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Integrated Operation of Electricity and Natural Gas Distribution Networks: A Reliability Analysis

Operación integrada de redes de distribución de energía y gas natural: un análisis de confiabilidad

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Abstract

Currently the world faces a great challenge, to achieve a sustainable production of energy, which allows the adequate development of humanity but at the same time does not irreversibly affect the environment. For this, it is absolutely necessary to make optimal and effective use of the available energy resources, in order to aim for energy transition objectives that result in the rational and efficient use of energy, the penetration of renewable resources, and social development. This requires that at a technical level, methodologies be proposed that allow for a holistic analysis of the different interactions and synergies present in the energy system. Therefore, it is essential to delve into the knowledge associated with the interaction between the electricity and natural gas networks, since natural gas is expected to be the energy source that supports the increase in generation from intermittent renewable energy sources. It is for the above that this research work analyzes the reliability of the electric power distribution network based on the impact associated with a contingency in the natural gas distribution network, when both networks are coupled through natural gas-based distributed power generators. A novel non-supplied energy index and a single contingency criterion are used for estimation purposes, considering failure rates and repair times of the natural gas network to obtain a more accurate in the estimation. Numerical results show that significant penetration of natural gas-based distributed generation can compromise the reliability of the power distribution network if the natural gas network is of low reliability.

Keywords

Reliability analysis, power distribution network, natural gas network, integrated energy system.

Resumen

Actualmente, el mundo enfrenta un gran desafío y es lograr una producción sustentable de energía que permita el adecuado desarrollo de la humanidad pero que al mismo tiempo no afecte irreversiblemente al medio ambiente. Para ello, es absolutamente necesario hacer un uso óptimo y efectivo de los recursos energéticos disponibles, con el fin de apuntar a objetivos de una transición energética que resulten en un uso racional y eficiente de la energía, la penetración de los recursos renovables y el desarrollo social. Esto requiere que a nivel técnico se propongan metodologías que permitan un análisis holístico de las diferentes interacciones y sinergias presentes en el sistema energético. Por ello, es fundamental profundizar en el conocimiento asociado a la interacción entre las redes de electricidad y gas natural, ya que se espera que el gas natural sea la fuente energética que sustente el incremento de la generación a partir de fuentes renovables intermitentes. Por lo anterior, en este trabajo de investigación se analiza la confiabilidad de la red de distribución de energía eléctrica a partir del impacto asociado a una contingencia en la red de distribución de gas natural, cuando ambas redes se acoplan a través de generadores de energía distribuida a base de gas natural. Para su estimación se utiliza un novedoso índice de energía no suministrada y un criterio de contingencia sencilla, considerando tasas de falla y tiempos de reparación de la red de gas natural para obtener una mayor precisión en la estimación. Los resultados numéricos muestran que una penetración significativa de la generación distribuida basada en gas natural puede comprometer la confiabilidad de la red de distribución de energía si la red de gas natural es de baja confiabilidad.

Palabras clave

Análisis de confiabilidad, red de distribución de energía, red de gas natural, sistema de energía integrado.

1. INTRODUCTION

In the last decade, distributed generation based on natural gas (DG-NG) has been considered an alternative solution to the operational difficulties associated with the continuous growth of the electricity demand [1], due to its multiple advantages such as low cost of NG, its short implementation times, and its low greenhouse gas emissions compared to other fuels.

Additionally, in the specialized literature, it has been demonstrated that the implementation of DG-NG facilitates low-cost planning and reduces the number of technical losses because the inclusion of sources in the distribution network helps reduce the magnitude of the currents that circulate through it. For example, in [2]-[5], the authors state that the most relevant benefits of implementing distributed generators are those associated with reduced technical losses, low greenhouse gas emissions, the relief of congestions, and tension support. Likewise, DG-NG implementation can improve the reliability of the electrical system since the occurrence of contingencies in the electrical distribution network generates islands, which can be supplied provisionally by the generators connected downstream of the failed element, thus reducing the number of unattended users [6], [7].

