account the optimal timing, location and sizing of transmission facilities to be installed in an existing network [2]. In other words, it is a planning problem that specifies where, how many and when new equipment must be installed in an electric system, so that it operates adequately within a specified planning horizon [3][4].

The network expansion, both at the distribution and transmission level, may be studied by using static or dynamic models. A static model determines the network configuration for a single future period and tries to answer questions like where and which type of new circuits should be built in an optimal way planning horizon; thus, the model does not consider when new circuit assets are to be built. Static planning applies some simplification; for instance, voltage and stability problems are not taken into account. Dynamic network planning deals with a longer planning horizon, which is divided into several periods, and it tries to answer the same questions but also answer the question of when to add new circuits. In other words, the dynamic model considers several horizons regarding the same issue [4][5].

At the present time, there are several papers that treat the transmission network expansion problem. For instance, in [6] a shifter transformer is used to redistribute the active power flow to optimize the power dispatch, and as a consequence, to decrease the total investment costs incurred in the construction of new lines. In [7] a model based on linearized power flow is used to treat the multistage expansion problem, among others. In addition, there are papers that analyze the transmission expansion problems by considering by incorporating renewable power sources and their impact on the network expansion [8]-[15], as well as the ones that solve the multistage transmission expansion planning [3][5][7].

On the other hand, end-users are demanding higher levels of power quality that is related to electrical disturbances, which can affect the electrical conditions of power supply, such as voltage sags that are one of the most important concerns of power quality [9].

In this paper, a multi-objective optimization formulation of the expansion of electrical networks' problem is presented. The approach searches the optimal topology by considering two objectives: the topology that has the lowest real power losses and minimizes the voltage sag number in the system or the topology that best fulfills specific requirements to be satisfied in particular buses.

There are several methodologies for computer-based optimization of network planning problems that can be classified into exact and heuristic optimization methods. Exact methods determine the optimal solution; however, in many cases computational effort increases exponentially. Heuristic methods find the best solution that in most cases is close to the global optimum within a short period of time [10]. Because of this, heuristic methods have been widely used to solve many kinds of optimization problems. The most frequently used methods are based on genetic algorithms, simulated annealing, tabu search, among others.

In this paper, to solve the optimization problem a multiobjective Tabu Search technique is implemented, which finds Pareto efficient solutions. In order to show the application of the developed multi-objective methodology, a static transmission expansion planning in two test systems is presented.

#### II. FORMULATION OF MULTI-OBJECTIVE EXPANSION PROCESS

In this paper, a methodology is proposed for the electrical network expansion in an optimal way by taking into account one or more objective functions. Furthermore, two objective functions are considered voltage sags and real power losses. In addition, an analysis about the construction cost is made.

The optimization problem is solved by means of a Multi-Objective Tabu Search (MOTS) algorithm. In all possible topologies, the process must take into consideration some restrictions, such as the system connectivity (ensuring that no areas of the systems are isolated), voltage limits and power balance [9].

Next in order to formulate the problem of multi-objective optimization, representation and similar considerations as those reported in the previous work in [9] are assumed. Note that in [9] the proposed approach is focused on the solution of the optimal network expansion with a single objective.

The way to represent if a line would be built to expand the electrical network is by means of a parameter that permits the use of a binary representation, where the x(i) value is obtained according to the next criterion [9]:

$$x(i) = \begin{cases} 1, & \text{line } i \text{ is built} \\ 0, & \text{otherwise} \end{cases}$$
(1)

The above representation is used to typify the built/unbuilt state of a transmission line proposed by means of a binary vector which has a length equal to the total number of lines to be built in the system [9].

In the expansion process every possible topology should be evaluated for finding the best one. Usually a large amount of possible topologies, however, could result in a procedure which requires a lot of computational time.

Voltage sags rates can vary depending on the system characteristics. Generally, statistical data about the occurrence voltage sags presented in an electrical system can be obtained. These values can be considered as typical values for a particular bus (or the whole system); on the other hand, in some utilities there are specific voltage sag directives. Furthermore, some special customers could require to the utility about specifications regarding the maximum number of voltage sags permitted in a period of time by particular contracts [11]-[19].

In this paper, an optimization process is applied to expand the electrical networks by searching the topology that minimizes the voltage sag number in the system (taking into account special voltage sags requirements in particular buses of the system [11] and that also minimizes the real power losses.

