A MULTI-OBJECTIVE APPROACH FOR PLANNING POWER AND NATURAL GAS DISTRIBUTION NETWORKS BASED ON AN EVOLUTIONARY ALGORITHM

Abstract— This paper presents a multi-objective mathematical model to plan natural gas and electricity distribution systems using a single optimization model. The model considers the impact of reliability, the operative costs and investment cost when planning both systems as one network. This multi-objective approach allows distribution companies (electric and natural gas) to have a set of optimal solutions to make the decisions according to their necessities. Two cases with different conflicting objectives are tested to evaluate the proposed methodology. That is, case 1 testes investment costs vs. non-served energy, and case 2 testes investment costs vs. non-served energy and total energy technical losses cost. A Strength Pareto Evolutionary Algorithm (SPEA-II) is used as solution technique and numerical results show the importance of considering in the same objective the reliability and operative costs, because i) they are not in conflict and ii) technical and economic aspects on both networks (electricity and natural gas) are improved.

Keywords— Distributed generation, power and natural gas distribution networks, multi-objective optimization, and evolutionary algorithm.

Resumo— Este artigo apresenta um modelo matemático multi-objetivo para planejar sistemas de distribuição de gás natural e eletricidade usando um único modelo de otimização. O modelo considera o impacto da confiabilidade, os custos operacionais e o custo de investimento ao planejar os dois sistemas. Esta abordagem multi-objetivo permite que as empresas de distribuição (elétrico e gás natural) tenham um conjunto de soluções ótimas para tomar as decisões de acordo com suas necessidades. Para avaliar a metodologia proposta, são testados dois casos com diferentes objetivos conflitantes: 1) custos de investimento vs energia não-servida e 2) custos de investimento vs energia não-atendida mais custo de perdas técnicas de energia. Um algoritmo evolucionário (SPEA-II) é utilizado como técnica da solução e os resultados numéricos mostram a importância de considerar no mesmo objetivo a confiabilidade e custos operacionais, devido a: i) não estão em conflito e ii) aspectos técnicos e econômicos de ambas redes (electricidade e gás natural) são melhoradas.

Palavras-chave— Redes de distribuição distribuída, energia e distribuição de gás natural, otimização multiobjetivo e algoritmo evolucionário.