Due the penetration of DG-NG is expected to be going up in next years, the interdependence will increase between both systems which has generated a special interest within the electricity sector in related studies to this topic. In [8]-[10], an integrated planning between both networks is carried out, considering technical, economic and reliability criteria. However, the proposed methodologies focus on transmission systems. In [11]-[15], an operative analysis between both networks is presented, based on the calculation of reliability criteria in the natural gas system and the verification of its impact on the electricity network. In [11]-[13], the analysis is carried out considering both networks in an integrated way and in [14],[15] in a decoupled way. As in the previous references, these papers also focus on transmission systems. In [16], a methodology that considers a coordinated dispatch of energy and natural gas systems in distribution systems is developed. In [17]-[19], an operative model integrating both networks at the transmission systems level is made. Nevertheless, [16]-[19] do not consider reliability criteria. In [20], a stochastic analysis to evaluate new infrastructure to increase the reliability of the natural gas supply is proposed, considering the operative uncertainty of the transport pipeline and the gas supply, in transmission systems.

In Table 1, a comparison of the main aspects considered in the mentioned references is shown. As can be seen, there are no methodologies to analyze in an integrated way the reliability of electricity and NG systems at the distribution level, considering the high penetration of distributed generation based on natural gas.

Table 1. Comparison of the listed references. Source: Created by the authors.

Reference	Type of study		Model		System		Aspects of reliability
	Planning	Operation	Decoupled	Integrated	Transmission	Distribution	
[1]-[9]	X			X		X	
[8]-[10]	X			X	X		X
[11]-[13]		X		X	X		X
[14],[15]		X	X		X		X
[16]		X		X		X	
[17]-[19]		X		X	X		
[20]	X		X		X		X

As such, this paper proposes a new, simple, and easy way to implement methodology that can be used to evaluate the effect of the reliability of the NG system on the reliability of the electrical system, considering the particular characteristics of the distribution systems and the characteristics shared by both systems in terms of topology, operation, and planning strategies [21]. To do so, the index in electrical systems known as a non-supplied energy level (NSEL) was adapted [22] in order to use information corresponding to the failure rates and repair times of the NG network.

The methodology consists of analyzing possible faults in the pipelines of the NG network and, for each case, calculating the energy that is not supplied in the electrical system. This calculation is compared with the energy that is not supplied when only existing faults in the electrical system are taken into account. In this way, the impact of the reliability of the NG network on the reliability of the electricity network can be determined. This impact must be taken into account when planning a new electricity network with DG-NG.

This paper is organized as follows. Section 2 outlines the mathematical formulation and describes the main aspects of the solution technique. Section 3 presents the results and discussion. Finally, Section 4 provides commentary on the conclusions of this paper.

2. MATERIALS AND METHODS

2.1 Problem formulation

To describe the problem addressed in this study, the integrated distribution network (electricity and NG) seen in Figure 1 must be considered. Assume that the electrical network has been designed under criteria of minimum cost and high reliability, considering the possibility of installing the DG-NG. Note that a minimum-cost design requires the maximum capacity of all the installed elements and that the criterion of high reliability promotes the installation of multiple sources (DG-NG) inside the network [7]. This implies that the resulting network has a high penetration of distributed generators with high utilization percentages. This leads to the presence of low chargeability in the conductors and electrical substations with respect to the maximum load currents presented in the system.

