# A Multi-Objective Analysis for Planning Electric and Natural Gas Distribution Networks

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*Abstract*— **This paper presents a multi-objective mathematical model to plan natural gas and electricity distribution networks as one system. The model considers two conflicting objectives, i.e., investment cost (for both networks) and energy losses (for the electric networks). This approach offers to decision maker (or network planner) a set of optimal solutions or wide variety of solutions (instead of one solution) so that a decision can be made based on planner's preference, utility budget constraints, etc. Numerical results demonstrate the advantage of this approach, when it is compared with a tradition single-objective optimization approach.**

***Index Terms* — *Distributed generation, electric distribution system, energy technical losses, multi-objective optimization, natural gas distribution system, SPEA 2.***

## I. INTRODUCTION

The oil price volatility and the foreign exchange rate volatility affect foreign investment in developing economies that have high dependence of commodity exports [1]-[2]. One special case is the investment in energy sector that is highly sensitive to such variations. In this context, traditional expansion planning methodologies applied to energy sector have to be carefully examined because 1) foreign investors or private debt funds execute most of the expansion plans and 2) financial benefits might not be realized due to financial uncertainty.

On the other hand, the central government of Colombia is expected to increase electricity and natural gas coverage for most of the population, i.e., to increase the percentage of population with access to electricity and natural gas. Other important objective is to improve the quality of service for electrical and natural gas customers. This is a crucial aspect, as the economic growth is demanding a better service. Energy efficiency is other objective that is under consideration, with special attention to energy losses [3]. All these government's expectations demand substantial investments by private utilities and therefore traditional planning methodologies have to be adjusted so that these considerations can be taken into account.

Other issue that requires special attention in planning power distribution systems is the high penetration of distributed generations. They are becoming an essential part of power distribution system due to the low operational cost (and in some cases low investment cost) and the benefits that brings to the system.

In summary, traditional network planning is a challenging task in fast growing economies (as Colombia) since there are financial uncertainties associated to the investment returns, quality and energy efficiency requirements require by the government regulation, and the expected high penetration of distributed generation. In particular, the problem becomes more demanding of computational resources and mathematical formulation if the utilities own the power and natural gas distribution networks. That is, it is common in some countries that a utility operates the power and natural gas distribution networks in the same service territory. These utilities are implementing an integrated distribution planning that has shown lower investment cost [4].

Multi-objective optimization is a mathematical technique that is applied if more than one objective function is optimized simultaneously and the objective functions are to be said conflicting. This tool provided a set of solutions (named Pareto optimal solutions) that are used by the decision maker to find a solution that satisfies his preferences. It is a tool that offers, in the context of the current situation of power and natural gas utilities in Colombia, a set of optimal solutions that evaluates simultaneously an investment cost (a crucial aspect due to existing financial uncertainty) and system quality and efficiency requirements (due to government expectation).

This paper uses a multi-objective optimization algorithm to plan power and natural gas distribution networks as one system taking into consideration two objectives. The first one is the investment costs and the second objective is the power network losses. The quality requirements are modeled as constraints that guarantee voltage and nodal pressure requirements for the electrical and natural gas networks respectively. Note that the two objectives are conflicting as lower investment cost implies, in most of the cases, higher energy losses. In fact, this approach provides Pareto optimal solutions that can be used by the networking planning to select one solution based on his investment risk preferences and the desired efficiency targets. The algorithm is used to plan power and natural gas distribution networks with high-penetration of natural gas distributed generation as this situation is becoming more common in many countries.

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Different approaches for planning electric distribution networks have been used [5]-[12]. In fact, multi-objective optimization has been used considering various objectives (investment cost [5]-[12], reliability [5]-[9], technical losses [8]-[10], voltage regulation [9]-[11] and risk investment [12]). However, multi-objective planning for natural gas distribution systems has not been reported in the academic literature as far as the authors of this paper know.

Distributed generation (DG) based on natural gas has also been taken into account in planning power distribution network [13]-[17]. However, these papers do not considered the interdependency of natural gas and power distribution network. In [4], on the other hand, a holistic approach for planning power and natural gas distribution networks is presented that shows that a lower investment and operational cost can be achieved if the both networks are considered as one system. This paper follows that approach but considering a multi-objective approach. That is, this paper builds on [4] so that a multi-objective approach is formulated that provides multiple solutions to the decision maker. The problem is solved using Strength Pareto Evolutionary Algorithm 2 (SPEA 2) since it has been proved to show excellent results for multimodal and combinatorial problems [10], [18]. Additionally, a comparison using the methodology of [4] is made.

