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A novel strategy to restore power systems after a great blackout. The Argentinean case

Gonzalo E. Alvarez

Instituto de Desarrollo y Diseño Avellaneda 3657, Santa Fe Santa Fe, Argentina

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ABSTRACT

This paper presents a multi-objective mathematical model to perform power restoration. It considers simultaneously the objective functions: restoration time, load shedding, and cost. New formulations are developed to improve the maneuverability of the system elements. This distinguishes the novel proposal from the rest of the one or two objective approaches. The linear nature of the formulation allows for obtaining feasible solutions within efficient times. The proposal includes in the main objective function the social view in terms of prioritize the restitution of the system for as many users as possible. It enables using this proposal to restore large scale systems. Results indicate that more equitable and faster restoration solutions can be obtained than the reported one in the mentioned case.

1. Introduction

The electricity sector is one of the most relevant fields worldwide in terms of investments. Today, almost all the development of the economy, health, education, and industry require electricity. All human activities are related to a greater or lesser extent of electricity. Many developments have been produced about the electric power systems, however, the essence and several concepts remain to this day since the installation of one of the first configurations of modern systems: the Niagara Falls facility. During the last 100 years, the spreading out of these systems was not conducted harmoniously in many countries. Sometimes the urgent needs conducted to building electric systems prone to instability and grid disturbances. It promotes the occurrence of damages, overload, or even, blackouts. Many reasons can conduct to blackouts. Some of them are line overloads, elevated levels of demands, maintenance issues, manoeuver mistakes, and weather phenomena. By the elevated degree of dependency on the electricity, if a blackout is produced, several issues can appear in many sectors. For example, the organization of the traffic in the cities is regulated by electric devices. Besides, telecommunications could be interrupted, industries will stop their production, hospitals have vital electrical devices such as artificial respirators, drinking water treatment plants depend on their water pumps, among other critical problems.

Every day, many blackouts occur around the world. Most are short and represent a low impact, in terms of users without electric services. However, during the last 21 years, there have been important blackouts with a great impact when the number of users affected is considered. Main blackouts are listed as follows (along with the number of affected people, in millions [1]): 1999 Brazil (97), 2001 India (230), 2003 US and Canada (55), 2003 Italy (56), 2005 Java (100), 2009 Brazil and Paraguay (60), 2012 India (620), 2014 Bangladesh (150), 2015 Pakistan (140), 2019 Java (120), 2019 Argentina, Paraguay, Brazil, Chile, and Uruguay (48). The study of the outages is important to reinforce the systems and prevent new outages in the upcoming days. In this regard, there are several approaches in the literature that address different techniques to avoid blackouts. In Ref. [2], a technique for the evolution of an extended series of blackouts is presented. It reflects the values of the contrary forces. In Ref. [3], an approach is proposed to predict potential blackouts. The model studies systems composed of insulated islands. The author of [4] analyzes the profiles of electricity system in Bangladesh, give suggesting to reduce the blackouts. A similar contribution is observed in Ref. [5]. But in this case, the case of the study is the power sector in Pakistan.

Although it is a matter of not having blackouts, many times the reasons that cause them are very deep and can lead to a total shutdown of the whole system. If this happens, there is no choice but to restore service as quickly and safely as possible. To achieve this purpose, there are numerous approaches that study the issue. Many authors divide the restoration processes into three stages: generation, transmission, and loads [6]. Most of these works consider the generation stage [6]. In this regard [7], presents a mixed integer linear programming model (MILP) to the sequence of generator start-up. Authors affirm that the model achieves an optimal solution that outperforms the heuristic or

E-mail address: galvarez@santafe-conicet.gov.ar.

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Nomenclature

Indexes

i, ld, t	Generator, load, time
bu, bu_i, bu_o	Bus, input bus, output bus
HI/LI	High/low importance elements
j	Next time period

Supra-Indexes

g	Generator, load, time
ng	Natural gas fired technology
h	Hydropower technology
n	Nuclear technology
w	Wind power technology
pv	Photovoltaic technology

Constants

T, BU, LD, I	Total number of periods, buses, loads, generators
δ	Generating cost ($/MW)
$c_{ld,bu,t}$	Power demand (MW)
$\overline{LS_{ld,bu,t}}/\underline{LS_{ld,bu,t}}$	Load shedding upper/lower bound (MW)
$p_{i,t}^{max}/p_{i,t}^{min}$	Power output limits (MW)
$ST_{i,bu}^{demand}$	Start-up demand of unit *i* (MW)
ε_n	Epsilon value of range *n*
ρ_{bu_i,bu_o}	Reactance of line (p.u.)
T^{ini}	Hours in on/off status for the unit *i* (h)
TSU_i/TSD_i	Minimum hours to remain in on/off status
DRT_i/URT_i	Maximum Ramp-down/ramp-up rate for a thermal generator (MW/h)
SDT_i/SUT_i	Shutdown/start-up rate limit for a thermal unit (MW)
SDT_i/SUT_i	Shutdown/start-up rate limit for a thermal unit (MW)
$cold\_t_i$	Hours for considering hot or cold start-up cost for the thermal generator (h)
H_SU_i	Hot start-up cost for thermal generator (USD)
$c\_SU_{i,bu}$	Conversion factor for start-up cost (USD/MW)
$Cold\_SU_i$	Cold start-up cost for thermal generator (USD)
$\mu\_\mathrm{g}_i^h$	Electric generator efficiency (p.u.)
$\mu\_\mathrm{turb}^h_{\_i}$	hydraulic turbine efficiency (p.u.)
$\mu\_\mathrm{cp}_i^h$	mechanical efficiency coupling (p.u.)
$\delta_{in}^{up}/\delta_{out}^{up}$	Input/output river flow for upper reservoir (m^3/s)
$\delta_{in}^{lo}/\delta_{out}^{lo}$	Input/output river flow for lower reservoir (m^3/s)
$ss_{bu_i-bu_o}$	Susceptance of the line that connects buses $bu_i - bu_o$ (p.u.)
$cd_{bu_i-bu_o}$	Conductance of the line that connects buses $bu_i - bu_o$ (p.u.)

