Research, Society and Development, v. 10, n. 2, e42110212641, 2021
(CC BY 4.0) | ISSN 2525-3409 | DOI: http://dx.doi.org/10.33448/rsd-v10i2.12641

Interdisciplinarity Applied to the Optimized Dispatch of Integrated Electricity and Natural Gas Networks using the Genetic Algorithm

A interdisciplinaridade Aplicada ao Despacho Otimizado das Redes Integradas de Energia Elétrica e de Gás Natural utilizando o Algoritmo Genético

Interdisciplinariedad Aplicada al Despacho Optimizado de Redes Integradas de Electricidad y Gas Natural mediante el Algoritmo Genético

Received: 02/03/2021 | Reviewed: 02/13/2021 | Accept: 02/15/2021 | Published: 02/21/2021

Heictor Alves de Oliveira Costa
ORCID: https://orcid.org/0000-0003-3611-3675
College Estácio Belém, Brazil
E-mail: heictor8@gmail.com
Denis Carlos Lima Costa
ORCID: https://orcid.org/0000-0003-3207-6934
Federal Institute of Education, Brazil
E-mail: denis.costa@ifpa.edu.br
Lair Aguiar de Meneses
ORCID: https://orcid.org/0000-0001-9503-2870
Federal Institute of Education, Brazil
E-mail: lair.meneses@ifpa.edu.br

Abstract

This paper proposes a method based on genetic algorithm (GA) for the security-constrained optimal dispatch of integrated natural gas and electricity networks, considering operating scenarios in both energy systems, demonstrating the importance of interdisciplinary teaching in the academic contents of Mathematics, Physics and Computing in modeling engineering problems. The mathematical formulation of the optimization problem consists of a multi-objective function which aims to minimize both costs of thermal generation (using processes based on diesel oil and natural gas) as well as the production and transportation of natural gas. The joint gas-electricity system is modeled by two separate groups of nonlinear equation, which are solved by the combination of Newton's method with the GA. The applicability of the proposed method is tested in the Belgian gas network integrated with the IEEE 14-bus test system and a 15-node natural gas network integrated with the IEEE 118-bus test system. The results demonstrate, with excellent levels of precision and accuracy, that the proposed method provides efficient and secure solutions for different operating scenarios in both energy systems, henceforth the case study carried out by the research group Gradient de Mathematical Modeling and Computational Simulation - GM²SC, linked to the Federal Institute of Education, Science and Technology of Pará - IFPA Campus Ananindeua.

Keywords: Interdisciplinarity; Electric power generation; Genetic algorithm; Natural gas.

Resumo

Este artigo propõe um método baseado em algoritmo genético (AG) para o despacho ótimo com restrição de segurança de redes integradas de energia elétrica e gás natural, considerando cenários operacionais em ambos os sistemas de energia, demonstrando a importância do ensino interdisciplinar nos conteúdos acadêmicos de Matemática, Física e Computação na modelagem de problemas das Engenharias. A formulação matemática do problema de otimização consiste em uma função multiobjetivo que visa minimizer, tanto os custos da geração térmica (utilizando processos baseados em óleo diesel e gás natural), quanto à produção e ao transporte do gás natural. O sistema gás-eletricidade é modelado por dois grupos separados de equações não lineares, que são resolvidos pela combinação do método de Newton com AG. A aplicabilidade do método proposto é testada na rede de gás belga integrada ao sistema de teste IEEE de 14 barras e em uma rede de gás natural de 15 nós integrada ao sistema de teste IEEE-118 barras. Os resultados demonstram, com excelentes níveis de precisão e acurácia, que o método proposto oferece soluções eficientes e seguras para diferentes cenários de operação em ambos os sistemas de energia, doravante o estudo de caso executado pelo grupo de pesquisa Gradiente de Modelagem Matemática e Simulação Computacional – GM²SC, vinculado ao Instituto Federal de Educação, Ciência e Tecnologia do Pará – IFPA *Campus* Ananindeua.

Palavras-chave: Interdisciplinaridade, Geração de energia elétrica; Algoritmo genético; Gás natural.

Resumen
Este artículo propone un método basado en algoritmo genético (AG) para el despacho óptimo con restricciones de seguridad de redes integradas de gas natural y electricidad, considerando escenarios operativos en ambos sistemas energéticos, demostrando la importancia de la enseñanza interdisciplinaria en los contenidos académicos de Matemáticas, Física y Computación en la modelización de problemas de ingeniería. La formulación matemática del problema de optimización consta de una función multiobjetivo que tiene como objetivo minimizar tanto los costos de generación térmica (mediante procesos basados en gasoil y gas natural) como la producción y transporte de gas natural. El sistema conjunto gas-electricidad está modelado por dos grupos separados de ecuaciones no lineales, que se resuelven mediante la combinación del método de Newton con el AG. La aplicabilidad del método propuesto se prueba en la red de gas belga integrada con el sistema de prueba IEEE 14-bus y una red de gas natural de 15 nodos integrada con el sistema de prueba IEEE 118-bus. Los resultados demuestran, con excelentes niveles de precisión y exactitud, que el método propuesto brinda soluciones eficientes y seguras para diferentes escenarios operativos en ambos sistemas energéticos, en adelante el estudio de caso realizado por el grupo de investigación Gradiente de Modelado Matemático y Simulación Computacional - GM²SC, vinculado al Instituto Federal de Educación, Ciencia y Tecnología de Pará - IFPA Campus Ananindeua.
Palabras clave: Interdisciplinariedad; Generación de energía eléctrica; Algoritmo genético; Gas natural.

1. Introduction

In 2020, the thermoelectric power sector in Brazil generated 29.369 GWh; whereas the share of natural gas increased by 53.4% (IDEC, 2020). This data provides evidence of the increasing importance of natural gas in the thermal power generation of Brazil, mainly resulting from the high efficiency, low-cost investment, operational flexibility and less environmental impact when compared to diesel (Kaplan, 2010). This significant increase in the installation of thermoelectric power plants using natural gas associated with increased electricity demand, prompted this type of power generation to assure a greater participation in electric power supply.

In the meantime, this fact creates a strong interdependence between the electrical system and the gas pipeline system, the latter being responsible for the transportation of natural gas from the production well to the consumption point. Traditionally, this interdependence is disregarded in studies of optimal planning of the operation of thermoelectric power plants using natural gas. However, this simplification may affect the safe operation and performance of the joint systems, as pressure losses, contingencies in gas pipelines, lack of storage or interruptions in the supply of natural gas may bring about a cut off of the generating units. In the occurrence of shutdowns of gas pipelines or power transmission lines, inconsistent procedures for cutting off the supply of natural gas to thermal electric generators may restrict the operation of the electrical system or even result in additional shutdowns (Shahidehpour et al, 2005). The active power adjustment in an arbitrary number of generators may affect the flows in the gas network, which shows the interdependence between both networks (Mares and Esquivel, 2012). Therefore, this strong dependence operation between these two systems requires a coordinated operation to obtain reduced operating costs and congestion without jeopardize the security of power systems.

Various models have been proposed to ensure optimal combined operation of natural gas and electrical networks by means of an unified formulation. In Shahidehpour et al (2002), the authors performed an assessment of interdependence between both networks in terms of the impact of market prices of natural gas in the dispatch of the generating units. In Quelhas et al (2007), the authors presented an multiperiod generalized network flow model focusing on the economic interdependence of the combined system (electric grid, coal and natural gas). In Munoz et al (2003), a model was presented to calculate the maximum amount of energy that should be provided to a natural gas combined cycle power plant. In Tao et al (2008), an integrated model of optimal dispatch was proposed to evaluate the impact of the interdependence of electricity and natural gas networks in the operational safety of the electric system. Other studies have proposed methods of optimal dispatch of joint natural gas and electric networks (An et al, 2003; Geidl and Andersson, 2007; Arnold and Andersson, 2008; Chaudry et al, 2008; Liu et al, 2009). All these cited works used conventional optimization methods as a solution to the problem of joint gas-electricity optimal dispatch.