Finally, this paper is organized as follow. Problem description and proposed solution methodology are in section II and III. Numerical Results and Conclusions are in section IV and V respectively.

## II. PROBLEM DESCRIPTION

A multi-objective optimization model is proposed in this paper to find a set of optimal solutions (Pareto solutions). The optimization model is a mixed integer nonlinear model. Two objective functions are considered in this paper (described in section II.A) subject to a set of constraints (described in section II.B). Different model formulations are proposed in this paper that are in section II.C. These formulations allow assessing the problem from different points of view.

### A. Objective functions

The first objective function (Eq. (1)) is the total investment cost of the electricity network (upgrading of electric feeders and installing of new distributed generators) and the natural gas network (upgrading of pipelines and citygates). For simplicity's sake, this paper only describes the equations as the complete mathematical formulation can be found in [4].

$$OF_1 = \left[\begin{array}{c} \textbf{Investment cost of electricity network} \\ \left(\begin{array}{c}\textit{upgrading of feeders and substations,} \\ \textit{distributed generators}\end{array}\right) \\ + \\ \textbf{Investment cost of natural gas network} \\ \left(\textit{upgrading of pipelines and citygates}\right) \end{array}\right] \tag{1}$$

The second objective function (Eq. (2)) corresponds to the operative cost of electricity network, i.e., technical losses cost:

$$OF_2 = \left[\textbf{Operative costs}\left(\textit{energy technical losses}\right)\right] \tag{2}$$

### B. Model constrains

Equation (3) guarantees that the Kirchhoff's law for the electric network and mass conservation law for natural gas network are met. Equation (4) guarantees that maximum operational capacity of the natural gas and electric distribution network elements is not exceeded. In (5), the operational limits of nodal voltage and nodal pressures of the electric and natural gas distribution networks are modeled; this constrain implies that the service quality is fulfilled. Finally, (6) establishes the natural gas consumption required by DG to inject power to the electrical network. Note that (6) links the electric network with the natural gas network.

- *Nodal equations: electric power (Kirchhoff laws) and natural gas (Conservation mass law)* (3)
- *Maximum capacity of the electric system elements (feeders, substations and distributed generation) and natural gas system elements (pipelines, citygates)* (4)
- *Operative limits of the electric system (nodal voltages) and natural gas system (nodal pressures)* (5)
- *Natural gas distributed generation consumption* (6)

### C. Model formulations

It was mentioning that this paper proposes different mathematical formulations to assess the problem from different points of view. To this end, two cases are numerically analyzed that only differ from how the objective function is formulated. Case 1 is a multi-optimization problem with objective function given by (1) and (2) as shown in (7).

$$\begin{array}{rl} min = & \{\text{Eq. (1), Eq. (2)}\} \\ s.t. & \text{Eq. (3)-(6)} \end{array} \tag{7}$$

On the other hand, case 2 is a single objective optimization problem with an objective function given by a linear combination of (1) and (2), as shown in (8).

$$\begin{array}{rl} min = & \{\alpha_1\text{Eq. (1)} + \alpha_2\text{Eq. (2)}\} \\ s.t. & \text{Eq. (3)-(6)} \end{array} \tag{8}$$

In (8), $\alpha_1$ and $\alpha_2$ are two scalars to weight the importance, based on planner expertise, of each objective. Note that (8) is used to compare with the proposal approach, i.e., a multi-optimization problem.

## III. SOLUTION TECHNIQUE

The mathematical models describe in section II.C are solved using Strength Pareto Evolutionary Algorithm II (SPEA 2) [19] for case 1 and a Chu-Beasley genetic algorithm for case 2. A summary of SPEA 2 is as follows:

i. Define the size $N$ of the population $P$, the size $M$ of the external population $Q$ and the maximum number of generations $G_{max}$.
ii. Begin with an initial population $P_o$ (randomly generated or using heuristic criteria), assign $Q_o=\phi$ and initialize $t=0$.
iii. Determine the value of the fitness function of each individual of the populations $P_t$ and $Q_t$.
iv. Find non-dominated individuals in $P_t$ and $Q_t$ and move them to new population $P_{t+1}$. If the size of $P_{t+1}$ is greater than $N$, apply a clustering technique to reduce $P_{t+1}$ to $N$. Otherwise, complete new population $P_{t+1}$ with dominated individuals of populations $P_t$ and $Q_t$.
v. If $t > G_{max}$ stop. In this case, the Pareto optimal frontier corresponds to non-dominated solutions that conform the actual population. Otherwise, go to next step.
vi. Apply the genetic operators of selection (using tournament), crossover and mutation to the individuals of the actual population and create the new population ($P_{t+1}$).
vii. Do $t=t+1$ and go to step iii.