Positive variables

$\tau_{ld,bu,t}$	Restoration time of the load *ld* (h)
$LS_{ld,bu,t}$	Load shedding (MW)
$p_{i,bu,t}$	Power Output (MW)
$f\_l_{bu\_i,bu\_o,t}$	Real power flow (MW)
$f\_l\_q_{bu\_i,bu\_o,t}$	Reactive power flow (MVAR)
$V_{bu\_i,bu\_o,t}$	Voltage between connected buses (MV)
$ST_{i,bu,t}$	Start-up demand (MW)
$\varnothing_{bu\_i=bu,bu\_o,t}$	Bus voltage angle (rad)
$WD_{i,bu,t}$	Water discharge (m^3/s)
$h_{i,bu,t}$	Water head (m)
$r_{i,bu,t}^{up}$	Upper reservoir volume (m^3)
$r_{i,bu,t}^{lo}$	Lower reservoir volume (m^3)

Binary variables

$\alpha_{ld,bu,t}$	Restoration status
$u_{ld,bu,t}$	Load shedding status
$y_{i,bu,t}$	Start-up status of unit *i*
$a_{i,bu,t}$	Generator *i* on/off status

enumerative techniques, in terms of quality of solutions, along with the reduction of computational effort. Regarding the MILP models, another one is presented in Ref. [8]. As authors affirm that the repairing times cannot be predicted with a high level of precision, a symmetric random variable is adopted to compensate. A two-stage robust restoration model is introduced to calculate the robust repairing strategy by minimizing the outage loss and the repairing time. Firstly, the optimal restoration strategy is achieved and, secondly the worst-case of repairing time is discovered. In the approach of [9], a heuristic method is presented. It guides the Distribution Management Systems in the determination of switching maneuvers for the isolation of fault zones and promotes the restoration of feeders. During each step, the method proposes possible switching sequences that minimize the impact of the interruption on services. The probabilistic stage includes several parameters, as failure rates, supposed traveling times between buses, etc. Besides, some approaches consider the social factor when the blackouts are analyzed.

Nowadays, the majority of approaches are focused on the stage of the restoration of the generation, as affirms authors of [6]. In this regard, in Ref. [10], the authors face the two main drawbacks of the most majority of the current papers that address the restoration problem. The first one, the scalability problems of the current algorithms, which are used in real-time applications to operate electric systems with thousands of elements. The second one, the problems of consideration of neighbor feeders in load restoration processes. In addition, the processes of power restoration after a blackout is hard and complex to be analyzed by only considering a single-objective. The major part of the literature studies the restoration by only considered the operating cost, the reduction of blackout times, or the load recovery of particular sectors. The fact of considering only one objective can conduct to achieve solutions that are convenient on the one hand, but they can represent important drawbacks on the other hand. For example, an interesting solution, in terms of operative costs, can be extremely large, in terms of time restoration. To face these issues, multi-objective models are powerful tools that are applied in several fields of engineering [11]. When these models are considered, each value of a single objective function is connected to the best one from the other single objectives. Besides, the solution of the whole problem is formed of an arrangement of the optimal solutions for every single objective [12]. The vast majority of multi-objective models that are applied to power systems consider the solving of economic dispatch and emission problems [13]. However, there are a few papers in the literature that also address the restoration problem by using the method. As [14], where three objectives are minimized: generating cost, load shedding, and restoration time. The model is divided into two levels: network sectionalization and electrical loads energizing. With similar reasoning, the authors of [15] minimize the amount of circuit breaker actions and outage durations of the non-black-start generators.

In this context, this paper proposes a multi-objective model that performs the following contributions:

- A new mathematical formulation is presented to address the restoration problem for large scale systems. The model is formulating satisfying a social view. It distinguishes this proposal from the classical ones where the load shedding or operative costs are prioritized.
- A model of MILP type is developed to obtain feasible solutions of large scale systems within convenient CPU times.
- The model proposes a novel formulation of some aspects that are no frequently represented in the literature with a sufficient level of accuracy: generating cost of units with different kinds of technologies,

the status variable of load shedding and generating, restoration priority levels, black-start capability, and dependence of the units that need power supplied to start-up. These aspects have been previously studied in the literature, but in an isolated manner, not in an integrated one.

- A multi-objective formulation for the restoration problem is presented. The vast majority of the classical approaches that address the restoration problem only consider a single or two objectives (the restoration time objective only, or the restoration time and the load shedding objectives). Lexicographic optimization is selected to solve the models by virtue of its advantages.

To prove the effectiveness of the novel method, the large-scale Argentine Power System (with real information about the great blackout that this country suffered in 2019) is tested. The system has about 40 GW of installed power and is composed of over 1500 generators and more than 20,296 km of the transmission lines.

The rest of the paper is planned in this manner: Section 2 details the single objectives models. Section 3 presents the multi-objective formulation. Section 4 solves the two test cases. Results are considered in section 5. The main conclusions are drawn in Section 6.

2. Single-objective models

This section describes the three single objectives which are considering by the novel method to restore systems after blackouts.

2.1. Restoration time model. A more equitable approach

The restoration time model consists of minimizing the number of hours that load *ld* of bus *bu* is unsupplied ($\tau_{ld,bu,t}$). The objective function can be observed in (1). Is the total sum of hours of all loads without service. Hours shall be counted from the moment when the blackout is produced. T is the programming horizon, and t is the time period set, which is 1 h. Besides, the model distinguishes between the high importance loads, as hospitals or other essential services ($ld \in HI$), and the lower importance ones ($ld \in LI$). This function is specially designed to penalize the maintenance of the outage in a particular load and thus favor the restoration. This pursues a social objective of returning the service in a more equitable way to the users. The effects of this formulation are deeply discussed in this subsection and Section 5.

$$\min f_1 = \sum_{t=1}^{T} \sum_{bu=1}^{BU} \sum_{ld \in HI}^{LD} \tau_{ld,bu,t} + \sum_{t=1}^{T} \sum_{bu=\in HI}^{BU} \sum_{ld \in LI}^{LD} \tau_{ld,bu,t} \tag{1}$$

Constraint (2) relates the value of variable τ with the value of the binary variable $u_{ld,bu,t}$. The operator $ord(t)$ indicates the relative position of the set t. To promote the understanding of the operator, if a programming horizon of one day is considered, the values of $ord(t)$ are [1, 2, 3, …, and 24] for the corresponding period. The last variable represents the status of restoration of the load*ld*, which is equal to 1 when the supply of this load is restored. M is a sufficiently large number.

$$\tau_{ld,bu,t} \geq ord(t) - M^{*} u_{ld,bu,t}, \quad bu = 1, \ldots, BU; ld = 1, \ldots, LD; \quad t = 1, \ldots, T \tag{2}$$

In connection with the relevance of loads, constraint (3) determines that a specified number of high importance loads (X) must be restored before starting to restore the first low importance load.

$$\sum_{t=1}^{T} \sum_{bu=1}^{BU} \sum_{ld \in HI}^{LD} \alpha_{ld,bu,t} \geq \sum_{t=1}^{T} \sum_{bu=1}^{BU} \sum_{ld \in LI}^{LD} \alpha_{ld,bu,t} + X \tag{3}$$