Nomenclature

$\sigma_{\mathrm{CS}_{i,s}}$	Binary decision variable to expand the capacity of an existing electrical substation at node *i*, type *s*
$\sigma_{\mathrm{CF}_{ij,f}}$	Binary decision variable to expand the capacity of an existing feeder between nodes *i-j*, type *f*
$\sigma_{\mathrm{CC}_{n,c}}$	Binary decision variable to expand the capacity of an existing city gate, at node *n*, type *c*
$\sigma_{\mathrm{CP}_{nm,p}}$	Binary decision variable to expand the capacity of an existing pipeline between nodes *n-m*, type *p*
$\sigma_{\mathrm{NG}_{i,g}}$	Binary decision variable to install a new distributed generator (DG) at electrical node *i*, type *g*
$\sigma_{\mathrm{CG}_{i,g}}$	Binary decision variable to expand the capacity of an existing DG at electrical node *i*, type *g*
$C_{\mathrm{CS}_{i,s}}$	Cost to expand the capacity of an existing electrical substation in electrical node *i*, type *s* ($)
$C_{\mathrm{CF}_{ij,f}}$	Overnight cost to expand the capacity of an existing feeder in electrical nodes *i-j*, to type *f* ($)
$C_{\mathrm{CC}_{n,c}}$	Cost to expand the capacity of an existing city gate at node *n*, type *c* ($)
$C_{\mathrm{CP}_{nm,d}}$	Cost to expand the capacity of an existing pipeline that connects node *n* and *m*, type *d* ($)
$C_{\mathrm{NG}_{i,g}}$	Cost to install a new DG at node *i*, type *g* ($)
$C_{\mathrm{CG}_{i,g}}$	Cost to expand the capacity of an existing DG at node *i*, type *g* ($)
β	Discount factor
AP	Annual average price of electricity ($/MWh)
LD_l	Total number of hours of the load level *l*
nL	Total number of load level demand
$S_{Si,l}$	Power injected by a substation for a load level demand *l*, at node *i* (MVA)
$S_{Gi,l}$	Power injected by a DG for a load level demand *l,* at node *i* (MVA)
$S_{Di,l}$	Forecasted load level demand *l,* at node *i* (MVA)
$V_{i,l}$	Bus voltage for a load level demand *l,* at node *i* (kV)
$R_{ij,f}$	Feeder resistance from node *i* to *j*, type *f* (Ohm)
r_j	Average outage time of contingency *j* (hours/failure)
$Z_{ij,f}$	Feeder impedance from node *i* to *j*, type *f* (Ohm)
V_i^{min}	Minimum voltage limit at node *i* (kV)
V_i^{max}	Maximum voltage limit at node *i* (kV)
$S_{Gg}^{\max}$	Distributed generator type *g* maximum capacity limit (MVA)
$S_{Ss}^{\max}$	Electrical substation type *s* maximum capacity limit (MVA)
I_f^{max}	Type *f* maximum current limit capacity (kA)
$\Psi_{C_{n,l}}$	Natural gas injected for the load level demand *l,* at city gate located at node *n* (m^3/h)
$\Psi_{D_{n,l}}$	Forecasted natural gas load level demand *l,* at node *n* (m^3/h)
$\Psi_{G_{n,l,t}}$	Natural gas consumption for a load level demand *l,* of a distributed generator located at gas node *n* (m^3/h)
$\Psi_{P_{nm,l}}$	Natural gas flow for the load level demand *l,* in pipeline between gas nodes *n-m*
λ_j	Average failure rate of contingency *j* (failure/year)
$P_{i,l}$	Active power demand for the load level demand *l,* at node *i,* (kW)
$P_{n,l}$	Natural gas pressure for the load level demand *l,* at node *n* (bar)
$P_{in_{nm,l}}$	Natural gas pressure for the load level demand *l,* at the input node of the pipeline that connects nodes *n-m* (bar)
$P_{out_{nm,l}}$	Natural gas pressure for the load level demand *l,* at the output node of the pipeline that nodes *n-mt* (bar)
P_n^{min}	Minimum natural gas pressure at node *n* (bar)
P_n^{max}	Maximum natural gas pressure at node *n* (bar)
$\Psi_{C_c}^{\max}$	Type *c* city gate capacity limit (m^3/h)
$\kappa_{nm,p}$	Pipe resistance of the pipeline between nodes *n-m*, type *p*
Ω_E	Set formed by electrical nodes
Ω_{EI}	Set formed by electrical nodes that are isolated due to a contingency *j*
Ω_G	Set formed by natural gas nodes
Ω_J	Set formed by number of outage events
Ω_S	Set formed by existing electrical substation
Ω_F	Set formed by existing feeders
Ω_C	Set formed by existing city gates
Ω_P	Set formed by existing pipelines
Ω_h	Set formed by gas nodes that have physical connection with gas node *n*
Ω_i	Set formed by electrical nodes that have physical connection with electrical node *i*

Ω_{GD}	Set formed by gas nodes that have DG
Ω_{TS}	Set formed by types of the electrical substation
Ω_{TC}	Set formed by types of the city gate
Ω_{TF}	Set formed by types of the feeders
Ω_{Tp}	Set formed by types of the pipeline
Ω_{TG}	Set formed by types of the DG

1 Introduction

The fast penetration and the benefits of distributed generation (DG) imply that power distribution systems have to be planned and operated differently when compared with traditional approaches. For planning purposes, for instance, disperse decision-making by decentralized small consumers is the most important source of uncertainty that planner has to take into account. On the other hand, reverse power flow is one of the aspects that distribution system operators are facing due to a considerable penetration of DG.