As in [9], considering a generic electrical system of N buses and NB new buses to be connected, it is assumed that NL is s set of possible lines to connect the new buses. Each  $L_{ij}^{k}$  line, which belongs to a NL, is a possible path to connect the new bus *i* with the new bus *j*. In addition, to represent the built/unbuilt status, an *x* can be associated with each line to show its status. Each line  $L_{ij}$  is represented as a switch that can change its status (built/unbuilt). Every configuration which is obtained by changing the built/unbuilt status of the  $L_{ij}$  lines can be described by means of an X vector. The X vector length is equal to the total NL lines, and it can be written as follows:

where the first element of the X vector is associated with the line that connects a and b buses. This element is denoted as  $L_{ab}^{l}$ , and its value is equal to zero, which means that this line will not be included in the network expansion. It is the same with  $L_{ij}^{k}$ . On the other hand, lines  $L_{cd}^{2}$  and  $L_{pq}^{NL}$  are part of the network expansion. Every configuration must be evaluated to ensure that all new buses are connected to the old system [9].

A power flow study is executed for every configuration in order to get pre-fault voltages. Next, a voltage sag evaluation by means of the methods in [20] and [21] is applied to get the total voltage sag number in the electrical system. Mathematically the multi-objective problem can be written as follows:

$$\min\left(\sum_{i=1}^{N} f_{esti}(x, V, \theta), \sum P_{Loss}\right)$$
(3)

subject to

$$\begin{split} P(V, \theta) + P_D - P_{gi} &= 0\\ Q(V, \theta) + Q_D - Q_{gi} &= 0\\ V_i^{\min} &\leq V_i \leq V_i^{\max}\\ P_{Gi}^{\min} &\leq P_{Gi} \leq P_{Gi}^{\max}\\ Q_{Gi}^{\min} \leq Q_{Gi} \leq Q_{Gi}^{\max}\\ \sum_{j=1}^{NL} (x_j) > 0 \end{split}$$

C1: No isolated buses in the network

where  $f_{esti}(x)$  is the voltage sags number for the *i* bus  $P_{Loss}$ total real power losses in the system  $V_i^{\min}$ is the minimum voltage at bus i  $V_i$ is the voltage at bus i  $V_i^{\max}$ is the maximum voltage at bus i  $P_{Gi}^{\min}$ is the minimum real generation limit at generator i  $P_{Gi}$ is the real generation at generator *i*  $P_{Gi}^{\max}$ is the maximum real generation at generator *i*  $Q_{Gi}^{\min}$ is the minimum reactive generation at generator i  $Q_{Gi}$ is the reactive generation at generator i  $Q_{Gi}^{\max}$ is the maximum reactive generation at generator i Ν number of buses in the network  $x_i \in \{0, 1\} \ j=1,..., NL$ *NL* set of new possible lines or paths.

The formulated expansion problem of a system in order to minimize the total voltage sag number and the total real power losses in (3) is solved by applying the implemented MOTS algorithm.

# III. IMPLEMENTATION OF THE EXPANSION PROCESS BY APPLYING MULTI-OBJECTIVE TABU SEARCH

In this work, the MOTS algorithm and the expansion methodology described in Section II have been implemented in Matlab®. Fig. 1 shows a flow chart of the expansion process that is proposed in this paper. Next, a description of each step of the methodology is presented [9].

- 1) Reading network data, type of fault, voltage sags reference values, among others.
- 2) Pre-fault voltages are obtained through a power flow analysis.
- 3) A stochastic assessment of voltage sags is carried out.
- 4) If there are some new buses to be connected, then an expansion process is performed.
- 5) The expansion process starts with an initial solution which is created in a random way. This initial solution is a binary vector, according to the definition of vector X(i) from the formulated problem (2).
- 6) The initial solution is evaluated to guarantee that no area of the new buses is isolated. If the initial solution has an isolated area, then this solution is discarded, and a new one is generated and so on.
- 7) When an initial solution accomplishes the goal of not having any isolated area of the new buses, then this particular topology is evaluated through a power flow analysis.
- 8) A stochastic assessment of voltage sags is realized for the current configuration.
- 9) A neighborhood is generated from the current configuration. The number of neighbors corresponds to the number of new lines which have been selected previously. In addition, the number of elements for each neighbor correspond to the number of new lines in the system.
- 10)Each neighbor is created by making a change -one by one- of each element of the current vector solution. All of the neighbors are evaluated: first pre-fault voltages are obtained, and then a voltage sag analysis is carried out.
- 11)In the proposed methodology, each neighborhood is sorted in two ways. The first one considers the voltage sag values; these values are sorted from the lowest to the highest. They are then normalized with respect to the highest. The second one is made equal to the first one, but now the real power losses are taken into account.
- 12) When the neighborhood is sorted in both ways, the configuration that offers the lowest value of objective function is selected if it does not belong to the tabu list. The tabu list is empty in the first iteration. As the best configuration is that being selected at each iteration, this configuration will form part of the tabu list for a determined number of iterations.
- 13)If the neighbor belongs to the tabu list, then the second