In addition, the restoration status variable $\alpha_{ld,bu,t}$ is 1 when the load is completed served again. It is modeled in (4), where the load shedding status variable ($u_{ld,bu,t}$) is equal to 1 when $LS_{ld,bu,t}$ is zero and 0 otherwise.

$$\begin{aligned} u_{ld,bu,t} - u_{ld,bu,t-1} &\geq \alpha_{ld,bu,t}, bu = 1, \ldots, BU; ld = 1, \ldots, LD; \tau_{ld,bu,t} \\ &\geq ord(t) - M^{*} u_{ld,bu,t}, \quad bu = 1, \ldots, BU; ld = 1, \ldots, LD; \quad t \\ &= 1, \ldots, T \; t = 1, \ldots, T \end{aligned} \tag{4}$$

The difference in the formulation of this model, compared to others available in the literature, is that it encompasses a social point of view. As can be seen in (1), the objective function is developed to make it more important that all system loads are restored to leave the least number of users without electrical service. This objective function makes it more costly when a load increases the amount of time it is not restored. This can be explained with a simple example. In a small system, there are two loads to restore. For the first scenario, the first load is restored after 2 h, and the second at 10 h. The total restoration based on (1) will be 58 h (3 h that corresponds to the first load and 55 for the second load). Suppose then that in scenario 2, both charges are restored at 5 h after the blackout has started. For this scenario, the value of the target function (1) will be 30 h (15 and 15). However, when comparing the two scenarios, it can be seen in the first that the last load is restored after 10 h of the blackout, and in the second scenario the last charge is restored after 5 h. As you can see, this second scenario seeks a more equitable restoration process.

This differentiates the current proposal from others where the efficiency of the system is prioritized to social demands. In most of the electrical systems, in cases of blackouts, heuristic techniques are applied based on previous experiences. These techniques consist of starting the reestablishment of the plants considered more efficient to start-up (generally hydraulic plants due to their black start capacity). From the start-up of these plants, the surrounding areas are fed and the whole system is gradually re-energized. However, these solutions may represent solutions that cause inequalities in the populations. For example, a burden corresponding to the consumption of a very large population may be reestablished, and close to this burden is the consumption of a small rural population. Many times the heuristic solution does not contemplate the restitution of the rural population, at that moment, because it considers the efficiency of the system or the cost of starting up the system. These problems often occur in systems with high vertical and traditional development [16]. Many times the development of electrical systems can lead to social inequalities if these aspects are not considered [17].

2.2. Load shedding model

This single objective function (5) determines the minimization of the load shedding ($LS_{ld,bu,t}$). The goal of the function is reducing to zero the demand for electricity that is not met due to a blackout.

$$\min f_2 = \sum_{t=1}^{T} \sum_{bu=1}^{BU} \sum_{ld}^{LD} LS_{ld,bu,t} \tag{5}$$

However, the variable load shedding is limited by bounds as is shown in (6).

$$\underline{LS_{ld,bu,t}} * \left(1 - u_{ld,bu,t}\right) \leq LS_{ld,bu,t} \leq \overline{LS_{ld,bu,t}} * \left(1 - u_{ld,bu,t}\right), \quad bu = 1, \ldots, BU; ld = 1, \ldots, LD; t = 1, \ldots, T \tag{6}$$

Besides, constraint (7) ensures that once the load ld is restored, their service is kept during the rest of the programming horizon. It avoids fluctuations in the power system.

$$\sum_{t=1}^{T}\alpha_{ld,bu,t}\leq 1,\quad bu=1,\ldots,BU;ld=1,\ldots,LD;t=1,\ldots,T \tag{7}$$

2.3. The generating cost model

The goal of this single-objective function is the minimization of the total generating cost (8). The objective function implies the sum of the variables that denote the power output of the vast majority sources, at the global level. They are thermal units with natural gas, thermal units with different fossil fuels, hydropower units, photovoltaic (PV) generation, nuclear plants, wind generators, and lower widespread renewables. All power outputs are affected by the associated generation costs. Regarding generating units, i is the set that corresponds to the generators, and I is the total amount of generators.

$$\min f_3=\sum_{bu=1}^{BU}\sum_{t=1}^{T}\sum_{i=1}^{I}p^{g}_{i,bu,t}\delta^{g}+p^{ng}_{i,bu,t}\delta^{ng}+p^{h}_{i,bu,t}\delta^{h}+p^{n}_{i,bu,t}\delta^{n}+p^{w}_{i,bu,t}\delta^{w}+p^{pv}_{i,bu,t}\delta^{pv}+p^{r}_{i,bu,t}\delta^{r} \tag{8}$$

Constraint (9) establishes the bus balance for the time t. Where the sum of the produced power, the flows of entering power (to bus bu_i through lines), and the load shedding is equal to the sum of loads, the leaving power flows (from bus bu_o to other buses trough lines), and consumptions of generators that do not have the black-starting capacity. The convention sign establishes as positive transmitted power flows that enter the bus, and negative the flows that leave the bus.

$$\sum_{i=1}^{I}p_{i,bu,t}+\sum_{bu\_i=1}^{BU}f\_l_{bu\_i=bu,bu\_o,t}+\sum_{ld=1}^{LD}LS_{ld,bu,t}=\sum_{ld=1}^{LD}c_{ld,bu,t}+\sum_{bu\_o=1}^{BU}f\_l_{bu\_i,bu\_o=bu,t}+\sum_{i=1}^{I}ST_{i,bu,t}$$
$$bu=1,\ldots,BU;bu\_i=1,\ldots,BU;bu\_o=1,\ldots,BU;t=1,\ldots,T \tag{9}$$

Spinning reserve constraint (10), which is the available but uncharged power (R_t), is implemented to respond within a few minutes supply in front to possible issues in the generation.

$$R_t\leq\sum_{bu=1}^{BU}\sum_{i=1}^{I}p^{max}_{i,bu,t}-\sum_{bu=1}^{BU}\sum_{i=1}^{I}p_{i,t},\quad t=1,\ldots,T \tag{10}$$

Besides, each generator has a power output bound. It is determined by (11). The value of $a_{i,bu,t}$ is 1 if the unit is online and 0 otherwise.

$$p^{min}_{i,t}*a_{i,bu,t}\leq p_{i,bu,t}\leq p^{max}_{i,t}*a_{i,bu,t},\quad i=1,\ldots,I;bu=1,\ldots,BU;t=1,\ldots,T \tag{11}$$

Constraint (12) determines the value of the necessary power that the generator i requires to start-up. To achieve this objective the binary variable $y_{i,bu,t}$ is implemented. Its value is 1 when the generator starts up, and otherwise 0 (behavior of the variable is detailed in Ref. [18]). If the unit has the black-starting capacity, the value of the parameter $ST^{demand}_{i,bu}$ is 0 (MW).

$$ST_{i,bu,t}\geq ST^{demand}_{i,bu}-M\left(1-\ y_{i,bu,t}\right),bu=1,\ldots,BU;i=I,\ldots,BU;t=1,\ldots,T \tag{12}$$

The value of variable $y_{i,bu,t}$ is determined in (13):

$$a_{i,bu,t}-a_{i,bu,t-1}\geq y_{i,bu,t},bu=1,\ldots,BU;i=I,\ldots,BU;\ t=1,\ldots,T \tag{13}$$

Each type of generation technology has its different characteristics. In connection with the main generation technologies, in terms of the global energy shares, nuclear reactors can operate in the base-load or load-following modes. Wind generation depends on the forecasts. Photovoltaic generation depends on the sunlight and radiation, and the production of hydropower plants is related to the volume of the reservoirs. In this regard, in the following subsections the two main technologies that are involved in the system restorations processes are described.