The aspects mentioned above are have been analyzed by different authors. For instance, (Greatbanks, 2003), (Chowdbhury, 2003), (Ziari, 2010) and (Mantway, 2008) study the optimal location of the DG so that voltage, system reliability, and technical losses are improved. In (Soroudi, 2010), a multi-objective model to determine the location and optimal sizing of the distributed generation based on natural gas (DG-NG) is presented. In (Zou, 2012), a distribution system expansion planning strategy is presented so that renewable DG and reactive power capabilities of those technologies are taking into consideration. In (Keane, 2006) and (Vinoth, 2009), the impact of DG on power distribution systems are presented so that the operative conditions are improved. In (Khattam,2005), an integrated model for solving distribution system planning with distributed generation is presented.

A different approach is shown in (Saldarriaga, 2013) and (Saldarriaga, 2015). These references show a holistic approach to plan electric power and natural gas distribution systems. That is, these papers consider the fact that a high penetration of DG-NG into power distribution network implies that the natural gas network needs to be planned as well. A holistic approach shows lower investment and operative costs. Both approaches are similar; however, demand uncertainty is considered in (Saldarriaga, 2015a).

A follow-up approach is shown in (Saldarriaga, 2015b) that analyzes a holistic approach as multi-objective optimization problem. The paper considers two conflicting objectives, i.e., investment cost and operative cost (power losses). Numerical results show a Pareto optimal frontier that gives the possibility, to the network planners, of choosing a topology (for power and natural gas distribution networks) from the set of possibilities. To the best of our knowledge, that paper is the only one of analyzing a holistic approach as a multi-objective optimization problem. It is worth mentioning that a state of the art review of a multi-objective optimization problem applied to power distribution system planning is presented in (Alarcon, 2010). The review does not include natural gas distribution networks.

This paper expands the scope of (Saldarriaga, 2015b) by introducing a reliability analysis since it is an aspect that most of the power distribution utilities evaluate during the planning process. That is, the impact of a network expansion on reliability indexes such as the SAIFI, SAIDI, ASIFI, and NSEL (IEEE Standard 1366, 2012) is often assessed when planning power distribution networks. This paper, therefore, proposes a multi-objective optimization problem to plan power and natural gas distribution networks as one single network. Three objectives are considered. The first one is the investment costs (IC) of 1) repowering network components (pipelines, city gates, electric feeders and electrical substations) and 2) installing new DG-NGs. The second objective is the operational cost given by the cost of technical losses (ETL) of the power distribution network. The last objective is the non-served energy level (NSEL) of the power distribution system based on n-1 contingency criterion. These three objectives are combined so that a multi-objective optimization problem is solved.

A master-slave approach is proposed as a solution approach. The master problem is based on a multi-objective evolutionary algorithm known as Strength Pareto Evolutionary Algorithm II (SPEA II) that determines the elements to be repowered and the DG to be built. The slave problem evaluates the feasibility of the solution given by the master problem.

Finally, this paper is organized as follow. Section 2 describes the problem. Section 3 details how the problem can be solved. Numerical results and conclusions are in section 4 and 5 respectively.

2 Problem Formulation

This paper uses a planning model for integrated electricity and natural gas distribution system. This paper assumes that a utility owns both systems so that there is not conflicting of interest that might arise if different stakeholders own the networks. Traditional planning model minimizes the investment cost of increasing the capacity of existing elements for the whole system (electricity and natural gas) and the cost of new DG-NG. However, this paper proposes a different approach to take more aspects into account that are relevant in a planning process.

A multi-objective mathematical model is used in this paper for planning electricity and natural gas distribution networks as one system. In this approach, three objective functions (OFs) are minimized.