The electricity-gas optimal dispatch is a mixed integer, nonlinear, non-convex problem with a very complex solution. Conventional methods of nonlinear programming may not be able to provide an optimal solution taking into account that generally the solution is trapped in at local minima. As an alternative to conventional optimization methods, an evolutionary computation has been used to solve a variety of problems due to its ability to find the global optimum. However, few studies have employed evolutionary computation to solve the problem of joint electricity-gas optimal dispatch. In El-Mahdy et al (2010), an optimization methodology based on genetic algorithms (GA) is proposed to determine the pipeline diameter to minimize the cost of the gas network. Nonetheless, the authors did not take into account the model of the electrical grid. A hybrid model is proposed in Unsihuay et al (2007), combining an evolutionary algorithm with Newton's methods and the interior points to plan for the optimal operation of the natural gas and electric systems. However, the work does not take into account the cost of transportation of natural gas in the objective function, which may reduce the overall efficiency of the system considering that the pipeline system must meet the demands for natural gas with the lowest production and transportation costs (Wolf and Smeers, 1996; Wolf and Smeers, 2000). Besides, the authors of Unsihuay et al (2007) did not evaluate the operating interdependence of the gas-electric system from different operational scenarios in both energy systems. In Costa et al (2016) the authors propose a security region, based on a decision tree, for the integrated dispatch of electricity and natural gas networks. Based on the values obtained by the decision tree of (Costa et al, 2016), it was possible to optimize the integrated dispatch of these networks.

Cruz et al (2019), they analyzed the energy potential of biogas that can be produced from the anaerobic biodigestion of food waste produced daily by restaurants in the city of Itajubá – MG. They found that there is a monthly availability of 6.569,86 kWh power.

Nascimento et al (2019) evaluated the potential of renewable Hybrid Systems in the Amazon Region. For this, the authors developed a comparative model of the types of renewable energy with potential use in Hybrid systems in a SWOT matrix.

Bernardes et al (2020) compare the main resources available to improvement of energy efficiency in urban public lighting. The authors found that there is a great possibility to deploy resources and technologies that allow monitoring of the entire electrical system, increasing energy savings in a safer way for the population.

Maimoni et al (2020) analyzed the economic viability of the total service of the consumption of electric energy with solar photovoltaic and thermal systems, having as primary goal of study the residences in the city of Sobrália - MG. The purpose of the work was to compare and choose the best option for the investor, from an economic point of view.

Spinola et al (2020) investigated interdisciplinarity in the Bachelor of Science and Technology (BC&T) course at the Federal University of ABC (UFABC) and found that it is not enough to conceptualize interdisciplinarity in documents and small actions, it is necessary to understand that it is the result of many plans, projects and actions that can give rise to changes in the modeling of phenomena that no single person planned or created.

In this context, this paper proposes a method interdisciplinary based on GA for security-constrained optimal dispatch of integrated natural gas and electricity networks, in order to minimize the costs associated with thermoelectric generation (natural gas and diesel), natural gas production and transportation. The nonlinear algebraic equations representing both systems are solved separately by Newton's method combined with GA in order to assess the optimal dispatch of the global energy matrix under a pre-specified operating condition.

The interdisciplinarity proposed method is described in detail hereinbelow in accordance with the following sections, whereas the introduction is Section I. Section II, methodology, shows the formulation of the natural gas flow system considering the pipeline and the production nodes and gas consumption, in subsection 2.1, natural gas system formulation. In subsection 2.2 describes the integrated electricity-gas optimal dispatch using the GA. The application of the proposed method in two coupled energy systems is presented in section III, as well as the results and discussions. Finally, section IV presents the conclusions of the work.

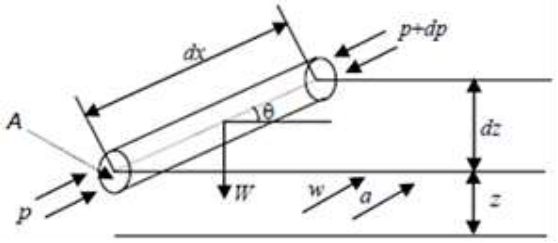
2. Methodology

The methodization performed in this article is, for the most part, structuralist, similarly to Pereira et al. (2018). Research is prescribed with the realization of a real phenomenon. Subsequently, it extends to the expectation of abstraction, through the formulation of mathematical and computational models. The scientific purpose is represented and, finally, the result of the investigation is evidenced, linked to information a priori from reality, idealized and correlated with the conditions and restrictions of areas such as Physics, Electrical Engineering and Computer Engineering.

2.1 Natural Gas System Formulation

In order to determine the gas flow model in pipelines, it may be admitted as a reference an element of a pipeline of infinitesimal length *dx* (m) and transversal section *A* (m^2) and consider *w* (m/s) and *a* (m/s$^{2)}$), respectively, the velocity and acceleration of the gas inside this element, *W* (Kg.m/s^2) weight of the gas particles, and *p* (bar) the external pressure as shown in Figure 1, according to (Osiadacz, 1987).

Figure 1. Parameters of the gas flow in pipelines.



Source: Osiadacz (1987).

Bernoulli's Equation is written as:

$$\frac{p}{\rho g} + \frac{w^2}{2g} + z = C \tag{1}$$

In steady state, the gas flow is constant, therefore:

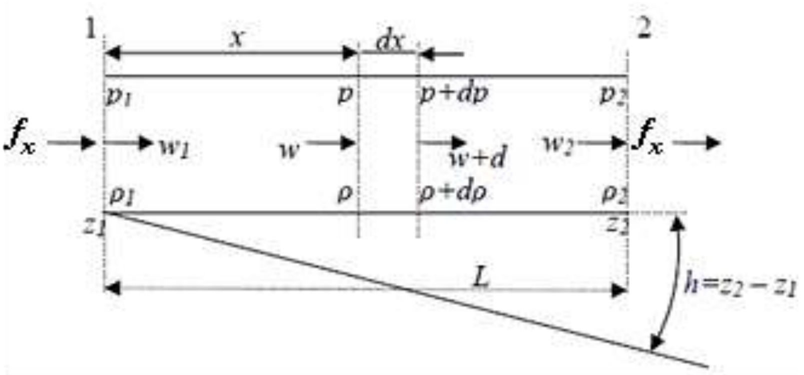
$$w_1.A_1 = w_2.A_2 = f_x \tag{2}$$

Figure 2 represents a gas flow in an infinitesimal portion of the pipeline, where:

$$w_1.\rho_1 = w_2.\rho_2 \tag{3}$$

$$\frac{p}{\rho g} + \frac{w^2}{2g} + z = \frac{p+dp}{\rho g} + \frac{\left(w+dw\right)^2}{2g} + \left(z+dz\right) + dh_f \tag{4}$$

Figure 2. Gas flow in an infinitesimal portion of the pipeline.



Source: Osiadacz (1987).

The term dh_f represents the losses in the form of heat due to friction of the gas against the pipeline wall and can be quantified by Darcy's equation.

$$dh_f = \frac{4fw^2}{D.2g}dx \tag{5}$$

Where f is the friction factor (dimensionless) and D is the inner diameter of the pipeline (m). By replacing (5) in (4), one has:

$$-dp = \frac{2f\rho w^2}{D}dx + \rho g dz \tag{6}$$

Considering equation (3) and the proportionality of density variations, pressure and gas velocity in the pipes, equation (7) is obtained according to Osiadacz (1987).

$$-pdp = \frac{2f}{D}\rho_1 p_1 w^2 dx + \frac{p^2}{p_1}\rho_1 g dz \tag{7}$$

The gas density is given by the inverse of the specific volume according to equation (8).

$$\rho = \frac{1}{v} \tag{8}$$

The gas compressibility factor in the pipeline is given by equation (9).

$$Z = \frac{pv}{RT} \tag{9}$$

From equations (7), (8) and (9), equation (10) is obtained.

$$-pdp = \frac{2f}{D}\rho_1^{\,2} w_1^{\,2} ZRTdx + \frac{p^2}{ZRT}gdz \tag{10}$$

From equations (2) and (3), equation (11) can be written as:

$$\rho_1^{\ 2} w_1^{\ 2} = \rho_n^{\ 2} w_n^{\ 2} = \rho_n^{\ 2} \cdot \frac{f_{x(n)}^2}{A^2} = \frac{\rho_n^{\ 2} \cdot f_{x(n)}^2}{\left(0,25\pi D^2\right)^2} \tag{11}$$

Where the subscript n indicates the values for the standard pressure and temperature conditions, which are $p_n \cong 0.1\ MPa$ and $T_n \cong 288K$.