As mentioned, case 2 is solved using a Chu-Beasley genetic algorithm that is not described in this paper since its full-blown formulation is in [4].

## IV. NUMERICAL RESULTS

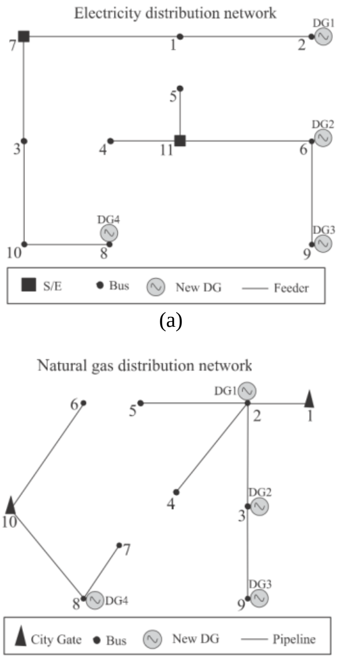
The proposed methodology is applied to an electric power distribution system and natural gas distribution system that are shown in Fig. 1. The electric network has 11 nodes, 2 substations (at nodes 7 and 11), and four nodes at which natural gas DG might be installed (at nodes 2, 6, 8 and 9). On other hand, the natural gas network has 10 nodes, 2 citygates (at nodes 1 and 10), and four nodes at which natural gas DG might be installed (at nodes 2, 3, 8 and 9). For both systems, power and natural gas demands are represented by filled black circles and electric substations and citygates are shown as black-square and black-triangle respectively. For planning purposes, there has been proposed 4 types of different wire gauge (or capacity) for electrical feeders, 2 types of electric substations, 5 types of DG, 5 types of pipeline, and 2 types of citygates. Finally, Table I shows the parameters that are used for the algorithm of section III that was implemented in Matlab and GAMS.

In order to assess the proposed approach of section II, the algorithm of section III performs 100 computer simulations, 80% of them converge to the same Pareto frontier, i.e., they have, at least, 90% the same individuals on the frontier. It is worth mentioning that each runs of the algorithm multi-objective is lower, on average, to find a solution when comparing with a single-objective optimization algorithm. That is, it takes more computational time to find a frontier rather than a single solution. However, it will be shown that it is more effective to have the frontier rather than a single solution.

Fig. 2 shows the result of one computer simulation that found a Pareto frontier. One solution at the frontier (i.e., an individual) was selected using the *maxmin* metric proposed in [20] and marked with a letter B. For comparison purposes, the operative cost (left vertical axis of Fig. 2) and investment cost

TABLE I
PARAMETERIZATION FOR THE ALGORITHM OF SECTION III

| **Description** | **Value** |
|---|---|
| Planning stages | 1 of 5 years |
| Load duration curve | 100% (1095 hours) |
| | 60% (5475 hours) |
| | 30% (2190 hours) |
| Crossing rate | 0.9 |
| Mutation rate | 0.8 |
| Crossing points | 4 |
| Size $N$ of population ($P$) | 20 |
| Size $M$ of population ($Q$) | 20 |
| Maximum number of generations ($G_{max}$) | 200 |
| Energy cost [US$/kWh] | 0.125 |



(a)

(b)

Fig. 1. Test distribution system: electric (a) and natural gas (b)

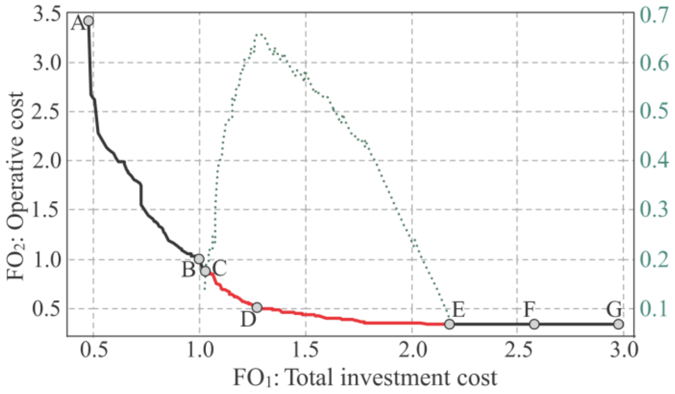


Fig. 2. Pareto optimal frontier

(horizontal axis of Fig. 2) are normalized with respect to the values of solution B that are 1.259 and 0.662 million US dollars respectively.