OF1 is the present value at the beginning of the planning period of the investment cost (IC) of upgrading existing elements (feeders, substations, pipelines, citygates and DG) and the installation cost of new DG. OF2 is the operating cost of the distribution network that is often assumed -for planning purposes- as the cost of the technical losses (ETL) that are technical losses (Joule effect) multiplied by the cost of energy over the planning period (20 years in this paper). OF3 is the network reliability cost that is the non-served energy level (NSEL) as a consequence of single network element failure. That is, it is the cost of the energy that is not supplied to power consumers that are located downstream of a fault location (Billinton, 1996). Equations (1), (2) and (3) are the mathematical formulation of OF1, OF2, and OF3 respectively.

$$\left\{\begin{array}{l} \sum_{ij\in\Omega_F}\sum_{f\in\Omega_{T_F}}\left(C_{\mathrm{CF}_{ij,f}}\sigma_{\mathrm{CF}_{ij,f}}\right)+\sum_{j\in\Omega_S}\sum_{s\in\Omega_{T_S}}\left(C_{\mathrm{CS}_{j,s}}\sigma_{\mathrm{CS}_{j,s}}\right)+ \\ \sum_{nm\in\Omega_P}\sum_{d\in\Omega_{T_P}}\left(C_{\mathrm{CP}_{nm,d}}\sigma_{\mathrm{CP}_{nm,d}}\right)+\sum_{m\in\Omega_C}\sum_{c\in\Omega_{T_C}}\left(C_{\mathrm{CC}_{m,c}}\sigma_{\mathrm{CC}_{m,c}}\right)+ \\ \sum_{i\in\Omega_E}\sum_{g\in\Omega T_G}\left(C_{\mathrm{NG}_{i,g}}\sigma_{\mathrm{NG}_{i,g}}\right)+\sum_{j\in\Omega_{GD}}\sum_{g\in\Omega T_G}\left(C_{\mathrm{CG}_{j,g}}\sigma_{\mathrm{CG}_{j,g}}\right) \end{array}\right\} \quad (1)$$

$$\beta\sum_{l=1}^{nL}\sum_{ij\in\Omega_F}\sum_{f\in\Omega_{T_F}}3*AP*LD_l*R_{ij,f}\left(\left|I_{ij,l}\right|^2\sigma_{\mathrm{CF}_{ij,f}}\right) \quad (2)$$

$$\sum_{l\in\Omega_i}\sum_{j\in\Omega_J}\sum_{i\in\Omega_{EI}}P_{i,l}*r_j*\lambda_j*LD_l \quad (3)$$

Equations (4)-(18) are the constraints. In particular, equations (4)-(8) model the electric network; that is, Kirchhoff's laws, the capacity of different elements -feeders, substations, and DG-, and voltage bounds. Equations (9)-(11) guarantee that only one type of DG, substation, or feeder is installed at each node or each network section of the power grid. Equations (12)-(15) model the natural gas network; that is, natural gas balance, the capacity of pipelines, the maximum pressure drop through the pipeline, and the maximum city gate capacity. Equations (16)-(17) guarantee that only one type of citygate or pipeline is installed at each network section. Equation (18) is the quantity of natural gas that is required by a DG to operate as a function of the electric power injected into the distribution network.

$$S_{S_{i,l}}=S_{D_{i,l}}-S_{G_{i,l}}+\sum_{j\in\Omega_i}\left(V_{i,l}\sum_{f\in\Omega_{T_F}}\sigma_{\mathrm{CF}_{ij,f}}*I_{ij,l}^{\ *}\right) \quad \forall i\in\Omega_E;\forall l\in\{1,2,...,nL\} \quad (4)$$

$$\left|I_{ij,l}\right|\le\sum_{f\in\Omega_{T_F}}I_f^{\max}*\sigma_{\mathrm{CF}_{ij,f}} \quad \forall ij\in\Omega_F;\forall l\in\{1,2,...,nL\} \quad (5)$$

$$S_{S_{i,l}}\le\sum_{s\in\Omega_{T_S}}S_{Ss}^{\max}*\sigma_{\mathrm{CS}_{i,s}} \quad \forall\ i\in\Omega_S;\forall l\in\{1,2,...,nL\} \quad (6)$$

$$S_{G_{i,l}}\le\sum_{g\in\Omega_{\mathrm{T_G}}}S_{G_g}^{\max}*\left(\sigma_{\mathrm{NG}_{i,g}}+\sigma_{\mathrm{CG}_{i,g}}\right) \quad \forall i\in\Omega_E;\forall l\in\{1,2,...,nL\} \quad (7)$$