By replacing equation (11) in equation (10), equation (12) is obtained as:

$$-pdp = \frac{32 f \rho_n^{\ 2} . Q_n^2}{\pi^2 D^5} ZRTdx + \frac{p_{av}^2}{ZRT} gdz \tag{12}$$

According to (Osiadacz, 1987), $p_{av} = \frac{p_1+p_2}{2}$ can be considered, and $p_n = \rho_n R T_n$ for gas, whereas $p_n = \rho_{(ar)n} R_{ar} T_n$ is for air. By dividing the two expressions for $(\rho_{ar})_n$, equation (13) can be written as:

$$\frac{\rho_n}{\left(\rho_{ar}\right)_n} = \frac{R_{ar}}{R} = S \tag{13}$$

With S being the specific gravity of gas, equation (14) is obtained:

$$\rho_n = \frac{S.p_n}{R_{ar}.T_n} \tag{14}$$

By replacing equations (13) and (14) in equation (12), equation (15) can be written as:

$$-pdp = \frac{32\, fSZT}{\pi^2 R_{ar} D^5}\ f_{x(n)}^2 \left(\frac{p_n}{T_n}\right)^2 dx + \frac{p_{av.}^2 S}{ZR_{ar}.T} gdz \tag{15}$$

By integrating equation (15) in the following intervals: $x = [0; L]$, $p = [p_1; p_2]$ and $z = h$, equation (16) is obtained:

$$p_1^2 - p_2^2 = \frac{64}{\pi^2 R_{ar}} \cdot \frac{fSLZT}{D^5} \left(\frac{p_n}{T_n}\right)^2 f_{x(n)}^2 + \frac{2 p_{av.}^2 S}{ZR_{ar}.T} gh \tag{16}$$

By isolating f_x, equation (17) can be written, which is the equation of gas flow according to [18].

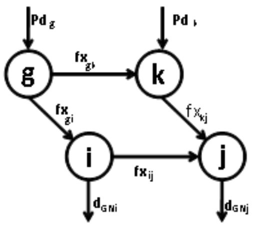
$$f_{x(n)} = \sqrt{\frac{\pi^2 R_{ar}}{64}} \cdot \frac{T_n}{p_n} \cdot \sqrt{\frac{\left[\left(p_1^2 - p_2^2\right) - \frac{2 p_{av.}^2 Sgh}{ZTR_{ar}}\right] D^5}{fSLZT}} \tag{17}$$

Figure 3 shows the nodes and arcs (Wolf and Smeers, 2000) in a simplified manner. In Figure 3, Pd is the gas production associated with that node, for example, Pd_g is the natural gas production at node **g**., $f_{x(gk)}$ is the flow from one node to another; this means that f_x is the gas flow from node **g** to node **k**. Still referring to Figure 3, $\mathbf{d_{GN}}$ are the demands for gas in each node.

The supply node, which can be a gas well, a reservoir or regasification terminal of LNG (Liquefied Natural Gas), may have contractual supply requirements. Depending on the flexibility of the contract, the supply of natural gas may have a pre-specified range of values, a minimum (Pd_{min}) and maximum ($Pd_{\max}$) production. Mathematically:

$$Pd_{\min} \le Pd \le Pd_{\max} \tag{18}$$

Figure 3. Simplified natural gas network.



Source: Costa et al, (2021).

For the nodes on-demand, the consumption value must always meet the demand **d_{GN}**.

In pumping gas in pipelines, there is a maximum value in the operating pressure, which refers to safe pressure levels for the operation and at delivery points to consumers. Moreover, for each node in the system, the gas demand should be met at a certain minimum pressure guaranteed to industries, local distribution companies and thermoelectric power plants. Mathematically:

$$p_{\min} \le p \le p_{\max} \tag{19}$$

In addition to restrictions of operating limits, there is the flow conservation equation at node **i**, shown below, ensuring gas balance (Figure 3). In pipelines, there is a relationship between the gas flow transmitted and the pressure difference between end nodes.

Mathematically, the flow conservation can be expressed as:

$$\sum_{j|(i,j)\in A} f_{(x)ij} = \sum_{j|(j,i)\in A} f_{(x)ji} + P_i - d_{GNi} \tag{20}$$

The gas flow through each passive pipeline $f_{(x)ij}$ is a quadratic function of the pressures at the end nodes:

$$sign(f_{(x)ij})\, f_{(x)ij}{}^2 = C_{ij}{}^2 (p_i^2 - p_j^2),\ \forall (i,j) \in A_P \tag{21}$$

The gas flow through an active pipeline is also a quadratic function of the pressures at the end nodes. In this case, the pressure at the incoming node *i* (or *j)* is lower than the pressure at the outcoming node *j* (or *i)* $(p_i < p_j)$ and the gas flows from node *i* (or *j)* to node *j* (or *i)* $(f_{ij} > 0)$ (or $f_{ij} > 0$). Mathematically,

$$sign(f_{(x)ij})\, f_{(x)ij}{}^2 \ge C_{ij}{}^2 (p_i^2 - p_j^2),\ \forall (i,j) \in A_a \tag{22}$$

Where **Ap** is the set of passive pipelines and **Aa** is the set of active pipelines and $\mathbf{C_{ij}}$ is a constant that depends on the length, diameter and absolute roughness of the pipeline and the gas composition as shown in (23) and (24)

$$C_{ij}{}^2 = 96,074830.10^{-15} \frac{D_{ij}^5}{\lambda_{ij} z T L_{ij} \delta} \tag{23}$$

$$\frac{1}{\lambda_{ij}} = \left[2\log\left(\frac{3,7D_{ij}}{\varepsilon} \right) \right]^2 \tag{24}$$

2.2 Combined Natural Gas and Electric Optimal Power Flow Formulation

The integrated gas-electricity formulation is obtained by the coupled model of power flow and natural gas flow, considering that the link between both systems is the thermal gas-fired generators which are connected to gas pipelines network.

The joint gas-electricity system is modeled by two separate groups of nonlinear equations, which are solved by the combination of Newton's method with the GA. Firstly, the optimal power flow is solved. Next, the gas flow is solved using the values of state variables provided by optimal power flow, in order to assess the steady-state of the overall network.

The attractiveness of using Newton's method is the solution with a local quadratic convergence, irrespectively of the dimension of the electric power grid, provided that all the state variables involved in the study are properly initialized. On the other hand, the solution provided by Newton's method can be trapped on local minima.

In the power flow solution, the voltage magnitudes are initialized 1.0 p.u. for all uncontrolled voltage bus. Meanwhile the voltage magnitudes and the active power at buses of thermal power generation (diesel and natural gas) are initialized by GA at specified values that remain constant throughout the iterative solution provided by the Newton-Raphson method. The active power of the slack generator is not initialized by GA, considering that this slack bus is responsible for supplying the entire imbalance of active power in the system, even when a sufficient spinning reserve exists on other generators.

The strategy adopted for the gas flow solution is similar to that of the load flow. The initial nodal pressures at the pipelines are measured in Baria. The initial values of pressures and gas flow in producing nodes are provided by GA, remaining constant throughout the iterative solution process provided by Newton's method. As for the power flow solution, the gas to be produced by the swing node is not initialized by GA. It is repeated while the maximum generation’s number hasn’t been reached. Therefore, the proposed approach fully takes the advantages of both evolutionary strategy optimization and classical method in the attempt to jump out from the local optimal point. It increases the precision and quickens the convergence. The flowchart of this approach is depicted in Figure 4.

The scope of this article is to propose a method of joint electricity-gas optimal dispatch, under security constraints that aims to minimize the total operating cost of the gas-electricity system.