### *A. Multi-objective vs. single-objective*

In order to compare how effective the Pareto frontier, which is shown in Fig. 2., with respect to a single-objective optimization solution, three pair of different values for $\alpha_1$ and $\alpha_2$ are used for (8). These values are necessary to solve a single-objective optimization approach. The decision-maker requires a prior knowledge of what objective is more relevant for the planning to select the values of $\alpha_1$ and $\alpha_2$.

Let assume that the pair has the following values: case 1 ($\alpha_1 = 1, \alpha_2 = 0$), case 2 ($\alpha_1 = 1$, $\alpha_2 = 1$) and case 3 ($\alpha_1 = 0$, $\alpha_2 = 1$). For each case, 100 computer simulations of Chu-Beasley genetic algorithm was done and the results are letter A (case 1), D (case 2) and F (case 3) in Fig. 2. Note that all single-objective solutions are located at the frontier that shows that a single-objective algorithm is a particular case of a multi-objective approach. Hence, it is not worth to solve a single-objective since its solution, at least for this example, is part of the frontier without establishing the values of $\alpha_1$ and $\alpha 2$ or without previous knowledge of what objective is more important. Although it requires more computational time to find a Pareto frontier, it provides a wider range of solutions to make the decision. For this particular example, it takes 30% more computational time to solve a multi-objective approach when comparing with a single-objective.

### *B. Choosing a solution from the Pareto frontier*

Section IV.A shows that it is more convenient solving a multi-objective approach rather than a single-objective. However, it is necessary to outline a strategy to guide the decision maker to choose one solution from the frontier. This section outlines a heuristic approach to narrow down the options.

A common approach to select one solution of the frontier is *maxmin* technique [20] that basically looks for the closest point to the origin of Fig. 2 that means that the two objectives are balanced. It is point B in Fig. 2. The technique is a good starting point for the analysis. However, it might be advisable to analyze different points on the frontier based on particular characteristics of the problem that is being solved.

For an integrated planning of an electric and natural gas distribution networks, the operative cost is based on power losses that depend of an estimation of the demand growth. An overestimation leads to an unnecessary investment cost due to most of capacity are being oversized. Additionally, the location and the capacity of natural-gas DG, which has a strong correlation with power losses as shown in [21], will be under-utilized. Overestimation might affect all solution to the right of point B. On the other hand, an underestimation leads to a network topology that might infeasible because the capacity of the network's elements were design for a lower demand growth. Underestimation might affect all solution to the left of point B.

Let begin the analysis with points A and G that are the extreme of the frontier. A is the cheapest option but with the highest operative cost. It is not advisable to have a solution with a high dependency of the operative cost because the topology might be infeasible if the demand is underestimated. It is, therefore, risky. Point G is also not advisable since it is the most expensive option.

Let analyze the effect of increasing investment cost and its impact on reduction operative cost at point B. In other words, points that are located to the right of B. Note that points to right are more convenient to analyze since it is often common to overestimate the demand grown rather than underestimate. Additionally, points to the left of B are topologies that might be faced supply shortage if demand is underestimate.

Let consider a point to the right of B, e.g., point C. The dotted curve above the red curve is the numerical result of $\left((OC^B - OC^C) - (IC^C - IC^B)\right)/(IC^B)$, where $OC^B$ and $OC^C$ are the operative cost of B and C respectively and $IC^B$ and $IC^C$ are the investment cost. The vertical axis of the dotted curve is in the right of Fig. 2. Note that a positive value of the dotted curve means that the incremental reduction of operative cost of C with respect to B is greater than the incremental investment cost of C with respect to B. That is, the additional investment cost is compensated by the reduction of operative cost. All points from B to E have positive values and they are shown in Fig. 2.

Observe that the tendency of the slope of the dotted curve is positive between C and D. It makes attractive any topology in that interval because they have the most significant cost reduction at the lowest investment cost when comparing to B. Table II shows the different types for the elements for topologies B, C and D and note that they have substation difference. The final decision should one of those topologies and might be based on other criteria. Finally, it is worth mentioning that this analysis narrow down to 3 topologies (the frontier has 150) and that two of them (B and C) were found using a multi-objective approach.

## V. CONCLUSIONS

In this paper the impact of operative costs and investment costs in the integrated planning of natural gas and electric distribution systems is presented. To describe this problem a multi-objective mathematical model is proposed, in order to verify the effect of multiple objectives.