$$V_i^{\min}\le V_{i,l}\le V_i^{\max} \quad \forall i\in\Omega_E;\forall l\in\{1,2,...,nL\} \quad (8)$$

$$\sum_{g\in\Omega_{T_G}}\left(\sigma_{\mathrm{NG}_{i,g}}+\sigma_{\mathrm{CG}_{i,g}}\right)\le 1 \quad \forall\ i\in\Omega_{\mathrm{E}} \quad (9)$$

$$\sum_{s\in\Omega_{T_S}}\sigma_{\mathrm{CS}_{i,s}}\le 1 \quad \forall\ i\in\Omega_S \quad (10)$$

$$\sum_{f\in\Omega_{T_F}}\sigma_{\mathrm{CF}_{ij,f}}\le 1 \quad \forall ij\in\Omega_F \quad (11)$$

$$\Psi_{C_{n,l}}-\Psi_{D_{n,l}}-\Psi_{G_{n,l}}-\sum_{m\in\Omega_n}\Psi_{P_{nm,l}}=0 \quad \forall\ n\in\Omega_G;\forall l\in\{1,2,...,nL\} \quad (12)$$

$$\Psi_{P_{nm,l}}=\left(\sum_{p\in\Omega_{T_P}}\left(\sigma_{\mathrm{NP}_{nm,p}}+\sigma_{\mathrm{CP}_{nm,p}}\right).\kappa_{nm,p}\right).\sqrt{\left(P_{in_{nm,l}}^2-P_{out_{nm,l}}^2\right)-\kappa_{z_{nm}}} \quad \forall nm\in\Omega_P;\forall l\in\{1,2,...,nL\} \quad (13)$$

$$\Psi_{C_{n,l}}\le\sum_{c\in\Omega_{T_C}}\Psi_{C_c}^{\max}*\sigma_{\mathrm{CC}_{n,c}} \quad \forall n\in\Omega_C;\forall l\in\{1,2,...,nL\} \quad (14)$$

$$P_n^{\min}\le P_{n,l}\le P_n^{\max} \quad \forall n\in\Omega_G;\forall l\in\{1,2,...,nL\} \quad (15)$$

$$\sum_{p\in\Omega_{T_P}}\sigma_{\mathrm{CP}_{nm,p}}\le 1 \quad \forall nm\in\Omega_P \quad (16)$$

$$\sum_{c\in\Omega_{T_C}}\sigma_{\mathrm{CC}_{n,c}}\le 1 \quad \forall\ n\in\Omega_C \quad (17)$$

$$\Psi_{G_{n,l}}=\sum_{g\in\Omega T_G}\left(k_{n,g,2}\left(S_{G_{i,l}}\right)^2+k_{n,g,1}\left(S_{G_{i,l}}\right)\right)*\left(\sigma_{\mathrm{NG}_{i,g}}+\sigma_{\mathrm{CG}_{i,g}}\right) \quad \forall n\in\Omega_{GD};\forall l\in\{1,2,...,nL\} \quad (18)$$

Note that these objectives can be used as one objective in an optimization problem if each term (IC, ETL, and NSEL) are weighed by different factors. However, multiple solutions can be provided to the utility company (of power and natural gas) if these objectives are considered as conflicting (Saldarriaga, 2015b). These solutions are presented as a Pareto frontier. This approach is more suitable to evaluate best what effect has one objective over another in the planning process. This is convenient for utilities to analyze the problem under different perspectives. Finally, for this paper, two cases are analyzed in section 4. Case 1 considers that IC and NSEL are conflicting objectives and case 2 considers that IC is in conflicting with NSEL and ETL.

3 Solution Approach

This paper uses a master-slave approach as solution strategy. It is a two-stage process in which a master routine performs a particular task and the slave, which use the solution of the master, complement the solution of the master. For this paper, specifically, the master stage proposes a topology for the entire system (power and natural gas distribution networks), and the slave stage evaluates IC, ETL, and NSEL. The master stage is based on SPEA-II that it is broadly described in steps *x* and *xi* of section 3.1. A full description of the mathematical formulation of the master stage can be found in (Saldarriaga, 2015b) and (Zitzler, 2001). The slave strategy is described in steps *i* to *ix* and complemented in section 3.2.