Thus, the formulated objective function is represented by:

$$Min \sum C_g . PG + \sum C_T . f_x + \sum \left(a + b.P_{ger} + c.P_{ger}^2 \right) \tag{25}$$

Subject to:

$$\sum_{j|(i,j)\in A} f_{(x)ij} = \sum_{j|(j,i)\in A} f_{(x)ji} + Pd_i - d_{GNi}$$

$$sign(f_{(x)ij})\, f_{(x)ij}{}^2 = C_{ij}{}^2 (p_i^2 - p_j^2),\ \forall (i,j) \in A_P$$

$$sign(f_{(x)ij})\, f_{(x)ij}{}^2 \geq C_{ij}{}^2 (p_i^2 - p_j^2),\ \forall (i,j) \in A_a$$

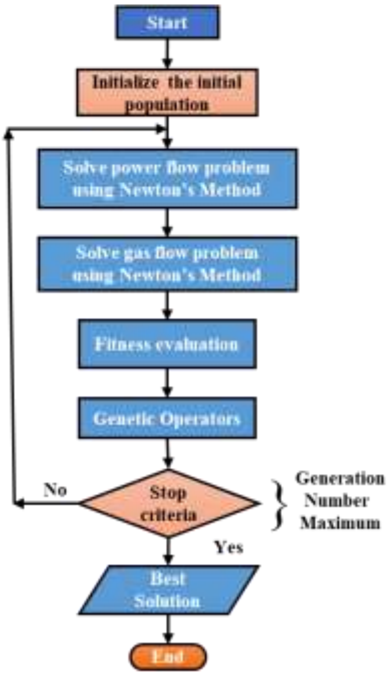
$$Pd_{\min} \leq Pd \leq Pd_{\max}$$

$$p_{\min} \leq p \leq p_{\max}$$

$$
\begin{aligned}
& P_{Gi} - \mathrm{Re}\left(\Psi_i\left(V,\theta\right)\right) = P_{Li};\forall i \in N_B \\
& Q_{Gi} - \mathrm{Im}\left(\Psi_i\left(V,\theta\right)\right) = Q_{Li};\forall i \in N_B \\
& V_{i,\min} \le V_i \le V_{i,\max};\forall i \in N_B \\
& |P_{ij}\left(V,\theta\right)| \le P_{ij,\max};\forall i \in N_B \\
& P_{Gi,\min} \le P_{Gi} \le P_{Gi,\max};\forall i \in N_G \\
& Q_{Gi,\min} \le Q_{Gi} \le Q_{Gi,\max};\forall i \in N_G
\end{aligned}
$$

The variables are described in the Appendix.

Figure 4. Flowchart of the proposed method.



Source: Costa et al, (2021).

3. Results and Discussion

The proposed method for optimal dispatch of the power grid combined with the natural gas network is tested in two systems, namely:

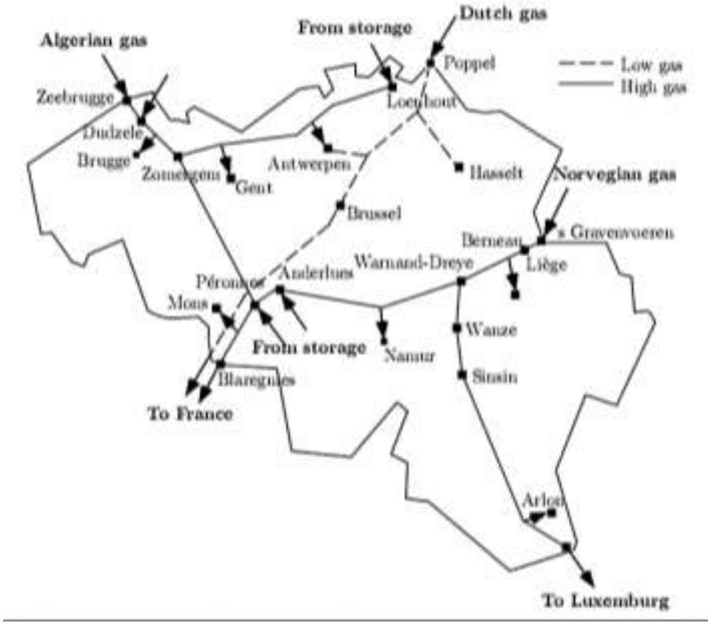
- Case 1: The Belgian natural gas network integrated to the IEEE 14-bus electric grid;
- Case 2: 15-node natural gas network integrated to the IEEE 118-bus electrical grid.

a) Case 1

The proposed method is applied to determine the optimal gas-electricity operation made up by the Belgian natural gas network (Wolf and Smeers, 2000), shown in Figure 5, and the IEEE 14-bus electric grid (*PSTCA*, *1993*), illustrated in Figure 6. The 20-node Belgian natural gas network consists of eight nodes for gas consumption for non-electrical purposes, seven nodes for gas production and 24 pipelines (Wolf and Smeers, 2000). The node referred to as Zeebugge is considered the slack node.

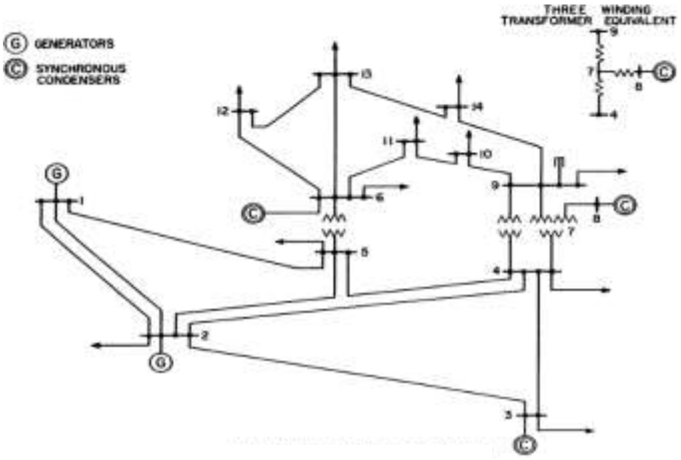
On the other hand, the electric grid is assumed to consist of two natural gas generators connected to bus bars 2 and 3, which are supplied by nodes 4 (Zomergen) and 12 (Namur) of the natural gas network, respectively. For analysis purposes, the optimal gas-electricity solution was obtained assuming the following operating conditions in both systems: (a) base case; (b) shutdown of the pipeline between nodes 4 and 14; (c) 20% increase in the total gas demand for non-electric purposes; and (d) 20% increase in the total load of the electrical grid.

Figure 5. Belgian natural gas network.



Source: Wolf and Smeers (2000).

Figure 6. IEEE 14-bus network.



Source: Wolf and Smeers (2000).

Table 1 shows the correspondence between the nodes of the Belgian natural gas network and the cities to the Figure 5.

Table 1. Nodes and Cities- Belgian Natural Gas Network.

Node	City	Node	City	Node	City	Node	City
1	Zeebrugge	6	Antwerpen	11	Warnand	16	Blaregnes
2	Dudzele	7	Gent	12	Namour	17	Wanse
3	Brugge	8	Voeren	13	Anderlues	18	Sinsin
4	Zomergem	9	Berneau	14	Péronnes	19	Arlon
5	Loenhout	10	Liège	15	Mons	20	Luxemburg

Source: Costa et al, (2021).

Table 2 shows the coefficients for the costs of thermal power generation using natural gas (connected to bus bars 2 and 3) and diesel (connected to the buses 1 and 4) of the 14-bus electric grid.

Figures 7, 8 and 9 show the results of the joint electricity-gas optimal dispatch with power provided by natural gas and diesel-fired generators, the natural gas flows and nodal pressures of the gas network, respectively. Table 3 presents the total costs of the integrated electricity-gas optimal dispatch with the cost of thermoelectric power generation (gas and diesel) and the production and transportation costs of natural gas. The results presented are related to the operating conditions: (a), (b), (c) and (d).

All generators have regulated their active powers to meet the economic criteria, according to the operation scenario without compromising the security of the gas-electricity system. The voltages in the buses of the electric system, the thermal capacity of lines and transformers and reactive capacity of the generators were not violated.

Table 2. Operational Characteristics of Gas- and Diesel-Fired Generators.

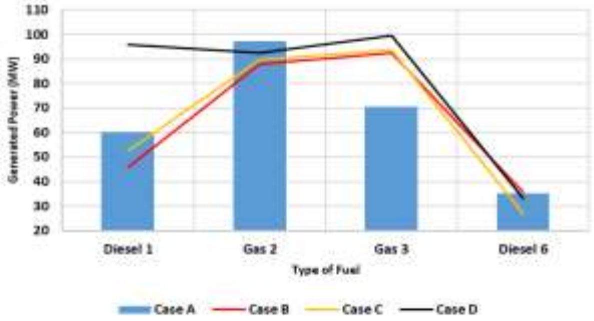
Unit	Cost coefficients ($/MWh)			$P_{G,min}$ (MW)	$P_{G,max}$ (MW)
	a1	b1	c1		
1	2239	21.02	0.009	10	150
4	1469	19.71	0.077	10	100

Tower (node)	Unit	Gas supply coefficients (Mm^3/Mw)			$P_{G,min}$ (MW)	$P_{G,max}$ (MW)
		K_0	K_1	K_2		
Zomergen (4)	2	0.00	0.005	0.00	0	100
Namur (12)	3	0.00	0.005	0.00	0	100

Source: Costa et al, (2021).