Numerical results show that the two proposed objectives (investment cost and technical losses) are conflicting objectives since decreasing technical losses necessary implies more investment by means of the need of more natural-gas based DG (that also requires more investment on the natural gas network) and higher wire gauges (that are more expensive).

Numerical results also show that a multi-objective approach is more suitable since it is able to provide to the network planner different alternatives to be analyzed. That is, the Pareto optimal frontier for the test system has 150 different solutions in contrast to the single solution of a single objective optimization. In fact, the single solution provide by the Chu-Beasly algorithm is part of the Pareto frontier. This paper also provides a heuristic method to help the decision maker (or planner) to select one solution of the Pareto optimal frontier.

Numerical results also show that a multi-objective optimization approach does not require a prior knowledge of which objective should have a higher weight. In other words, a single objective optimization approach requires that the planner should have a clear understanding of which objective should have a higher weight so that the values of $\alpha_1$ and $\alpha_2$ can be fixed. These values are not relevant (in fact, they do not exist) for the multi-objective approach and it becomes one of its more important advantages.

Finally, a multi-objective approach for integrated electricity and natural gas expansion planning is more convenient since numerical results make clear that a single objective does not provide a wide variety of solutions. Decision makers often prefer to have multiples solutions since most of fast growing economies are facing a challenging environment that requires different alternatives before a final decision can be made.

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## REFERENCES

[1] U.S. Energy Information Administration, "Oil: Crude and Petroleum Products Explained," [Online]. Annual Energy Outlook, 2014. Available: http://www.eia.gov/energyexplained/index.cfm?page=oil_prices

[2] F. Angel, "Rhetoric of Colombian Currency," [Online]. The Huffington Post, 2015. Available: http://www.huffingtonpost.com/felipe-angel/rhetoric-of-colombia-currency_b_5410493.html

[3] Resolution 172/2011 (In Spanish), CREG, 2011.

[4] C.A. Saldarriaga, R.A. Hincapié and H. Salazar, "A Holistic Approach for Planning Natural Gas and Electricity Distribution Networks," *IEEE Trans. on Power Systems*, 28(4), pp. 4052-4063, Nov. 2013.

[5] I. Ramírez and J.L. Bernal, "Reliability and costs optimization for distribution network expansion using an evolutionary algorithm," *IEEE Trans. on Power Systems*, 16(1), pp. 111-118, Feb. 2001.

[6] E. Carrano, L. Soarez, R. Takahashi, R. Saldanha and O. Neto, "Electric distribution network multiobjective design using a problem-specific genetic algorithm," *IEEE Trans. on Power Delivery*, 21(2), pp. 995-1005, Apr 2006.

[7] S. Ganguly, N. Sahoo and D. Das, "Multi-objective planning of electrical distribution systems using dynamic programming," *Int. Journal of Electrical Power and Energy Systems*, vol. 46, pp. 65-78, March 2013.

[8] T. Kong, H. Cheng, Z. Hu, C. Wang, C. Chen and Y. Gao, "Multiobjective planning of open-loop mv distribution networks using ComGIS network analysis and MOGA," *Third International Conference on Electric Utility Deregulation and Restructuring and Power Technologies*, 2008, pp. 1340-1346.

[9] S. Ganguly, N. Sahoo and D. Das, "Multi-objective planning of electrical distribution systems incorporating shunt capacitor banks," *International Conference on Energy, Automation, and Signals (ICEAS)*, 2011, pp. 1-6.

[10] H. Mori and Y. Yamada, "An efficient multi-objective meta-heuristic method for distribution network expansion planning," in *Proc. IEEE Lausanne Power Tech*, 2007, pp. 374-379.

[11] A. Mantway and M. Al-Muhaini, "Multi-objective BPSO algorithm for distribution system expansion planning including distributed generation," in *Proc. Transmission and Distribution Conference and Exposition*, 2008, pp. 1-8.

[12] I. Ramírez and J. Domínguez, "Possibilistic model based on fuzzy sets for the multiobjective optimal planning of electric power distribution networks," *IEEE Trans. on Power Systems*, 19(4), pp. 1801-1810, Nov. 2004.

[13] W. El-Khattam and M.M.A. Salama, "Distribution system planning using distributed generation," in *Proc. IEEE CCECE*, vol. 1, pp. 579–582, 2003.