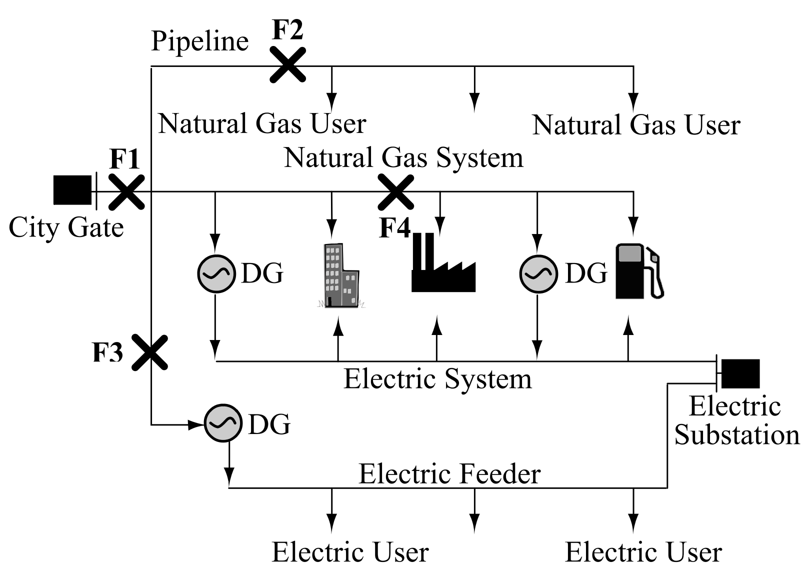


Figure 1. Integrated electrical and natural gas system with DG. Source: Created by the authors.

Given the design conditions, however, the resulting network is expected to present a low affectation at the occurrence of contingencies (*n-1*) in the electrical system. However, if the design of the electrical network does not consider the effect of the reliability of the NG network, there is a high possibility that the expected results in terms of low cost and high reliability will not be met, since the occurrence of a contingency in the gas network can disconnect one or more DG-NG and thus increase the levels of non-supplied electrical power.

To illustrate the above, observe Figure 1 and assume the occurrence of the F1 fault in the NG system. Note that this fault simultaneously disconnects three DG-NG. This disconnection implies that the electrical demands must be dealt with only by the electrical substation, which could cause operational problems such as network congestion, voltage regulation problems, equipment overload, increased technical losses, and unmet demand.

However, not all the failures of the NG system have the same impact on the electrical network. Note that failure F2 has no effect on the electrical system since it does not disconnect any DG-NG. However, while other faults, such as F3 and F4, disconnect the same amount of DG-NG, failure F3 has a greater impact than failure F4 due to the location of the DG-NG over the electrical network. In other words, faults in a NG distribution system have different impacts on the electrical network, so an adequate analysis to verify the impact of these faults should be considered.

The above information illustrates the importance of developing integrated methodologies to analyze the reliability of electricity and NG distribution systems when considering a high penetration of DG-NG. The results of such analysis can then be used to quantify the effect of the reliability of the NG network on the reliability of the electric system.

2.2 Proposed methodology

This section presents the methodology developed to determine the impact of the reliability of the NG system on the reliability of the electrical network. This study seeks to determine relationships between the reliability of both systems, considering the effect of the contingencies that occur in each. Initially, an electrical network reliability index that does not consider the contingencies of the NG network will be calculated, which will establish the reference value for subsequent comparisons. Then, this index will be adapted to include the effect of the NG network, and its value is calculated, considering the reliability of the NG network. The comparison of the calculated indices with the reference value will make it possible to determine the relevance of the NG network over the operation of the electric power distribution network. The formulation of the indices is described below.

2.2.1 Non-supplied energy level

The reliability of a system refers to its capability to ensure continuity of the service in the face of fault occurrence. This is considered a qualitative characteristic, for which indices that allow its adequate quantification are required. Among these, SAIDI, SAIFI, CAIDI, and NSEL stand out [22],[23]. In this work, the NSEL index is used because it can verify the impact of the reliability in the electrical network in function of the unavailability of the unattended load. This indicator represents the total energy that is not supplied by the system, and it is calculated according to (1):

$$NSEL^{E} = T * \sum_{L} \left| \lambda_{L}^{E} \times r_{L}^{E} \times Long_{L}^{E} \times \sum_{i} P_{i,L}^{E} \right| \quad (1)$$

Where,

$NSEL^E$: Index of the non-supplied energy level by contingencies in the electrical network, without considering contingencies in the NG network.
L : Set of line sections of the electrical network.
T : Study period.
λ_L^E : Failure rate of the L section of the electrical network.
r_L^E : Repair time of the electric section L.
$Long_L^E$: Length of section L of the electrical network.
i : Set of loads of the electrical network.
$P_{i,L}^E$: Power not supplied to the load i due to a contingency in section L of the electrical network.