3.1 Master-slave approach pseudo-code

The master problem establishes a topology -or mathematically the value of the binary variables- that satisfies equations (9)-(11) and (16)-(17). It is worth mentioning that the topology might not be feasible from the operative point of view so that a slave problem is required to assess the feasibility (see section 3.2).

The following pseudo-code is a high-level description of the master-slave approach to solving multi-objective planning of power and natural gas distribution networks.

i. Generate the initial population and define the stop criterion
ii. Set counters to individual of the population (I=1), load duration curve level (T=1), and electric feeder (L=1)
iii. Evaluate the objective function IC and set ETL=0 and NSEL=0 for each I
iv. Solve the optimization problem of section 3.2 for a load duration curve level (T)
v. Set I=I+1 and go to step *ii* if $\sum_i real\{S_i^R\} + \sum_n \psi_n^R \neq 0$, i.e., an individual is infeasible. The three objective functions (IC, ETL and NSEL) are penalized. Otherwise, go to the next step.
vi. Update $ETL = ETL + \sum_i real\{Z_i\} I_i$ and set T=T+1. If all load levels have been evaluated, go to the next step. Otherwise, go to step *iv*.
vii. Start the contingency strategy (criteria n-1) to electric feeder L.
viii. Solve (19)-(20) of section 3.2 and update $NSEL = NSEL + \zeta \sum_i real\{S_i^R\}$ and set L=L+1.
ix. Go to the next step if contingency in all electric feeders have been evaluated. Otherwise, go to step *vii*.
x. Go to the next step if all individuals have been evaluated; apply the genetic operators of selection, crossover and mutation to the individuals of the actual population, to create the new population. Otherwise, set I=I+1 and go to step *iii*.
xi. Go to step *ii* if stop criterion is not reached. Otherwise, stop and print results.

3.2 Integrated optimal power flow

Note that steps *iv* and *viii* require solving the following optimization problem that, for the purpose of this paper, is named integrated optimal power flow (IOF).

$$\min \quad \underbrace{\alpha \sum_l real\left\{Z_l \left|I_l\right|^2\right\}}_{\text{Technical Losses}} + \underbrace{\left(\sum_i real\left\{S_i^R\right\} + \beta \sum_n \Psi_n^R\right)}_{\text{Non-supplied demand}} \quad (19)$$

$$\text{s.t.} \quad \begin{array}{l} \text{Equations (4)-(8)} \\ \text{Equations (12)-(15)} \\ \text{Equations (18)} \end{array} \quad (20)$$

For the above optimization model, equation (19) is the weighted sum of the active power losses and rationing of demand in both systems. To have consisting units in both terms of the objective function of (19), i.e., Watt, the factor β is expressed as Watt/m3. The numerical values of the two weight factors (α and β) are often determined by trial and error.

Note that the slave problem (equations (19)-(2)) is a non-linear programming problem (NLP) because the master problem has defined the numerical value of binary variables (σ).

4 Numerical Results

Figure 1 shows the electric and natural gas distribution systems that are used as the test case. The electric network has eleven nodes in which there are four nodes with the possibility of having DG (nodes 2, 6, 8 and 9), and there are two substations located at nodes 7 and 11. On the other hand, the gas network has ten nodes in which there are four nodes with the possibility of having DG (nodes 2, 3, 8 and 9), and there are two citygates located at nodes 1 and 10. In Fig. 1, power and natural gas demands are represented as black circles; and electrical power substations and citygates are the black squares and black triangles respectively.

A type for this test case is the capacity of one element. For instance, if there are four types of electrical feeders, it means that the planner -or the optimization model- has the possibility of choosing one type among four possible options of the feeders each of them with different capacity of the conductor. For the test case, there are four types of electrical feeder, two types of electrical power substations, five types of GD, five types of pipelines, and two types of citygates. The number in parenthesis in Fig.1 is the type of the element, and the full database is available with the authors upon request. Finally, table 1 shows the general data used by the algorithm –setting values- and the algorithms were implemented in Matlab and Gams.