2.3.1. Thermal generation for the system restoration

The initial status specifies the number of hours that a thermal generator has been working or in off status before the first period of the programming horizon. The aforementioned constraints influence the value of the binary variable $a_{i,bu,t}$ and they are presented in (13) and (14). If the value of $T^{ini}_{i}>0$, the parameter specifies the number of hours that the thermal unit i was working before the first period of the programing horizon. Likewise, when $T^{ini}_{i}>0$, the parameter specifies the number of hours that the generator was in off status.

$$a_{i,bu,t}=0\quad\forall i:T^{ini}_{i}<0;\quad t=1,\ldots..\left(TSD_{i,bu}+T^{ini}\right) \tag{14}$$

$$a_{i,bu,t}=1\quad\forall i:T^{ini}_{i}>0;\quad t=1,\ldots..\left(TSU_{i,bu}-T^{ini}\right) \tag{15}$$

The *minimum up (or down) time* is a constraint that specifies the number of hours that a thermal unit must continue working (or offline), after that it has been turned on (or off). They are imposed by (16–19):

$$a_{i,bu,t}-a_{i,bu,t-1}\leq a_{i,bu,t+j},i=1,\ldots\ldots I;t=2,\ldots\ldots T;j=1,\ldots\ldots(TSU_i-1);$$
$$bu=1,\ldots,BU \tag{16}$$

$$a_{i,bu,1}\leq a_{i,bu,1+j},\quad\forall i:T^{ini}_{i}<0;\quad j=1,\ldots..(TSU_i-1);bu=1,\ldots,BU \tag{17}$$

$$a_{i,bu,t+j}\leq a_{i,bu,t}-a_{i,bu,t-1}+1,\ldots..i=1,\ \ldots\ldots I;t=2,\ \ldots\ldots T;j=1,\ \ldots\ldots(TSD_i-1);\ bu=1,\ldots,BU; \tag{18}$$

$$a_{i,bu,1+j}\leq a_{i,bu,1}\quad,\quad\forall i\ /\ T^{ini}_{i}>0;\ j=1,\ \ldots\ldots(TSD_i-1);bu=1,\ldots,BU \tag{19}$$

The ramp constraints (20–21) are imposed to avoid potential unit damages because of excessive increases or decreases in the levels of power generations.

$$p^{g}_{i,bu,t-1}-DRT_ia_{i,bu,t}-SDT_i\left(1-a_{i,bu,t}\right)\leq p^{g}_{i,bu,t};\ i=1,\ \ldots\ldots I;t=2,\ \ldots\ldots T;$$
$$bu=1,\ldots,BU \tag{20}$$

$$p^{g}_{i,bu,t}\leq p^{g}_{i,bu,t-1}+URT_ia_{i,bu,t-1}-SUT_i\left(1-a_{i,bu,t}\right)\quad,i=1,\ \ldots\ldots I;t=2,\ \ldots,T;$$
$$bu=1,\ldots,BU \tag{21}$$

Besides, the variable start-up cost is included, and it is influenced by several technical factors. The number of hours that the generator has been working (or offline) before the generator is turned on (or off) is the main factor. If the off status value is lower than $TSD_i+cold\_t_i$, the start-up cost is calculated as the hot-start value H_SU_i .On the other hand, If the off status value is higher, the start-up cost is calculated under the cold start value. Hot start-up conditions are modeled in (22–23). The cost is obtaining by multiplying the power output and the conversion factor.

$$\left(a_{i,bu,t} - a_{i,bu,t-1}\right)H_{SU\ i} \leq p^{g}_{i,bu,t}c_{SU\ i,bu}, \quad i=1,\ \ldots,I;t=2,\ldots,T;bu=1,\ldots,BU \tag{22}$$

$$a_{i,bu,1}H\_SU_i \leq p^{g}_{i,bu,t}c\_SU_{i,bu}, \quad \forall i : T_i^{ini} < 0 \tag{23}$$

Similarly, the *cold start cost* constraints are represented in (24) and (25) as follows:

$$\left(a_{i,bu,t} - \sum_{j<TSD_i+T_i^{cold}+1} a_{i,bu,t-1}\right)Cold\_SU_i \leq p^{g}_{i,bu,t}c_{SU\ i,bu}, \quad i=1,\ldots,I;t=2,\ldots,T; \\ bu=1,\ldots,BU \tag{24}$$

$$\left(a_{i,bu,t} - \sum_{j<t} a_{i,bu,t-j}\right)Cold_{SU\ i} \leq p^{g}_{i,bu,t}c_{SU\ i,bu} \quad , \quad \forall i \\ : T_i^{ini} < 0; (TSD_i + cold\_t_i + 1) < t \leq (TSD_i\ + cold\_t_i) \tag{25}$$

In some situations, there are shut-down costs. In this situation, constraints (24–25) are rewritten but applied to the shut-down costs. A full description can be observed in Ref. [19].