2.2.2 Contingencies criterion (n-1)

As previously mentioned, a comparison pattern is required to determine how relevant the effect of the reliability of the NG network is on the reliability of the electrical network. The index formulated in (1) can be used to establish the reference level for later comparisons, not considering the effects of the contingencies of the NG network and using the contingency criteria (*n-1*) to perform an evaluation of the NSEL index for all electrical network contingencies. The procedure is illustrated in the flow chart of Figure 2. As can be seen in this figure, the calculation of the NSEL index requires an iterative process in which an optimal power flow is evaluated for each contingency (see (2) - (10)). Such evaluation is necessary to determine the dispatch of each of the generation resources embedded in the distribution network (including substations) due to the topological changes that occur in the network after the contingency occurs.

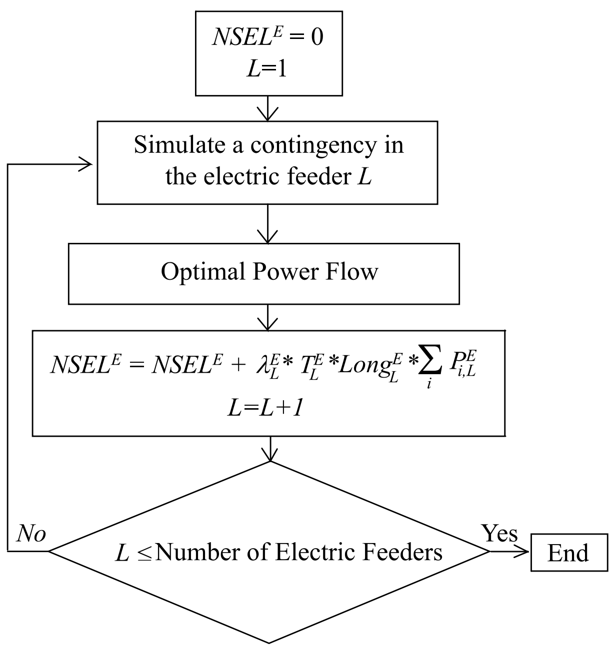


Figure 2. Calculation of the NSEL index according to the electrical network.
Source: Created by the authors.

In (2) - (10), the dispatch of all electricity sources (substations and DG-NG) is determined in such a way that the non-supplied energy in each node is minimized (S_i^R), guaranteeing compliance with the Kirchhoff laws in (3), (4) and the capabilities of all network elements using (5) – (10). The mathematical model is as follows:

$$min\,OF = \sum_{i} real\{S_i^R\} \tag{2}$$

$$s.t.\ S_i^{ES} + S_i^{GD} - V_i \sum_{\forall l} a_{l,i}^E\ I_l^* = S_i^{LD} - S_i^R \tag{3}$$

$$\sum_{\forall i} a_{l,i}^E\ V_i = Z_l * I_l \tag{4}$$

$$0 \leq S_i^{SE} \leq S_i^{SE\_MAX} \tag{5}$$

$$0 \leq S_i^{GD} \leq S_i^{GD\_MAX} \tag{6}$$

$$V^{min} \leq V_i \leq V^{max} \tag{7}$$

$$|I_l| \leq I_l^{MAX} \tag{8}$$

$$0 \leq real\{S_i^R\} \leq real\{S_i^{LD}\} \tag{9}$$

$$imag\{S_i^R\} = imag\{S_i^{LD}\} * \frac{real\{S_i^R\}}{real\{S_i^{LD}\}} \tag{10}$$