best neighbor is selected and so on. 14)The tabu list is updated.



Fig. 1 Flow chart of the expansion process.

This process is repeated until a convergence criterion is satisfied. In this work, the MOTS process can stop in two ways: when it reaches the maximum iteration number or when the total voltage sag number does not decrease [9].

#### IV. CASE STUDIES

The proposed methodology is applied to the IEEE RTS 24-Bus Test System and a 190-Bus Mexican Electrical System in order to find the best new topology for obtaining Paretooptimal solutions and minimizing the value of total voltage sags, as well as the total power losses. The cases are analyzed considering that voltage sags are caused by balanced threephase faults. Moreover, in order to consider the system operation state, pre-fault voltages are obtained by means of power flow studies using the PSS/E software [22].

### A. The IEEE RTS 24-Bus Test System Expansion

The system consists of 24 buses interconnected by 33 lines and 5 transformers of 230/138 kV and 10 generation units [23]. When a voltage sag analysis is carried out in this system, the system is found to have a total of 548 voltage sags/year.

The expansion methodology is applied by assuming that the system has eight new buses that require connection to the existing net as shown in Fig. 2. The dashed lines indicate 16 possible paths. The X vector in this case is formed according to the order indicated as a superscript in Fig. 2. For example,



Fig. 2 New buses in the IEEE RTS 24-Bus Test System and new possible paths.

$$\begin{aligned} L_{25-1}^1 & L_{25-2}^2 & L_{25-26}^3 & \cdots & L_{31-4}^{16} \\ X &= \begin{bmatrix} 1 & 1 & 1 & \cdots & 1 \end{bmatrix} \end{aligned}$$

In this case study, a cost of each line is assumed by considering random values among 1 and 3 \$/line.

Table 1 shows the results of the multi-objective expansion process for the IEEE RTS 24-Bus Test System. It shows seven possible configurations to connect the new buses to the existing grid. Configuration 1 is the worst one because it represents that all possible paths should be built. This configuration has a total of 1394 voltage sags/year, which means that the system would increase the total of voltage sags/year for almost 55% of the original system while the total real power losses are almost unchanged. In addition, this configuration would signify spending 100 percent of investment.

Configurations 2 to 7 reduce the total of voltage sags. With regard to actual power losses, note that configurations 3 to 5 have the same amount of losses; this is similar for configurations 6 and 7. Although configurations 6 and 7 have the lowest power losses, configuration 7 has the lowest total of voltage sag throughout the network. Fig. 3 shows the scenario of configuration 7.

Fig. 5 shows the Pareto front curve for the IEEE RTS 24-Bus Test System, and clearly configuration 7 belongs to this curve, which means that it is a good solution.

Table 1 Multi-objective expansion process results, IEEE RTS 24-Bus Test System

	2		
No.	Configuration (Vector X)	Sags/year	Power Losses (MW)
1	1111111111111111111	1394.2	63.4000
2	0110011110100011	1047.0	58.2114
3	1110011101011010	1052.5	58.2065
4	$1\ 0\ 1\ 0\ 0\ 0\ 1\ 1\ 0\ 1\ 0\ 1\ 0\ 1\ 0$	1018.7	58.2065
5	1010001011011010	1009.3	58.2065
6	0100011010110011	1008.4	58.2057
7	0100011010111010	1001.4	58.2057



Fig. 3 Optimal configuration of IEEE RTS 24-bus expansion problem.



Fig. 4 IEEE RTS 24-Bus Test System savings (%) for configurations 1 to 8.



Fig. 5 Pareto front for the IEEE RTS 24-Bus Test System.