4.1. Case 1

Figure 2 shows the optimal Pareto frontier for this case (continuous red line). For comparative purposes, the value of total energy technical losses for each individual in the frontier (black dotted line) is shown in the same figure. All values in Fig. 2 are

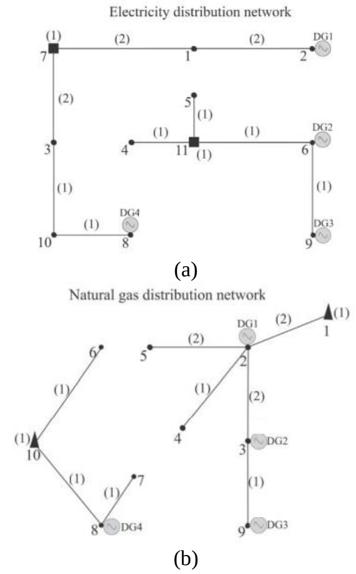


Fig. 1. Power distribution network (a) and natural gas distribution network (b)

TABLE I
SETTING VALUES

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 the population (*P*)	20
Size *M* of the population (*Q*)	20
Maximum number of generations (*Gmax*)	200
Failure rate [failure/Year-km]	2.95
Reparation rate [hour/failure]	3.28
Energy cost [US$/kW-h]	0.125

normalized respect to the individual with the lowest IC (point A in Fig. 2). That is to say, vertical right and left axes and horizontal axis are normalized respect to the values of NSEL, ETL and IC of the individual A. These values are 26183*10^6 W-h, 6.45 and 4.43 million US dollars respectively.

Note that minimizing IC and NSEL imply a reduction of ETL so that NSEL and ETL are not conflicting objectives. It is because the planning actions that are required to improve the reliability of the electric power system also implies the installation of NG-DG which tends to reduce the currents on the electrical feeders and hence the technical losses.

It is important to point out that all individuals (network topologies for power and natural gas distribution systems) at Pareto frontier are optimal and the decision maker has the possibility, based on his or her preference, to choose one of them. For comparative purposes, three individuals are analyzed and they are individuals marked with letters A, B, and C in Fig. 2. Note that points A and C are extreme points at the frontier and point B is selected so that there is not a significant reduction (around of 1%) of NSEL with respect to the NSEL of A.

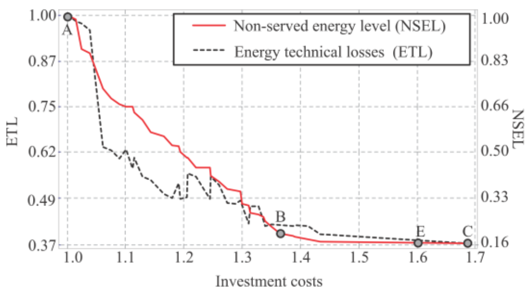


Fig. 2. Pareto optimal front for Case 1

TABLE II
CONFIGURATIONS*

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

*E: electric system nodes, G: natural gas system nodes

Table II shows the final configuration for A, B and C in which each number represents a type or capacity for electrical feeders, electrical substation, pipelines, city gates or DG-NG. Observe that individual C requires an investment cost 67.1% higher than the individual A, which allows reducing the NSEL in 84% compared to the same individual. It is because individual C has 4 DG-NG located at the electric nodes 2, 6, 8 and 9 with capacity 3, 2, 5 and 2 respectively; and individual A has only 2 DG-NG located at electric nodes 8 and 9 with capacity 2 and 1 respectively.