Where,

$\boldsymbol{V_i}$	:	Voltage in the node i (kV).
$\boldsymbol{I_l}$	:	Current through the network section l (kA).
$\boldsymbol{S_i^{ES}}$	:	Injected power by a substation in the node i (MVA).
$\boldsymbol{S_i^{GD}}$	:	Injected power by a DG in the node i (MVA).
$\boldsymbol{S_i^{LD}}$	:	Power demand in the node i (MVA).
$\boldsymbol{S_i^{R}}$	:	Power rationing in the node i (MVA).
$\boldsymbol{Z_l}$	:	Impedance of the network section l (Ohm).
$\boldsymbol{a_{l,i}^E}$	:	Element l-i of the nodal incidence matrix.
$\boldsymbol{S_i^{SE\_MAX}}$	:	Maximum capacity of a substation in the node i (MVA).
$\boldsymbol{S_i^{GD\_MAX}}$	:	Maximum capacity of a DG in the node i (MVA).
$\boldsymbol{V^{max}}$	:	Maximum voltage limit (kV).
$\boldsymbol{V^{min}}$	:	Minimum voltage limit (kV).

To determine the value of the non-supplied power given the contingency of the feeder L, the model represented by (2) – (10) is executed, eliminating the network element under contingency, that is, making $a_{l=L,i}^E = 0$. Then, the value of the non-supplied power is obtained by making $P_{i,L}^E = real\{S_i^{R^*}\}$. It is important to highlight that the mathematical model implemented in this work is non-convex, given the characteristics of the non-linearities it contains. However, although it is not possible to guarantee the global optimality of the results, it can be affirmed that these correspond to good quality solutions and that therefore the proposed reliability results obey a pessimistic scenario, guaranteeing the validity of the conclusions and the presented analysis. Additionally, the fact that most of the world's distribution systems are operated using computational tools that are based on non-linear OPF models should be considered. So there is a high probability that the daily operation of the system will be programmed around operation points other than the global optimum, which highlights the importance of ensuring that even in suboptimal conditions, reliability is adequate.

2.2.3 Evaluation of the reliability level

Given that an electrical network with a high percentage of penetration of DG-NG can present a strong interdependence with the NG network that supplies these generators, it is necessary to quantify the impact of the contingencies of the NG network on the energy that is supplied in the electrical network. To quantify the effect of the reliability of the NG network, an adaptation of the NSEL electrical index is proposed, which is presented in (11):

$$NSEL^{G} = T * \sum_{P} \left| \lambda_{P}^{G} \times r_{P}^{G} \times Long_{P}^{G} \sum_{i} P_{i,P}^{E} \right| \tag{11}$$

Where,

$\boldsymbol{NSEL^{G}}$	:	Index of the non-supplied energy level by contingencies in the NG network.
$\boldsymbol{P}$	:	Pipeline of the NG network.
$\boldsymbol{T}$	:	Study period.
$\boldsymbol{\lambda_{P}^{G}}$	:	Fault rate of pipeline P of the NG network.
$\boldsymbol{r_{P}^{G}}$	:	Repair time of the P pipeline of the NG network.
$\boldsymbol{Long_{P}^{G}}$	:	Length of the P pipeline of the NG network.
$\boldsymbol{i}$	:	Set of loads of the electrical network.
$\boldsymbol{P_{i,P}^{E}}$	:	Power not supplied to the load i due to a contingency in the P pipeline of the NG network.

To evaluate the reliability index of the electrical network using the reliability of the elements of the NG network, an optimal power flow is used to evaluate the operating conditions of the network, as illustrated in (2) – (10). To determine the value of the power not supplied due to the contingency of the pipeline, the model represented by (2) – (10) is executed, eliminating all the DG-NG that were disconnected by the contingency in said gas pipeline; that is, by making $S_{i}^{GD\_MAX} = 0$ for the disconnected generators. Then, the value of the non-supplied power is obtained by making $P_{i,P}^{E} = real\{S_{i}^{R^{*}}\}$.