Figure 7 shows that natural gas-fired generators injected a greater amount of active power compared to diesel generators for the base case (a), showing the efficiency of the method to minimize the cost of thermal power generation (natural gas and diesel). For cases (b) and (c), which correspond to different scenarios of the gas network in relation to the base case, Figure 7 illustrates that natural gas-fired generators also injected more active power when compared to diesel-fired generators.

Figure 7. Optimal dispatch of diesel and gas-fired generators [MW].

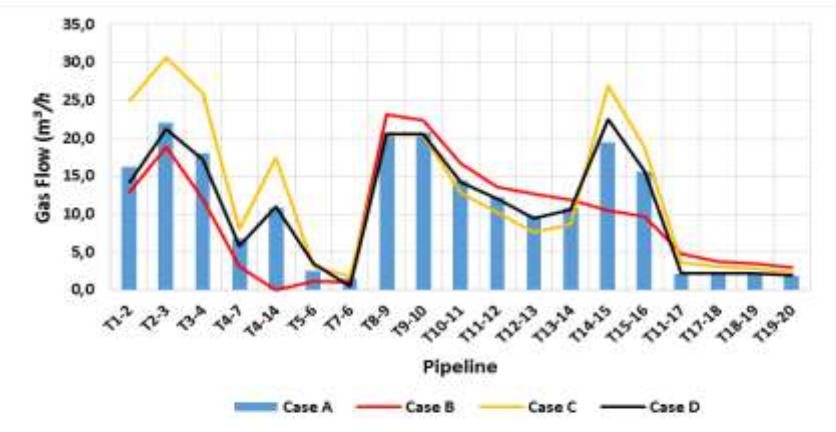


Source: Costa et al, (2021).

The model adopted first solves the optimal power flow through Newton´s method combined with GA, and subsequently solves for the gas flow also by Newton's method combined with GA. In other words, in case there are no changes in the scenarios in the electric grid, the results to be obtained for the optimal dispatch of thermal units tend to be very close. These similar results take into account that the GA has associated structures to the probability. For this reason, the generation levels obtained for cases (b) and (c) are close to those in case (a). On the other hand, cases (b) and (c) could have been critical considering that both the shutdown of a pipeline and the increase of gas consumption for non-electrical purposes could have restricted the supply of natural gas to generating units. However, the solution of the gas flow converged to cases (b) and (c), ensuring the supply of natural gas to nodes 4 and 14, which in turn correspond to the nodes that supply the gas-fired generators. It is important to note that producing nodes store gas for supply in scenarios of increased natural gas demand. For case (d) both the diesel and gas-fired generators contribute with the increase in electric demand.

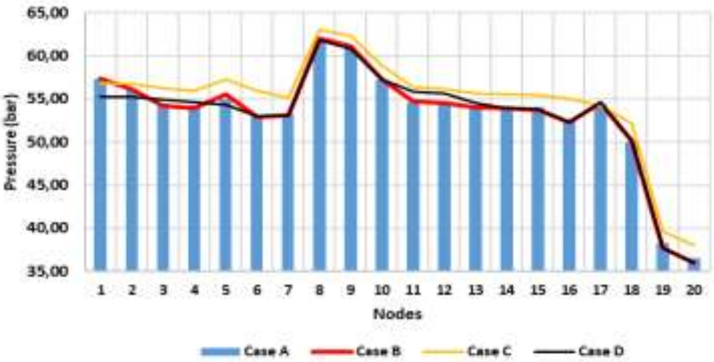
Figures 8 and 9 illustrate the flow in the pipeline network and the pressures at each node of the network, respectively. It is possible to notice in case (b) an interruption of the gas flow in the branch between nodes 4 and 14. Such contingency causes a reduction in gas production illustrated in Figure 10 in nodes 1, 2 and 5, reducing the flow in the pipelines located in the upper part of the gas system. Since node 14 does not receive gas from node 4, gas production in nodes 8, 13 and 14 increases to maintain the systems supplied.

Figure 8. Natural gas flows at pipelines [m^3/h].



Source: Costa et al (2021).

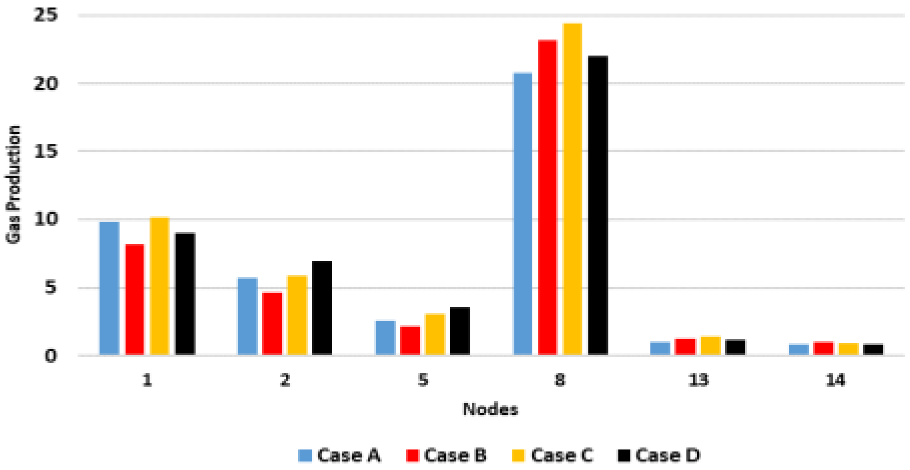
Figure 9. Nodal pressures [bar].



Source: Costa et al, (2021).

Case (c) reflects an increase in the demand for gas for non-electrical purposes. This condition causes an increase in gas supply and an increased gas flow transported in pipelines and the pressures of the nodes, as can be observed in Figure 8 and Figure 9. For the scenario applied in case (d), which refers to an increased electrical power demand, it can be observed in Figure 8 and Figure 9 that the branches responsible for supplying nodes 4 and 12 (nodes that supply the thermal gas-fired generators) undergo an increase in gas flow without a significant pressure variation in the nodes.

Figure 10. Gas Production [Mm^3].



Source: Costa et al, (2021).

The scenario presented in Case (b) simulates an interruption in the pipeline between the cities of Zommergen (node 4) and Perrones (node 14). This contingency causes a division of the gas network in two systems, generating an islanding pipeline. So producers nodes located in the cities of Zeebrugee (node 1), Dudzele (node 2) and Lorenhout (node 5) decrease the level of natural gas production, as shown in Figure 10. Consequently, the gas flow in the branches 1-2, 2-3, 3-4, 5-6, 6-7 and 7-4 reduces in the same proportion in accordance with Figure 8, since there isn´t a demand gas from node 4 to node 14.

In the lower portion of the gas system an inverse process occurs. Without the amount of gas transported from node 4 to 14, the producers nodes located in the cities of Voeren (node 8), Anderlues (node 13) and Perrones (node 14) increase their level of gas production (Figure 10), causing an increase in the gas flow in that part of the pipeline network (Figure 8). Thus, the Genetic Algorithm (GA) evaluate the levels of security of electric and gas system and optimizes the solution to new values of the costs, as shown in case (b) of the Table 3 below.

This scenario demonstrates the importance of the security-constrained studies related with integration of gas network and electric systems. In the same time it´s possible to guarantee the process of cost optimization (minimization of costs) based on GA as described previously.

Table 3 depicts the operating costs for each scenario. It is observed that the costs are subject to individual variations due to the contingency brought about in the respective simulation. The largest identified cost refers to the increase in electricity demand, represented by scenario (d).

Table 3. Optimal Dispatch Costs.