2.3.2. Hydropower generation for the system restoration

The hydropower generation is modeled in (26), based on [20]. In the equation, $WD_{i,bu,t}$ is the variable of water discharge, $h_{i,bu,t}$ is the variable that represents the hydraulic head. Besides, there are some factors of efficiency: $\mu\_g_i^h$ is the electric generator coefficient (with values between 0.92 and 0.97), μ_s^{turb} is the hydraulic turbine coefficient (with values between 0.75 and 0.94), and $\mu\_\mathrm{cp}_i^h$ is the mechanical efficiency coupling coefficient (with values between 0.95 and 0.99).

$$p^{h}_{i,bu,t} = 9800\frac{WD_{i,bu,t}h_{i,bu,t}\mu^{h}_{\mathrm{g}\ i}\mu^{h}_{\mathrm{turb}\ i}\mu^{h}_{\mathrm{cp}\ i}}{1*10^6}, \quad i=1,\ \ldots,I;t=1,\ \ldots,T;bu \\ = 1,\ldots,BU \tag{26}$$

The water volumes of the reservoir are important because the hydropower generation depends on them. In this regard, the constraints (27–28) determinate the values of the reservoirs. They include the variables of turbined water flow, along with factors of river inflow (or outflow) for the upper (or lower) reservoirs. The case considers an ideal case where each hydropower plant is composed of one generator. The constraint must be adequate for the cases that a power plant is composed of a higher amount of turbines.

$$r^{up}_{i,bu,t} = r^{up}_{i,but-1} + \delta^{up}_{in} + \delta^{up}_{out} - WD_{i,bu,t} \quad , \quad i=1,\ \ldots,I;t=1,\ \ldots,T;bu \\ = 1,\ldots,BU \tag{27}$$

$$r^{lo}_{i,bu,t} = r^{lo}_{i,bu,t-1} + \delta^{lo}_{in} + \delta^{lo}_{out} + WD_{i,bu,t}, \quad i=1,\ \ldots,I;t=1,\ \ldots,T;bu \\ = 1,\ldots,BU \tag{28}$$

Constraint (29) guarantees the energy reserve in the form of water for the next programming horizon.

$$r^{up}_{i,bu,t=T} \geq r^{up}_{i,bu,t=1} \tag{29}$$

To maintain a MILP model, constraints (26) must be linearized. The implemented technique is detailed in Ref. [21]. The model considers the head variation over the programming zone, along with the net head changes that influence power generation. The linearization technique is based on a three-dimensional interpolation method that denotes the operating function of each turbine.

2.3.3. Transmission line restoration

The power flow is modeled by using the AC power flow model [22]. In (30), the real power transmitted between bus bu_i to bus bu_o is represented.

$$f\_l_{bu\_i,bu\_o,t} = V_{bu_i}\sum_{bu_o=1}^{BU}V_{bu_o}\left(ss_{bu_i-bu_o}Cos\theta_{bu_i-bu_o,t} + cd_{bu_i-bu_o}Sin\theta_{bu_i-bu_o,t}\right) \\ bu_i=1,\ \ldots,BU;bu_o=1,\ \ldots,BU;t=1,\ \ldots,T \tag{30}$$

Besides, the constraint (31) model the reactive power flow that is transmitted between bu_i and bu_o.

$$f\_l\_q_{bu\_i,bu\_o,t} = V_{bu_i}\sum_{bu_o=1}^{BU}V_{bu_o}\left(g_{ij}Sin\theta_{bu_i-bu_o,t} - b_{ij}Cos\theta_{bu_i-bu_o,t}\right), bu_i=1,\ \ldots, \\ BU;bu_o=1,\ \ldots,BU;t=1,\ \ldots,T \tag{31}$$

The major drawback of this AC model is the computational requirement to solve it. Consequently, the DC power flow model is developed based on the AC model to reduce the computational effort and maintain the MILP characteristic of the formulation. The DC model is detailed in Ref. [23].

3. Multi-objective model

The next multi-objective model considers single objective functions (32). In this generic formulation, x represents a vector of decision variables and FS is the feasible solution region (33).

$$\min f(x) = [f_1(x), f_2(x), f_3(x))] \tag{32}$$

$$s.t. \quad c(x) \leq 0, \quad x \in FS \tag{33}$$

Multi-objective problems have replaced the classical optimality concept by the called Pareto optimality [24]. When this idea is taken into account, classical methods reveal that if a single-objective solution is enhanced, the solutions of the other objectives can get worse. The majority of the multi-objective methods can be divided into two categories: *preference* and *generating* methods. The first category groups the great majority of these methods. They pay attention to a singular objective in front of the rest. The main drawback of this category is the high level of subjectivity that the operators of the system can handle. By contrast, the called *generating* methods comprise the epsilon-constraint methods (EC, [25])and weighting methods. The EC method is composed of a single objective function and the rest objective ones are included in the formulation as constraints. The main difference between EC and weighing methods is that the last one considers an objective function that will be obtained by merging all objective functions with the implementation of weighted coefficients (the procedure is described in Ref. [26]). Besides, some differences between the two methods have been investigated in Ref. [27]. They are i) EC methods reach efficient solutions within the whole Pareto frontier in linear problems, by contrast, the weighting method only reaches these solutions at the extremes. ii) The EC methods can reach non-supported solutions at multi-objective integer models or multi-objective mixed integer models. iii) The scaling of the objective functions can be a problem for the weighting methods. However, this is not required in EC problems.

As a result of the aforementioned statements, the EC method is selected to address the multi-objective problem of power restoration. The feasible region of solutions could turn into a complicated mission. The most extended option, and the selected one for this paper, is the development of the called payoff table. The table is composed of the results that were obtained from the individual resolution of the single-objective functions. The satisfactory performance of the EC method only is obtained if the range of each single-function is presented. The multi-objective EC problem, in terms of the proposed paper (three single-objective functions), is formulated below in (34). Where f_1, f_2, and f_3 are the single-objective functions previously defined in Section 2.

$$\begin{array}{l} \min f(x) = f_1(x) \\ s.t. \quad f_2(x) \geq \varepsilon_2 \\ f_3(x) \geq \varepsilon_3 \\ x \in FS \end{array} \tag{34}$$

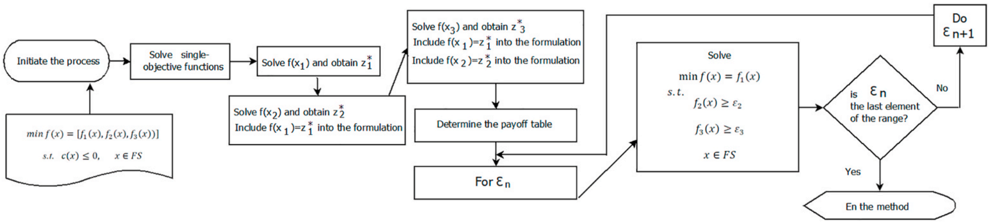

Fig. 1. Flowchart of the multi-objective method.