2.2.4 Calculation of the impact percentage

To determine the impact of the reliability of the NG network on the reliability of the electrical network, we analyze the relationship between the $NSEL^{G}$ index that is presented to the NG network contingencies with the $NSEL^{E}$ index of non-supplied energy under contingencies in the electrical network without contingencies in the NG network (defined as the reference value). The proposed formulation is presented in (12). The value in this equation is expressed as a percentage, where a higher percentage indicates a greater relevance of the contingency in the NG network over the electrical network.

$$Impact = \frac{NSEL^G}{NSEL^E} \times 100\% \quad (12)$$

If the contingencies in the NG network lead to lower $NSEL^G$ values compared to the reference $NSEL^E$ value, it is assumed that the NG network does not affect the operation of the electrical network. Otherwise, it indicates that both networks depend on said operation. It is important to keep in mind that these formulations are highly dependent on the failure rates and repair times of both systems. Therefore, the final evaluation requires real values and ranges of these parameters for both the electrical and NG systems to obtain results that reflect reality.

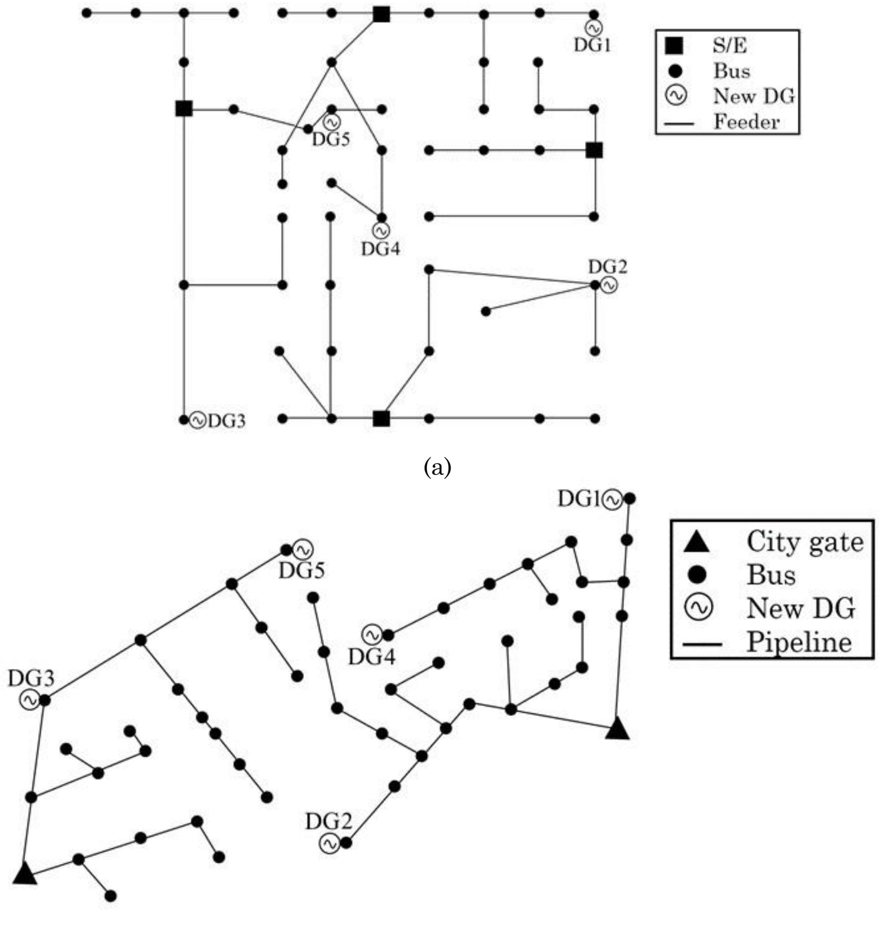
3. RESULTS AND DISCUSSION

3.1 System description

To apply the proposed methodology, the test system presented in [1] is used (see Figure 3). The test system consists of an electrical distribution system and a NG system that operate jointly and are interrelated by DG-NG. The electrical system has a voltage of 29 kV (Figure 3a) and has 54 nodes (black circles), 49 network sections (solid lines), and 4 substations (black squares). The NG network (Figure 3b) is composed of 50 nodes (black circles), 48 pipelines (solid lines), and 2 city gates (black squares). The connection between both networks (electrical system and NG) is given by 5 DG-NG (white circles). The complete database is available with the authors.

3.2 Discussion of the results