TABLE II
CONFIGURATIONS OF THE OBTAINED RESULTS

| **Element** | **Node*** | **Type** | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | **Initial** | **A** | **B** | **C** | **D** | **E** | **F** | **G** |
| **Electric feeders** | E7 - E1 | 2 | 2 | 4 | 2 | 4 | 4 | 4 | 4 |
| | E1 - E2 | 2 | 2 | 2 | 2 | 2 | 4 | 4 | 4 |
| | E7 - E3 | 2 | 3 | 4 | 2 | 4 | 4 | 4 | 4 |
| | E3 - E10 | 1 | 3 | 2 | 1 | 3 | 4 | 1 | 4 |
| | E10 - E8 | 1 | 1 | 4 | 2 | 4 | 4 | 4 | 4 |
| | E6 - E9 | 1 | 1 | 3 | 2 | 4 | 2 | 4 | 1 |
| | E11 - E4 | 1 | 1 | 4 | 4 | 4 | 4 | 4 | 4 |
| | E11 - E5 | 1 | 1 | 4 | 3 | 4 | 4 | 4 | 4 |
| | E11 - E6 | 1 | 3 | 4 | 3 | 4 | 4 | 1 | 4 |
| **Electric substations** | E7 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| | E10 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| **Pipelines** | G1 - G2 | 2 | 4 | 4 | 4 | 4 | 4 | 4 | 4 |
| | G2 - G4 | 1 | 1 | 1 | 1 | 1 | 2 | 1 | 5 |
| | G2 - G5 | 2 | 2 | 2 | 2 | 2 | 2 | 5 | 5 |
| | G2 - G3 | 2 | 2 | 2 | 2 | 2 | 2 | 3 | 3 |
| | G7 - G8 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| | G3 - G9 | 1 | 1 | 1 | 1 | 2 | 2 | 5 | 5 |
| | G6 - G10 | 1 | 1 | 1 | 1 | 1 | 1 | 2 | 2 |
| | G8 - G10 | 1 | 2 | 3 | 3 | 3 | 3 | 3 | 3 |
| **City Gates** | G1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| | G10 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| **DG** | E2 - G2 | 0 | 1 | 1 | 1 | 1 | 2 | 3 | 5 |
| | E6 - G3 | 0 | 0 | 0 | 0 | 0 | 2 | 2 | 2 |
| | E9 - G9 | 0 | 0 | 0 | 1 | 1 | 1 | 2 | 2 |
| | E8 - G8 | 0 | 0 | 2 | 1 | 2 | 5 | 5 | 5 |

* E: electric node, G: natural gas node

[14] W. Khattam, Y. G. Hegazy and M.M.A. Salama, “An integrated distributed generation optimization model for distribution system planning,” *IEEE Trans. on Power Systems*, 20(2), pp. 1158-1165, May 2005.

[15] A. Kazemi and M. Sadeghi, “A load flow based method for optimal location of dispersed generation units,” in *Proc. IEEE/PES Power Systems Conf. and Exposition*, pp.1–5, 2009.

[16] M.F. Shaaban, Y.M. Atwa and E.F. El-Saadany, "A multi-objective approach for optimal DG allocation", *International Conference on Electric Power and Energy Conversion Systems*, pp.1-7, 2011.

[17] M.F. Shaaban, Y.M. Atwa and E.F. El-Saadany, "DG allocation for benefit maximization in distribution networks", *IEEE Trans. on Power Systems*, 28(2), pp. 639-649, May 2013.

[18] F. Rivas-Dávalos and M.R. Irving, "The Edge-set Encoding in Evolutionary Algorithms for Power Distribution Network Planning Problem Part II: Multi-objective Optimization Planning," *Electronics, Robotics and Automotive Mechanics Conference*, vol.2, pp.251-257, Sep. 2006.

[19] E. Zitzler, M. Laumanns and L. Thiele, “SPEA 2: Improving the Strength Pareto Evolutionary Algorithm,” *Tech. Rep*, Computer Engineering and Networks Laboratory (TIK), Department of Electrical Engineering, Swiss Federal Institute of Technology (ETH) Zurich, 2001.

[20] G. A. A. Brigatto, C C. B. Carmargo and E. T. Sica, "Multiobjective optimization of distributed generation portfolio insertion strategies," IEEE/PES Transmission and Distribution Conference and Exposition: Latin America (T&D-LA), 2010, pp.622,628.

[21] C.A. Saldarriaga, R.A. Hincapié and H. Salazar, "An Integrated Expansion Planning Model of Electric and Natural Gas Distribution Systems Considering Demand Uncertainty," IEEE PES General Meeting, pp.1-5, 2015