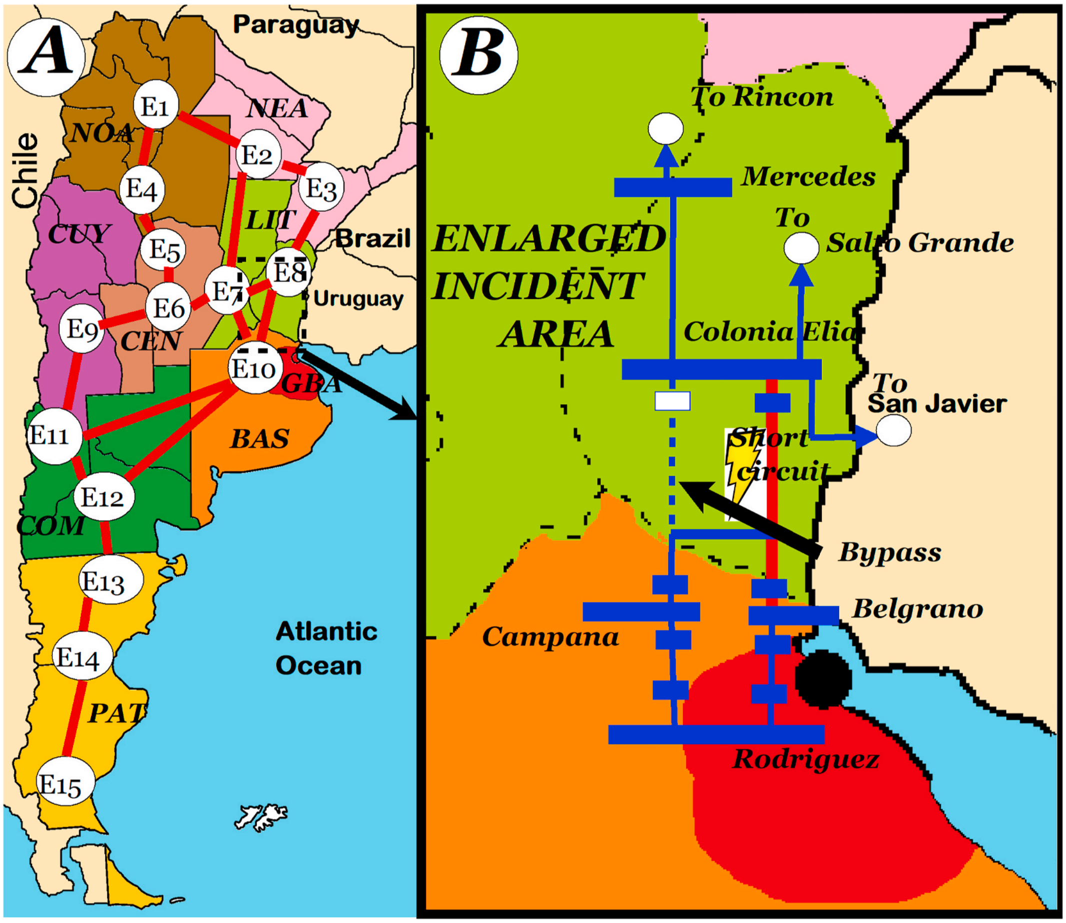

Fig. 2. **A.** SADI one-line diagram. **B.** Area of the incident on 16 June 2019.

The lexicographic procedure ([28]) is applied to reach solutions by applying the EC method. It is performed in a few steps, which are described in the flow chart of Fig. 1.

4. Test cases

The effectiveness of the model is tested the blackout occurred in the Argentine Electric System (called SADI due to its name in Spanish) on 16 June 2019. Technical data of the SADI during this year can be found in Refs. [29,30]. The system produces the necessary power to cover the demand of the whole population of the county (more than 40 million people). Also, SADI trades power with neighboring countries. The system is composed of nine electrical regions: Litoral (labeled as LIT), Noreste (NEA), Gran Buenos Aires (GBA), Comahue COM, Cuyo (CUY), Buenos Aires (BAS), Noroeste (NOA), Patagonia (PAT), and Centro (CEN). The structure of the system is performed by many actors. There are over a hundred of generation companies (called GENCOs), only one transmission operator of the high voltage lines (TRANSCO), along with more than 70 distribution companies (DISCOs). The one-line diagram of the system, along with the nine electrical regions and the 500 kV structure, is illustrated on the Argentine map in Fig. 2A. The system is composed of 15 main buses (labeled from E1 to E15), and each bus has 10 main loads. The data for the system is based on [31] and details about the restoration process of the SADI is detailed in Ref. [32].

The models are programmed using the software GAMS with a Pavilion DV7 notebook of Pavilion DV7, with a 1.4 GHz AMD processor AMD and 8 GB of RAM.

4.1. *The Argentine System. A brief blackout analysis*

Based on the official report [33], at 7:06 a.m. on 16 June 2019, the power demand of the Argentine System was about 13,200 MW. In this regard, the Noroeste region was contributing by generating 2600 MW. The transmission of this power flow was being transmitted throughout the line that connected two cities: Colonia Elía city and Belgrano city. The TRANSCO (Transener) was performing maintenance tasks in the zone for two months before. As a result, a bypass connection was performed between the lines Colonia Elía-Campana and Colonia Elía-Belgrano. It meant the unavailability of the first line. Early in the morning of this day, thunderstorm activity was produced in the area.

A short circuit was produced due to climatological conditions on the remaining line (Colonia Elía–Belgrano) at 7:06:22. After 0.9 s, the extremes of the line were opened. The area of the incident was marked in Fig. 2A and the details of the short circuit were enlarged and illustrated in Fig. 2B. The operation of generation shedding of the hydropower plant of Yacyretá was not accomplished because the modification due to the bypass in the line not was included in the configuration of the TRANSCO. The remaining action to increase the frequency and save the system was the load shedding. This action depended on the 74 DISCOs. But, only 5 of these companies fulfilled the task in the right way. Aggravating the situation, many GENCOs took their units out of service before the time that was previously accorded for these situations (30 s). The combination of all these problems led the system to total collapse. When the restoration maneuvers began, the last load was restored after more than 14 h. It can be observed many human failures due to the Transener maneuvers along with non-correct maneuvers from the GENCOs and DISCOS. Some GENCOs also failed in the black start that increased the restoration time. The planning and operation of the TRANSCO fail in several aspects, not only in a wrong topographic configuration that did not consider the effects of the Colonia Elía bypass but in the transmission during the restoration.

4.2. The Argentine System process restoration with the novel strategy

With similar reasoning of the previous case, the objective function is the total time restoration. And the functions affected by the epsilon values are the load shedding and the total cost. The problem considers 1 h as preparation time after the blackout has occurred. This hour includes the time to fix the damages produced, contemplates the minimum shutdown of the fastest generators after leaving service, and the coordination of the restoration maneuvers. Due to the computational effort required to solve the system by its scale, a lower amount of iterations that the previous case is performed.

The model to be solved at each iteration is composed of 91,950 single equations, 65,977 single variables, and 32,400 binary variables. Fig. 3A shows the generation and load shedding profile of the recommended solution.

It is important to note again that the solution values of almost 4000 h for the restoration process do not mean that it takes that many hours to restore the entire system, but rather that it is the sum of the hours that it takes for all the loads to be restored. This value also includes the penalty that the target function does for every hour that each load goes by without being restored, which is why the value of the target function increases exponentially.