Scenaries	Case A	Case B	Case C	Case D
Generation cost	5365,50	5,371.82	5,351.17	6,654.60
Gas production cost	2880,20	2905.00	2,991.40	3,032.76
Gas transport cost	709,83	763.20	819.77	777.67
Gas total cost	3590,00	3,668.20	3,811.17	3,810.43
Total cost	8955,50	9,040.02	9,322.37	10,465.03

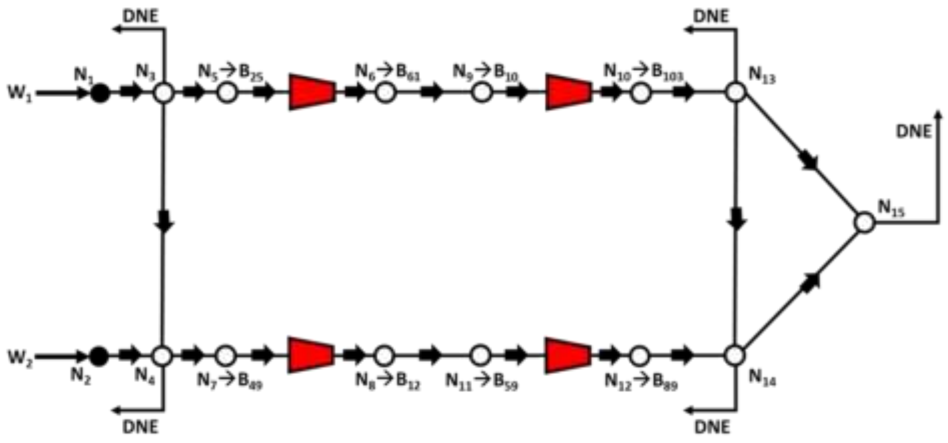
Source: Costa et al, (2021).

It's verified that contingency in the pipeline between 4 and 14, represented by the case (b) causes an increase in the cost of gas production and a reduction in cost of transportation. The 1st situation is explained by the need of the node 8 from the gas network to produce a portion of gas higher than its optimal value. The 2nd situation is related to disruption in the gas flow in a branch of 55 miles long.

b) Case 2

The proposed method is also applied to obtain the optimal dispatch of the electricity-gas system made up of the 15-node natural gas network (An et al, 2003), shown in Figure 11, and the IEEE 118-bus electric grid (PSTCA, 1993), shown in Figure 12. The 15-node natural gas network consists of five nodes for the consumption of gas for non-electrical purposes, and two nodes for gas production, and 16 gas pipelines. Node 1, is considered the slack node.

Figure 11. 15-node natural gas network.



Source: Costa et al, (2021).

Where:

DNE → Non-Electrical Dispatch

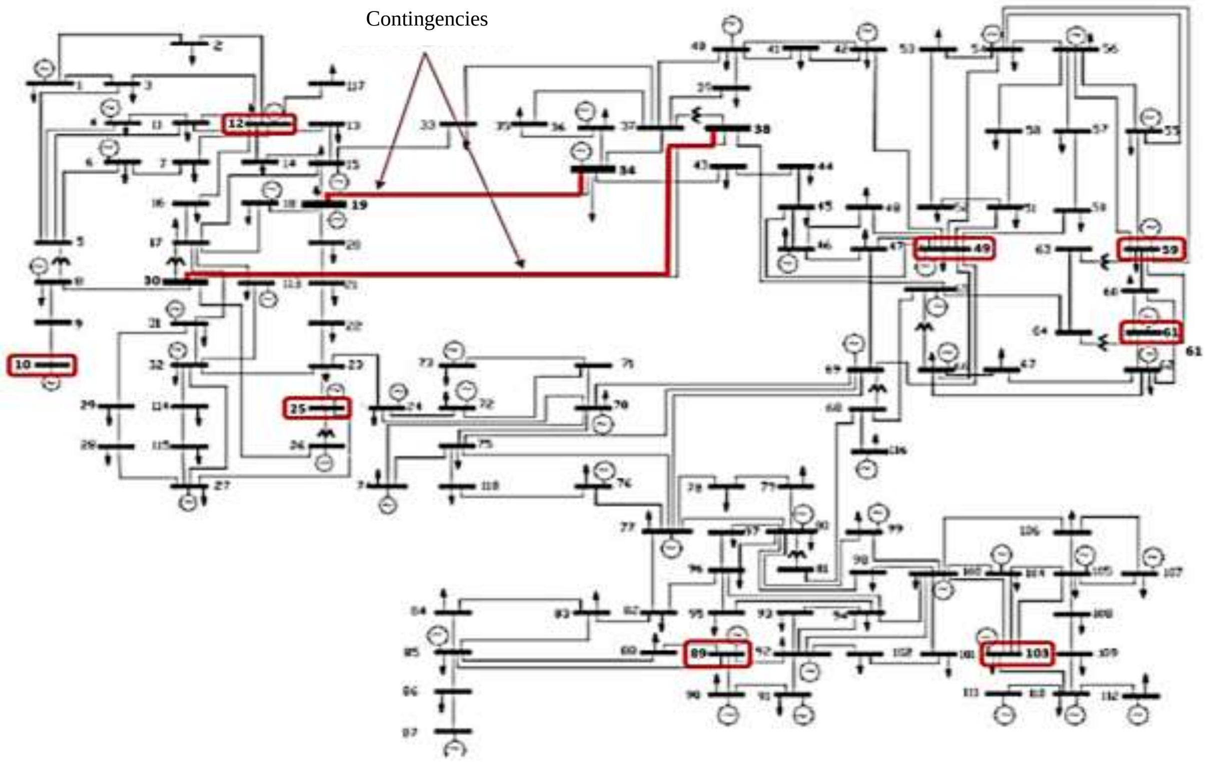
W_n → Are the wells

N_n → Are the nodes

B_n → Electric bus

On the other hand, the 118-bus electric grid is assumed to be made up of 118 buses for nineteen generators, out of which 8 gas-fired generators and 11 diesel-fired generators. For analysis purposes, the optimal gas-electricity solution was obtained assuming the operating conditions in both networks: (a) base case; (b) shutdown of two gas pipelines between nodes 3 and 4 and another between nodes 13 and 14; (c) 20% increase in the total gas demand for non-electric purposes; and (d) a 20% increase in the total power of the electric grid.

Figure 12. IEEE 118-bus network.



Source: Osiadacz (1987).

Table 4 shows the coefficients for the costs of thermal power generation using natural gas (connected to bus bars 10, 12, 25, 49, 59, 61, 89 and 103) and diesel (connected to the buses 26, 31, 46, 54, 65, 66, 69, 80, 87, 100 and 111) of the 118-bus electric grid.

Table 4. Operational Characteristics of Gas and Diesel-Fired Generators.

Unit	Cost coefficients ($/MWh)			$P_{G,min}$ (MW)	$P_{G,max}$ (MW)
	a1	b1	c1		
26, 31, 46, 54, 65, 66	2239	21.02	0.009	10	150
69, 80, 87, 100, 111	1469	19.71	0.077	10	100

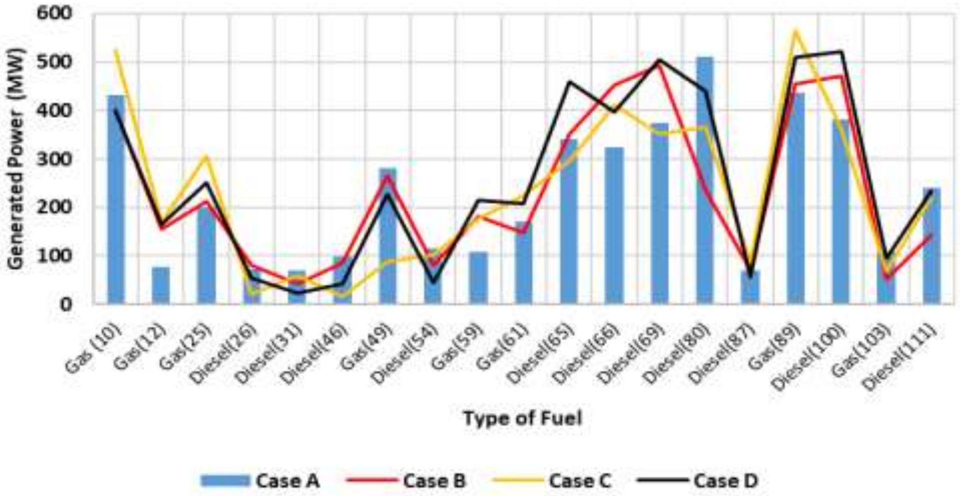
Node	Unit	Gas supply coefficients (Mm^3/Mw)			$P_{G,min}$ (MW)	$P_{G,max}$ (MW)
		K_0	K_1	K_2		
5, 6, 7, 8	10, 12, 25, 49	0.00	0.005	0.00	0	100
9, 10, 11, 12	59, 61, 89, 103	0.00	0.005	0.00	0	100

Source: Costa et al, (2021).