The resulting values are presented by means of level curves, which increase their value as they move away from the origin of coordinates and whose numerical values appear on the right vertical axis. These curves illustrate the percentage impact of the contingencies in the natural gas network on the reliability of the electrical network. When applying the described methodology to the system illustrated in Figure 3, it was found that the $NSEL^E$ index is 804.44 (MWh/year). Figure 4 shows the evaluation results of the impact factor of the NG network. This figure evaluates the impact of the NG network on the electrical network (see (11), (12)) for different repair times (left vertical axis), failure rates (horizontal axis), and contingencies of the NG network. The resulting values are presented via level curves, which increase in value as they move away from the origin of coordinates and whose numerical values appear on the right vertical axis. These curves illustrate the percentage impact of the contingencies in the NG network on the reliability of the electrical network.



(b)

Figure 3. Test system: a) Electrical network b) Natural gas network. Source: Created by the authors.

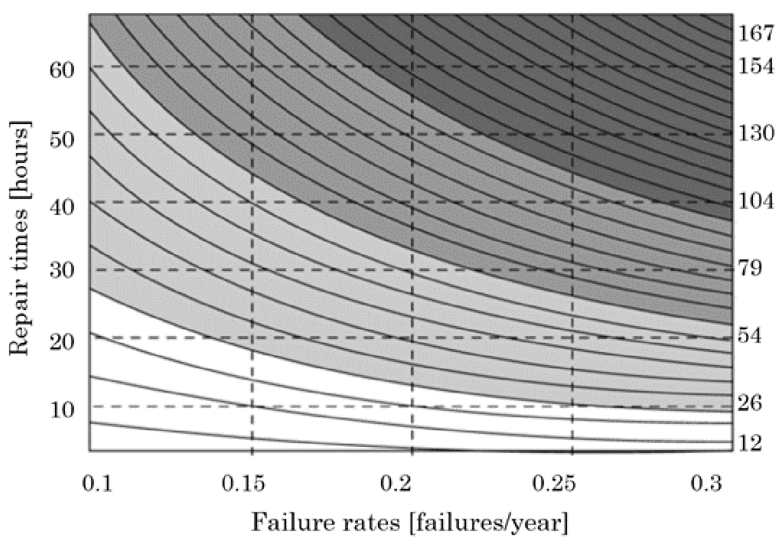


Figure 4. Impact of the natural gas network on the electrical network. Source: Created by the authors.

It is observed that if the failure rates and repair times of the NG network are low, the impact of the NG network on the electrical network is not significant (see percentages in the curved lines on the right axis). For example, for a repair time of 10 hours and a failure rate of 0.15 failures/year, there is an impact percentage of 12%. This indicates that the $NSEL^G$ is low compared to the $NSEL^E$, so the reliability of the NG network does not have a considerable effect on the study of the electrical network.

To illustrate the opposite case, consider in the same figure a repair time of 60 hours and a failure rate of 0.25 failures/year. In this case, reliability problems in the NG network have a negative impact on the electrical network, in which case the $NSEL^G$ is 130 % of the $NSEL^E$ indicator. The impact in this case is very high, making the operation of the electrical network unreliable compared to the previous case, since the distributed generators cannot operate continuously due to the discontinuity in their gas supply.