In this regard, all possible solutions are shown in Fig. 3B. To obtain an appropriate spectrum of solutions, 38 iterations are performed and the total CPU time is 24 min. The recommended solution has a total restoration value of 489 h, 52,000 MW of the total load shedding, and 16 million USD of the total cost. This recommendation is made based on try to keep a low number of the total restoration time, due to the social purpose of prioritizing the welfare of the population. Also, as shown in the curve, the fact of reducing the restoration time by only a few hours exponentially increases the total cost values. This turns it virtually unjustifiable to try to reduce the amount of restoration time. The last loads to be restored are the ones located in buses E10 and E11 due to the low amount of generators with the black start capability that there are in these regions. The loads are completely restored 12 h after the blackout.

5. Analysis and discussion of results

In this section, the results of the test cases will be studied in detail. The differences between the presented model and other approaches available in the literature will be studied. From the two test cases, the second one will be more detailed because it is best suited for the selected target of this proposal, which is composed of the operators of very large scale systems. This is the case of the Argentinean system that is operated by an Independent System Operator named CAMMESA. However, the model can be extended to other operators that handle large systems in different countries. As for the Argentinean power system (SADI), Fig. 4A shows the most important thermal generation amounts per bus in the country, in terms of quantity produced. It is considered the solution recommended in section 4.2.2. The graph shows the 10 largest generations of the system. When the generators have an important installed power, they are individualized as it is the case of the generator number 2 of Villa Gesell thermal power station, or the G2 of Mar del Plata thermal power station. In the rest of the cases, the units are grouped by bus because they have a lower capacity. When the number of generators is very big, several groups are organized on the same bus. The largest case is the E10 bus that has 6 groups of thermal generators. Several of these generators of the figure have the capacity of black starts. As for the graph, it is observed that most of the thermal generators produce electricity during the first 4 h of the blackout, to energize the generators that require power from the network to start. Then the thermal generation activity decreases and increases again between 12 and 22 h, coinciding with the demand peaks.

At the same time, Fig. 4B shows the top 10 amounts of hydraulic

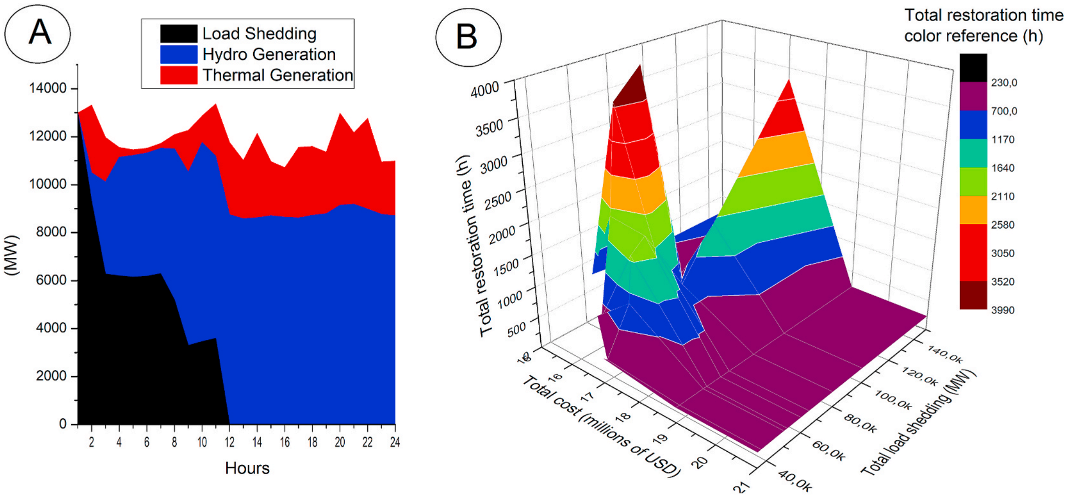

Fig. 3. **A**. Argentine system blackout profile. **B**. Result curve of multi-objective problem.

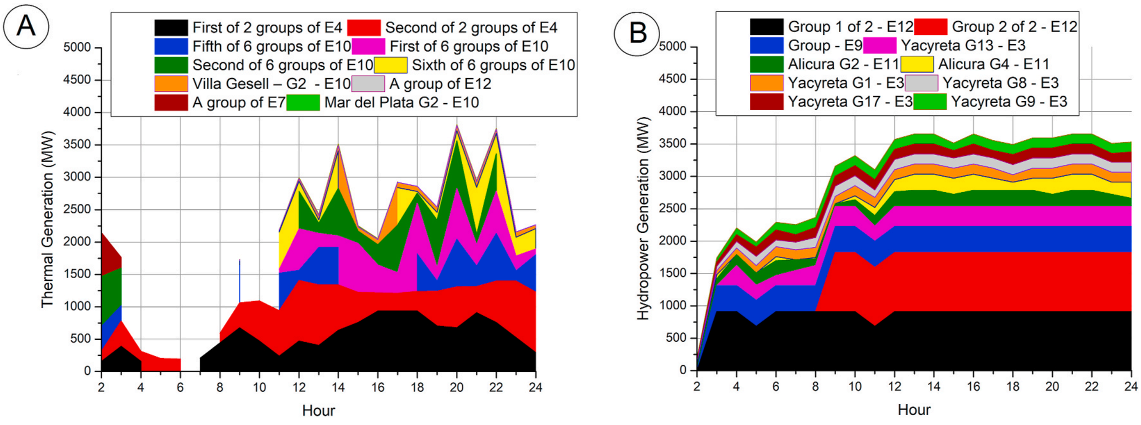

Fig. 4. **A**. Argentine system. Thermal generation profile. **B**. Argentine system. Hydropower generation profile.