The Figures 13, 14 and 15 show the results of integrated gas-electricity optimal dispatch with the powers provided by natural gas and diesel generators, the natural gas flows, and the nodal pressures of the gas network, respectively. Table 5 presents the total costs of integrated gas-electricity optimal dispatch with the cost of thermoelectric power generation (gas and diesel) and the costs for the production and transportation of natural gas. The results presented are related to the operating conditions: (a), (b), (c) and (d).

As can be observed in Figure 13, all generators regulate their active powers to meet the economic criteria according to the operation scenario without compromising the security of the gas-electricity system. Figure 13 shows that natural gas-fired generators connected to buses 10 and 89, respectively, injected a greater amount of active power compared to the other generators in the system to the base case (a), showing the efficiency of the method to minimize the cost of thermoelectric power generation (gas and diesel).

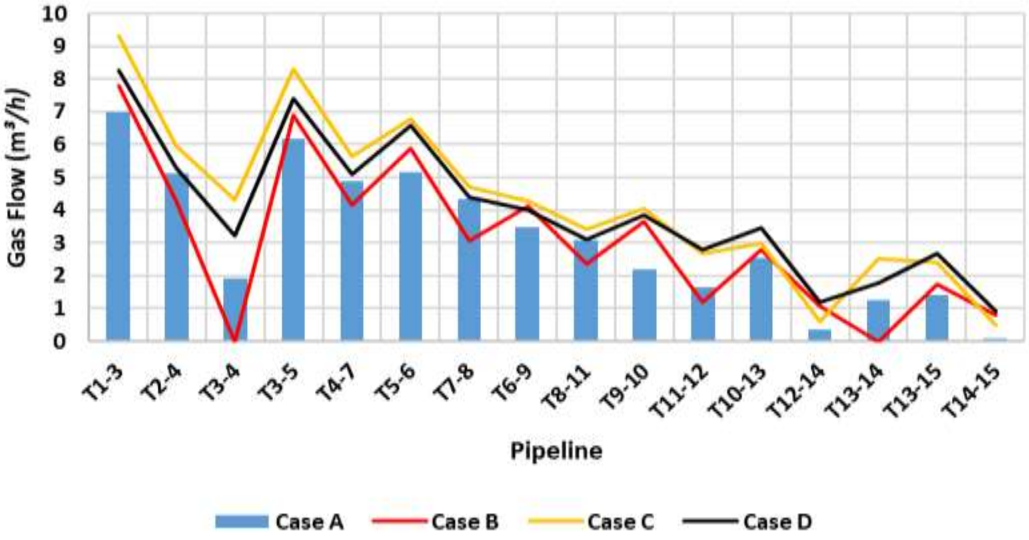
Figure 13. Optimal dispatch of diesel and gas-fired generators [MW].



Source: Costa et al, (2021).

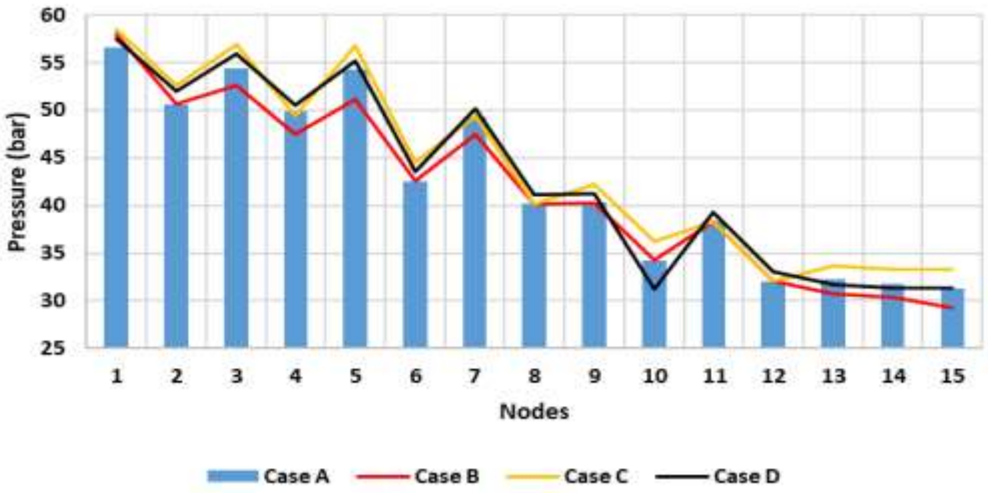
It’s noted that contingency in the pipelines between the nodes 3→4 and 13→14, represented by the case (b), causes an increase in the cost of gas production and a reduction in cost of transportation. Again the 1st situation is explained by the need of the node 2 produce a quantity of gas higher than its optimal value. The 2nd situation is related to disruption in the gas flow in the branches cited above, as shown in Figure 14.

Figure 14. Natural gas flows in pipelines [m^3/h].



Source: Costa et al, (2021).

Figure 15. Nodal pressures [bar].

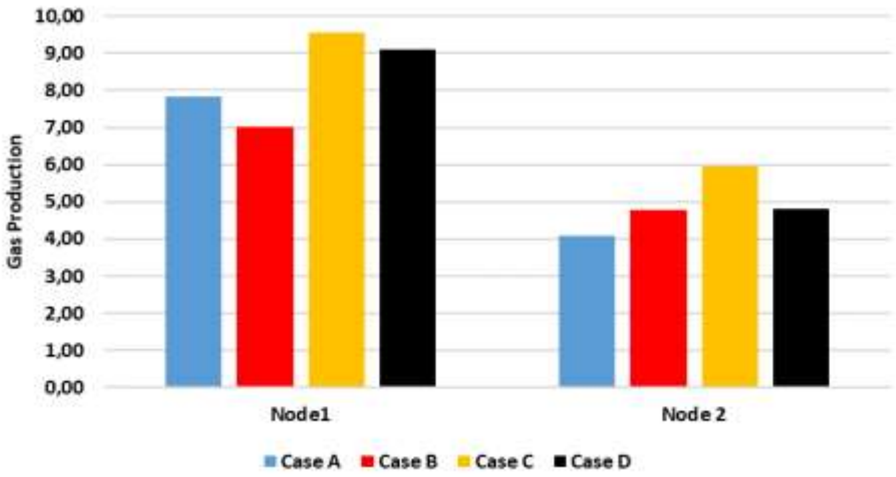


Source: Costa et al, (2021).

As expected, case c) returns an increase in gas flow transported in pipelines, the pressures of the nodes and in gas production, as can be observed in Figures 14, 15 and 16 respectively.

Table 5 shows the operating costs for the scenarios presented herein. It is verified that the costs are subject to individual variations due to the contingency brought about in the respective simulation. Similar to case 1, the largest identified cost refers to the increase in electricity demand, represented by scenario (d), because this scenario reflects an increase in the generation of electricity in diesel-fired power plants.

Figure 16. Gas Production [Mm^3].



Source: Costa et al, (2021).

Table 5. Optimal Dispatch Costs.

Scenaries	Case A	Case B	Case C	Case D
Generation cost	136,344.23	137,025.77	136,437.12	228,560.00
Gas production cost	10,277.05	10,538.00	12,129.00	11,278.00
Gas transport cost	1,461.63	1,406.00	1,855.40	1,739.90
Gas total cost	11,738.68	11,944.00	13,984.40	13,017.90
Total cost	148,082.91	148,969.77	150,421.52	241,577.90

Source: Costa et al, (2021).

4. Final Considerations

This paper proposes a genetic algorithm-based optimal dispatch method of integrated gas-electricity networks, considering operating scenarios, emphasizing the interdisciplinarity of the contents of Mathematics, Physics and Computing in the modeling of phenomena studied in Engineering. A mathematical model of this problem was formulated as an optimization problem where the objective function is to minimize both cost of thermal generation (diesel and natural gas) as well as the production and transportation of natural gas subject to electric system and natural gas pipeline constraints.