# B. The 190-Bus Mexican Electrical System

The 190-Bus Mexican Electrical System consists of 190 buses interconnected by 265 lines, 46 generation units and 90 loads [24]. It is assumed to have a fault rate of 1 fault/year per line. When a voltage sag analysis is carried out in this system, the system is found to have a total of 1466.8 sags/year.

In order to apply the expansion methodology, it is considered that the actual network would grow randomly and would have 18 new buses with 37 possible lines that would be associated with these new buses. Fig. 6 shows the entire system, and the gray shadows indicate the zones where the new 18 buses and their respective lines would be located. Fig. 7 through Fig. 10 show in detail the areas that are considered as new. In order to show the process which leads to obtaining the optimal solution, four possible configurations are shown: current state (C1), two intermediate solutions (C2 and C3) and finally the optimal solution (C4). Table 2 shows the results of the expansion process of the 190-Bus Mexican Electrical System. It illustrates four possible configurations to connect the new buses to the existing grid. Configuration C1 represents the worst configuration of the system; it means all buses and lines (including the new ones) are taken into account, and this configuration has a total of 3102 voltage sags/year and a power loss of 347.1 MW. Configurations C2 to C4 reduce the total of voltage sags and the real power losses respectively. Configuration C4 is the one that improves both the voltage sag number and the real power losses throughout the network.



Fig. 6 The 190-Bus Mexican Electrical System.



Fig. 7 First section of the 190-Bus Mexican Electrical System.



Fig. 8 Second section of the 190-Bus Mexican Electrical System.



Fig. 9 Third section of the 190-Bus Mexican Electrical System.



Fig. 10 Fourth section of the 190-Bus Mexican Electrical System.

	Table 2	Expan	sion pro	cess result	s for th	e 190-Bus	Mexican	Electrical	System
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Lines	C1	C2	C3	C4
191-88	1	1	1	1
191-74	1	1	1	1
192-73	1	1	1	1
193-47	1	1	1	1
192-193	1	0	0	0
194-191	1	1	1	1
194-65	1	1	1	1
194-68	1	1	1	0
193-195	1	0	0	0
190-196	1	1	1	1
196-82	1	1	1	1
197-62	1	1	1	1
197-60	1	1	1	0
198-60	1	1	1	1
198-197	1	1	1	1
198-199	1	1	1	1
199-63	1	1	1	1
200-109	1	1	1	1
200-104	1	1	0	1
201-113	1	1	1	1
201-102	1	1	0	1
201-202	1	0	1	1
202-62	1	1	1	0
203-160	1	1	1	1
203-166	1	1	1	1
203-204	1	1	1	1
204-185	1	0	0	0
205-187	1	1	0	0
205-140	1	1	1	1
205-156	1	0	0	0
206-147	1	1	1	1
206-173	1	1	1	1
205-206	1	1	1	1
207-178	1	1	1	1
208-144	1	0	0	0
208-141	1	1	1	1
208-173	1	0	0	0
Total lines connected	37	30	28	27
Total voltage sags	3102	2592	2537	2488
Power losses (MW)	347.1	335.2	334.7	334.6

In this case study, for the line with the largest impedance a unitary cost is assigned (assuming 100% of the line cost). According to this unitary cost, for the other lines the cost has been assumed to be in proportion to their impedance values.



Fig. 11 Savings of the 190-Bus Mexican Electrical System.

Fig. 11 shows a comparison of savings (%) with respect to the worst configuration. As is clearly seen the configuration that offers the greatest savings is configuration 4, which in this case is the one that improves the number of voltage sags and the real power losses.

## V. CONCLUSIONS

In this paper, an optimal expansion of electrical networks' methodology was proposed, taking into consideration two objective functions. In this case, voltage sags and real power losses were considered, and the optimization problem is solved through an implemented Multi-Objective Tabu Search algorithm which leads to finding Pareto efficient solutions.

In order to show the performance of the proposed methodology, two case studies using the IEEE RTS 24-Bus Test System and a 190-Bus Mexican Electrical System were presented. In general, the results obtained show the potential of the proposed methodology in solving the expansion problem while considering more than one aspect to optimize, which can be very useful in the network planning.

In the case studies presented, considering voltage sags and power losses, the results show the importance of a multiobjective analysis in finding Pareto optimal solutions which, while minimizing voltage dips and minimizing losses power, also makes it possible to quantify the savings they have with the optimal expansion.

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