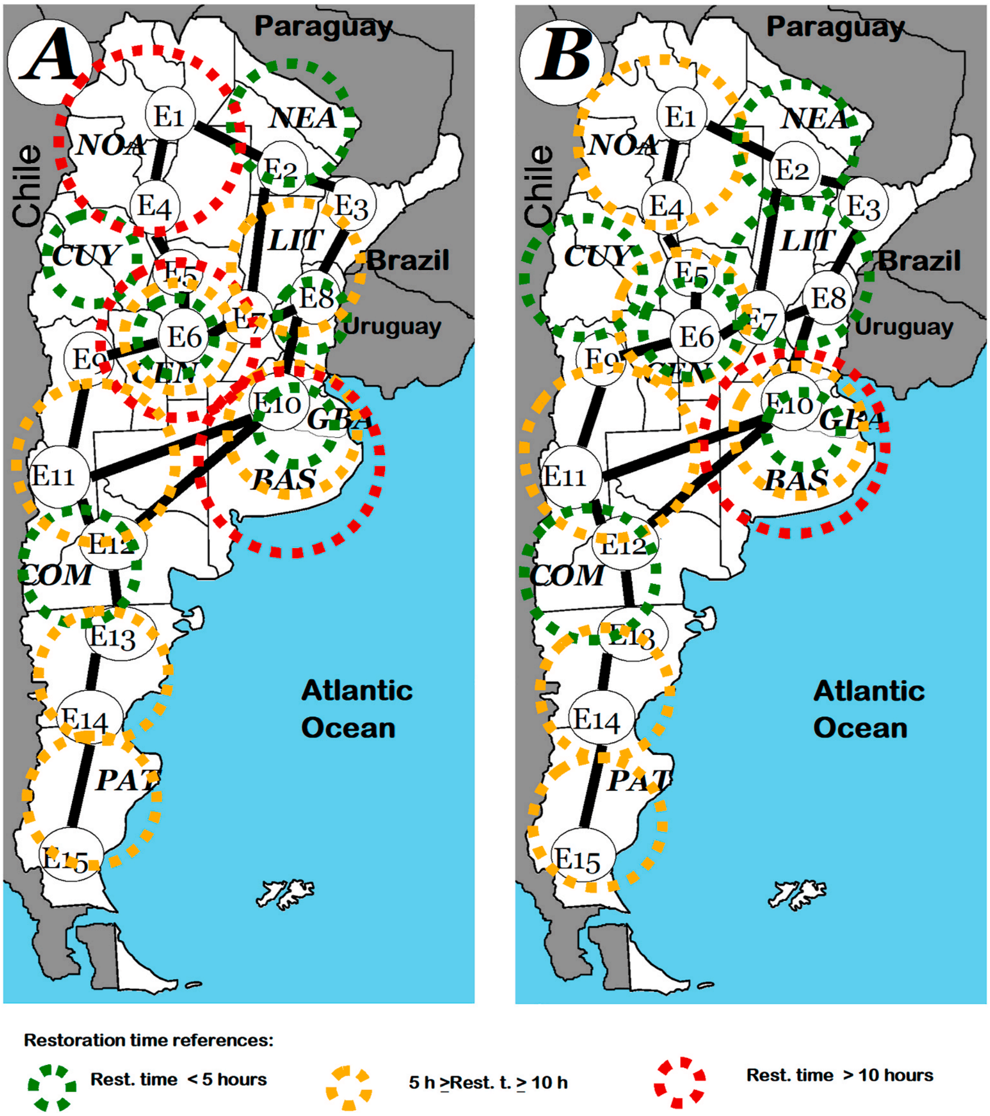

Fig. 5. **A**. The original restoration process. **B**. Restoration based on the new proposal.

source generation for the system. In the first place of production are the smaller generator groups of the buses E12 and E9 (the three groups shown in the image total 43,066 MWh). And in terms of individual generations, the generators of the Yacyreta power plant stand out (the five shown total 18,714 MWh) and two generators of the Alicura power plant (total 7401 MWh). It is important to mention that although there are other generation sources in the system, these are not enabled to be used in the system restoration process. In some cases, this is because the process to dispose of the sources after a blackout is long, as in the case of the two nuclear power plants in the country. Or also because they are not accepted by the operators to coordinate a restoration due to their intermittence, as is the case of wind generation. However, the novel mathematical model supports all these sources for restoration in case they are applied to systems where these technologies are supported. Regarding line restoration, the required restoration establishes two levels of priority: level 1 which requires restoration from the first hour that the units start, and level 2 which implies a secondary level of importance in the restoration. This means that these lines may not be restored within the first hour of the start of the restoration, and the system may still be stable. This list determined from the recommended solution is in concordance with the maneuvering procedure established for the SADI in Ref. [32].

Similarly, Fig. 5A shows the original restoration process that took place in 2019. In the figure, the green circles indicate that in these areas the services were established in less than 5 h, in orange they were restored in more than 5 h and less than 10, and finally, the red circles indicate that these areas were restored in more than 10 h. As shown in the figure, there were 3 red zones with restoration times of more than 10 h, NOA, CET, and BAS zones. These reasons were since they are areas with a large population and because not enough machines with black start were operated to reduce downtime.

On the other hand, Fig. 5B shows the restoration process with the proposed solution based on the multi-objective model. As can be seen, the areas with red circles are smaller, and this means that more people have received their electrical service faster. This is crucial because many people can be seriously affected if the electrical service takes too long to be restored. Indeed, many people are electro-dependent in their homes, there are stocks of medicines that can be rendered useless if the cold chains are broken, and a similar situation occurs with food that needs refrigeration. In the figure, only the GBA area has places where it takes more than 10 h to restore service, it occurs mainly due to the lack of black start units.

6. Conclusion

This paper develops a novel method to restore power systems after blackouts, considering a multiple objective function problem from a point of view of the impact on its entire population. The paper combines new formulations as the total restoration time, which favors an equitable way to restore the system, with mixed linear models that reduce the computational time, and lexicographic optimization. The benefits of this combination distinguish the novel proposal from the other restoration techniques available in the literature. Finally, the proposed method is tested in the real case of the blackout of the Argentine system in 2019. The situation of this blackout is carefully recreated to study the method under real conditions.

As for the real case, from the comparison of results between the solutions obtained and the historical restoration process performed during 2019 due to the great blackout, several analyses can be derived. The evaluations indicate that the actual response to the restoration was good. It must be considered that a similar situation never occurred in the country, which required the restoration of the entire system. Although simulations are periodically carried out to deal with situations such as this, when the pre-established solutions are applied in practice, unexpected events or events not originally contemplated in the simulation may occur. This is why the real results are considered satisfactory. Especially, when compared to the time it took other countries to solve similar situations when population and topography equivalencies are established. However, the approach proposed in the present work tends to improve this response to a massive blackout, offering other solutions to those obtained by heuristic methods, thanks to the capacity that the proposed model has to explore all the solutions as a consequence of the advantages of the linear integer mixed models.

Results indicate that the Argentine system can be completely restored 3 h before the reported results by using conventional maneuvers. This is due to the difference in formulation between the proposed model and the rest of the classical approaches in the literature. The present model penalizes when the hours in which the service has not been restored in some loads are important, unlike the classic models where the search for solutions based on the efficiency of the system is focused. Although the new model proposes different solutions from the conventional ones, to achieve greater equality among users, the obtained solutions satisfy all the constraints inherent in real systems. In fact, the reported solutions satisfy constraints of minimum times of generators, ramp conditions, flow limits in the lines, minimum maneuvering times, demand for units that do not have black starting, in addition to other technical limitations. Besides, the proposed model can be extended to other systems thanks to the versatility of its formulation.

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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