This article, based on the interdisciplinarity of the scientific areas applied to the generation of thermoelectric energy, presented an efficient model, capable of aggregating all the control variables of each individualized method.

The integrated electricity-gas optimal power flow problem is solved using a hybrid approach which combines genetic algorithm with Newton's method. The tests on the Belgian gas network integrated with the IEEE 14-bus test system and the 15-node natural gas network integrated with the IEEE 118-bus test system demonstrate the effectiveness of the proposed optimal dispatch approach taken into account Gas transportation cost and security-constrained which were guaranteed even in contingencies conditions of the gas system and demand variable as demonstrated in both cases.

The methodology based on a hybrid model (GA and Newton) for dispatch in electrical energy systems, presented exceptional results in the case study. The feasibility of the process is extremely feasible. Another important factor to highlight is the strategy of interdisciplinarity and transversality of the knowledge used, since several applications from the areas of knowledge were used, such as Mathematics, Physics, Electrical Engineering and Computer Engineering, for example.

The integrated knowledge, applied in a practical and systemic way, ratifies the article as a didactic learning proposal, given that it adds value to the practical results of the reported hybrid system, as well as being efficient to be used as a knowledge integration procedure. across teaching and research.

Acknowledgments

Author one → To the Estácio Belém College for its instruction and structure, and to my undegraduation Advisor Larissa Luz Gomes from whom i received guidance and support to keep on my academical Journey.

Author two → To the Federal Institute of Education, Science and Technology of Pará (IFPA), for encouraging Research; to the research groups GM²SC (Gradient of Mathematical Modeling and Computational Simulation) and LICTI (Languages, Cultures, Technologies and Inclusion), for their support and cooperation.

Author three → To God, for his health and willingness to work; To the Federal Institute of Education, Science and Technology of Pará (IFPA) for promoting Research and Innovation; and to Researchers Denis Costa and Heictor Costa, for the opportunity to contribute to the research that resulted in this work.

References

An, S., Li, Q., & Gedra, T. W., (2003). Natural gas and electricity optimal power flow, in Proc. *IEEE/PES Transmission and Distribution Conf. Expo. 1*, 7–12.

Arnold, M. & Andersson, G. (2008). Decomposed electricity and natural gas optimal power Flow. *Proceedings of 16th Power Systems Computation Conf.* (PSCC), Glasgow, Scotland.

Bernades, D. M., Celeste, W. C., Diniz Chaves, G. de L. (2020). Energy efficiency in urban public lighting: literature review of equipment and technologies. *Research, Society and Development, 9(7), e606973957*. 10.33448/rsd-v9i7.3957. https://rsdjournal.org/index.php/rsd/article/view/3957.

Chaudry, M., Jenkins, N. & Strbac, G. (2008). Multi-time period combined gas and electricity network optimization. *Elec. Power Syst. Research, 78(7), 1265-1279*. 2008.

Costa, Denis C. L., Nunes, Marcus V. A., Vieira, João P. A. & Bezerra, Ubiratan H. (2016). Decision tree-based security dispatch application in integrated electric power and natural-gas networks. *Electric Power Systems Research* 141 (2016) 442–449.

Cruz, H. M., Barros, R. M., Santos, I. F. S. dos, Tiago Filho, G. L. (2019). Study of the potential of generation of electric energy from the biogas of digestion anaerobia of food residues. *Research, Society and Development, 8(5), e3785811*. 10.33448/rsd-v8i5.811. https://rsdjournal.org/index.php/rsd/article/view/811.

El-Mahdy, O. F. M., Ahmed, M. E. H. and Metwalli, S. (2010). Computer aided optimization of natural gas pipe networks using genetic algorithm. *Applied Soft Computing*, *10(4)*, 1141-1150.

Geidl, M. & Andersson, G. (2007). Optimal power flow of multiple energy carriers. *IEEE Trans. Power Syst. 22(1)*, 145-155.

IDEC, Brazilian Institute of Consumer Protection, 2020. Published by: *Climate and Society Institute - ICS*. www.idec.org.br.

Kaplan, S. M. (2010). Displacing coal with generation from existing natural gas-fired power Plants. *CRS Report for Congress, 7-5700, R41027*. http://assets.opencrs.com/rpts.

Liu, C., Shahidehpour, M., Fu, Y., & Z. Li. (2009). Security-constrained unit commitment with natural gas transmission constraints. IEEE Trans. Power Syst., 24(3), 1523–1536.

Maimoni, F. P., Cardoso, R. B. (2020). Economic feasibility analysis for alternatives to use solar energy in homes in the State of Minas Gerais, Brazil. *Research, Society and Development*, 9(8), e853986221. 10.33448/rsd-v9i8.6221. https://rsdjournal.org/index.php/rsd/article/view/6221.

Mares, A. M. & Esquivel, C. R. F. (2012). A unified gas and power flow analysis in natural gas and electricity coupled networks. *IEEE Trans. Power Syst., 27(4)*, 2156–2166.

Munoz, J., Jimenez-Redondo, N., Perez-Ruiz, J. & Barquin, J. (2003). Natural gas network modeling for power systems reliability studies. in *Proc. IEEE/PES General Meeting*, *4*,. 23–26.

Nascimento, B. Z., Catelan, T. C., Chaves, G. de L. D., Celeste, W. C. (2019). Evaluation of the Viability of Implementation of Renewable Hybrid Systems for Energy Access in the Amazon Region. *Research, Society and Development*, 8(10), e448101415. 10.33448/rsd-v8i10.1415. https://rsdjournal.org/index.php/rsd/article/view/1415.

Osiadacz, A. J. (1987). Simulation and analysis of gas networks. *London: E. & F. N*. Spon. 273.

Pereira, A. S., Shitsuka, D. M., Parreira, F. J. & Shitsuka, R. (2018). *Metodologia da pesquisa científica*. UFSM. https://repositorio.ufsm.br/bitstream/handle/1/15824 /Lic_Computacao_Metodologia-Pesquisa-Cientifica.pdf?sequence=1.

PSTCA. *Power Systems Test Case Archive.* (1993). http://www.ee.washington.edu/research/pstca/.

Quelhas, A., Gil, E., McCalley, J. D. & Ryan, S. M. (2007). A multiperiod generalized network flow model of the U.S. integrated energy system: Part I - Model description. *IEEE Trans. Power Syst.*, *22(2)*, 829–836.

Shahidehpour, M., Fu, Y. & Wiedman, T. (2005). Impact of natural gas infrastructure on electric power systems. *Proc. IEEE*, *vol. 93, n°. 5*, pp. 1042–1056.

Spinola, L., Almeida, F. C. P. de, Menezes, M. A., Facó, J. F. B. (2020). Contextualizing interdisciplinarity: a case study at the Federal University of ABC. *Research, Society and Development*, 9(3), e81932456. 10.33448/rsd-v9i3.2456. https://rsdjournal.org/index.php/rsd/article/view/2456.

Tao, L., Eremia, M. & Shahidehpour, M. (2008). Interdependency of natural gas network and power systems security. *IEEE Trans. Power Syst.*, *23(4)*, 1817–1824.

Unsihuay, C., Lima, J. W. Marangon, & Souza, A. C. Zambroni. (2007). Modeling the integrated natural gas and electricity optimal power flow. in *Proc. IEEE/PES General Meeting*, 24–28.

Wolf, D. & Smeers, Y. (1996). Optimal dimensioning of pipe networks with application to gas transmission networks. *Operations Research, 44(4)*, 596-608.

Wolf, D. & Smeers, Y. (2000). The Gas transmission problem solved by an extension of the simplex algorithm. *Management Science, 46(11)*, 1454-1465.

Appendix

C_g → electricity generation cost;

C_T → natural gas transportation cost;

PG → active power generated;

P_{ger} → Active power from gas and diesel-fired generators;

N_B → bus number;

N_G → generators number;

Ψ_i → complex power injection;

P_{Gi}, P_{Li} → active power generated and demand at bus *i*;

Q_{Gi}, Q_{Li} → reactive power generated and demand at bus *i*;

$V_{i,\min}, V_{i,\max}$ → voltage limits;

V, θ → Voltage Magnitude and angle of electric bus;

P_{ij} → Active power between bus *i* e *j*;

$P_{ij,\max}$ → active power limitation in line *ij*;

$Q_{Gi,\min}$; $Q_{Gi,\max}$ → reactive power limits.