Given the above, observe the lower left region (white region) of Figure 4, where the impact of the reliability of the natural gas network on the reliability of the electrical network is low, so it can be said that, if the gas network repair times are less than 20 hours, the gas network does not substantially affect the reliability of the electrical network. However, for higher values of repair times, the impact of the gas network becomes increasingly critical each time. For this, look at the upper right area (dark gray region), where it is reflected that the gas network failures lead to higher power demand cuts, even those associated with the electrical network own contingencies, which makes it possible to affirm that the low reliability of the gas network prevents the DG-NG from improving the reliability indexes of the electrical network and, on the contrary, it generates greater load cuts.

Therefore, it is important to keep in mind that, if the NG network is highly reliable, the distributed generators will operate continuously, and the electrical network can be planned, considering these sources as a firm generation, thus reducing the costs associated with a high-capacity substation and the drivers required for the laying of the network. If the NG network presents a low reliability, however, it will be necessary to dimension the elements of the electrical network so that they support the total requirements of the demand since the distributed generators cannot operate constantly, thus increasing the investment costs of the electrical network.

Finally, it should be noted that although the main objective of this paper is to draw attention to the importance of carrying out holistic analyzes of the impact of decision-making associated with multi-energy systems, specifically showing how and under what conditions the reliability of the natural gas network affects the reliability of the electricity network, an aspect that is very relevant, since it is common to assume that the generation that comes from the burning of fuels is equivalent to firm energy. In this sense, the numerical results presented show the stated problem and demonstrate the importance of holistic analysis. Despite this, the reliability analysis could be extended and refined if an integrated optimal flow model of electricity and natural gas were used, which would allow not only to evaluate the effect on the electrical network of the simultaneous disconnection of generators, but also the effect on non-electric gas users and in general on the entire energy system, however, said analysis is beyond the scope of this paper and is part of the future work that stems from it.

4. CONCLUSIONS AND FUTURE WORKS

The energy transition demands the efficient and appropriate use of all available energy resources, in this sense, the electricity and natural gas systems play an important role and therefore their interactions and synergies are essential for decision making. This paper discusses and presents evidence on the impact of the reliability of the natural gas network on the reliability of the electrical network when there is an important participation of distributed generation based on natural gas. A simple but effective methodology is presented to determine the degree of affectation caused by the gas network to the electrical network when simple contingencies occur in the distribution of natural gas. That obeys a first approximation to the analysis of the reliability of integrated energy systems.

With the purpose of guaranteeing the adequate operation of DG-NG in the electrical network, this paper develops a methodology that can be used to quantify the impact of the reliability of the NG system on the reliability of the electrical system.

The results affirm that the reliability of the electrical networks with important concentrations of DG-NG depends heavily on the NG network when the latter presents a low reliability. This implies that, when planning methodologies for integrated electricity and NG distribution systems, it is important to consider the effect of the reliability of the gas network on the design of the infrastructure and on the location and sizing of DG-NG.

Although the proposed methodology appropriately and satisfactorily addresses the impact of the reliability of the gas network on the electricity network, it should be noted that a better approximation could be achieved through OPF models that are linearized, allowing to guarantee the global optimality of the response. Likewise, building an integrated flow model that includes an optimal gas flow model, which jointly allows the evaluation of the impact on the entire energy system, would allow further refinement of the reliability impact calculation, however, these aspects go beyond the scope of this paper and will be addressed in future works. Futures developments of the research should include also the modelling and calculation of the NG network in order to consider also constrains of it (maximum velocity of the gas in pipes, minimum pressure of gas delivered, and maximum flow supply by source nodes).

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CONFLICTS OF INTEREST

The authors declare that there is no conflict of interest.

AUTHOR CONTRIBUTIONS

A Conceptualization, methodology, software and writing-review and editing, where realized by Carlos A. Saldarriaga Cortés, Ricardo A. Hincapié Isaza and Harold Salazar Isaza. All authors have read and agreed to the published version of the manuscript.

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