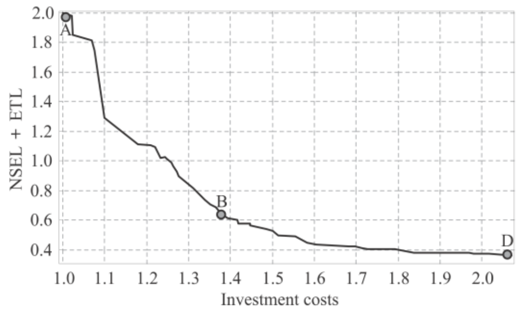
On the other hand, individuals A and C have two different types of electrical feeder, i.e., feeders E7-E3 and E11-E6 in Table II. It is because the capacity of electrical feeders does not have a significant impact on the reliability of the power network. However, the natural gas network for A and C has several differences because C has more DG-NG. Hence, the capacity of the pipelines contributes improving the reliability of the electric power network when there is a high penetration based on natural gas.

Let's analyze individual B. It has a higher NSEL when comparing with C, but its investment costs are considerably lower. This is because the main difference between individuals B and C is the capacity of pipelines G2-G3 and G3-G9 that is lower for B. This difference reduces the amount of gas that can be provided to the NG-DG at gas nodes G3 and G9 that slightly increases the value of NSEL. Therefore, all individuals that present higher investment than B, they have a slightly reduction of NSEL.

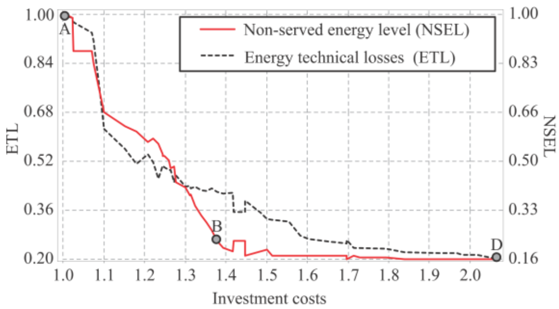
Finally, let's consider individual E and the only difference with individual C is the capacity of the electrical feeder E7-E3 based on Table II. The new capacity increases in 6.8% the investment cost when comparing A. However, the effect of such difference on the NSEL corresponds to a 1.1% reduction.

4.2. Case 2

Figure 3(a) and Fig 3(b) show the optimal Pareto frontier for case 2. As in Fig. 2, all values are normalized with respect to individual A. Note that the individuals A and B are the same as case 1 and individual D is more expensive than C since it requires an IC of 105.9% more than A.



(a)



(b)

Fig. 3. Pareto optimal front for Case 2: (a) Sum of ETL+NSEL and (b) ETL and NSEL

However, despite of higher IC, there is not an improvement of the NSEL in comparison to individual C. This is because the location and sizing of the DG of the individuals C and D are equal and their respective natural gas networks provide enough gas to get a maximum NSEL reduction. The cost changes due to: 1) individual D has 4 electrical feeders with a higher capacity in comparison to individual C and 2) the natural gas network of individual D presents a pipeline and a citygate with higher capacity, which permits a higher use of the DG-NG. This does not impact on the NSEL, but it creates an important reduction in the ETL, since individual D presents an ETL reduction of 80% in comparison to individual A, while the improvement of individual C is of 63%.

Finally, observe in Fig. 3(b) that between points B and D the NSEL reduction is marginal while the ETL changes are significant. Most of the differences between the individuals located in the region between point B and D are associated with repowering the feeders. Even though this aspect does not impact significantly the improvement of the reliability, it does have a significant impact on the reduction of the technical energy losses.

5 Conclusions

The impact of the reliability, operative costs and investment costs in integrated planning of natural gas and electric distribution systems is presented in this paper using a multi-objective approach based on an evolutionary algorithm. Numerical results show that the objectives associated with energy technical losses and reliability are not conflicting. However, investment cost is conflicting with technical losses and reliability. Additionally, numerical results show that the installation of DG-NG in the electric network and the repowering of pipelines in the natural gas network have a considerable impact on losses and reliability; whereas repowering of the electric feeders only impacts the objective associated with energy losses. This paper shows that is advisable to use the approach of case 2, since the Pareto border has the best individuals with the three aspects of interest. These findings are important for utilities that plan power and natural gas distribution networks since the planning process is analyzed in a broader perspective.

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