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Robust Static Transmission Expansion Planning Considering Contingency and Wind Power Generation

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Abstract

This paper proposes a framework based on the Benders decomposition to obtain a scenario-based robust static transmission expansion planning by considering N-1 security criterion, transmission losses and uncertainties in wind power generation. The model is solved by a bi-level approach that seeks to minimize investment cost as well as penalty costs of wind spill and load curtailment. The wind uncertainty is modeled by grouped historical wind series through k-means clustering technique maintaining the wind correlation between different geographic regions. Case studies are performed in the well-known power systems: IEEE-RTS 24-bus test system and an equivalent Brazilian Southern 46-bus system. In addition, a detailed tutorial case is also presented with a modified version of Garver 6-bus test system.

Keywords Transmission expansion planning · Transmission active losses · Benders decomposition · N-1 security criterion · Wind power uncertainty · k-means clustering algorithm

List of Symbols

Subscripts and Superscripts

i	System bus
ij	Branch between terminal buses i and j
kij	Transmission line in branch ij
c	Operational state
w	Wind scenario
s	Iteration number

Variables

pg_{iwc}	Active power generation at bus i, scenario w and state c (MW)
rd_{iwc}	Load shedding at bus i, scenario w and state c (MW)
rw_{iwc}	Wind spilled at bus i, scenario w and state c (MW)
θ_{ijwc}	Angular difference between terminal buses i and j in scenario w and state c (rad)
f^E_{kijwc}	Active power flow of existing line k in branch ij, for scenario w and state c (MW)
f^C_{kijwc}	Active power flow of candidate line k in branch ij, for scenario w and state c (MW)
Φ_{iwc}	Active power flow coming out of the bus i through the lines connected to it for scenario w and state c
L_{kijwc}	Half of active losses of line k in branch ij, for scenario w and state c (MW)
S_{kijwc}	Sensitivity of candidate line k in branch ij, scenario w and state c ($)
OBF_{wc}	Objective function value in scenario w and state c ($)
IC	Investment cost ($)
X_{kij}	Expansion decision (binary variable) for reinforcement in line k in branch ij
λ_{iwc}	Lagrange multiplier of power balance constraint at bus i for scenario w and state c ($/MW)

Parameters

$\overline{pg}_i$	Active power generation capacity at bus i (MW)
pw_{iw}	Sampled generation from wind farm at bus i and scenario w (MW)
d_i	Active demand at bus i (MW)
b_{kij}	Susceptance of line k (℧)
g_{kij}	Conductance of line k (℧)
$\bar{f}^E_{kij}$	Active power flow limit of existent line k (MW)
$\bar{f}^C_{kij}$	Active power flow limit of candidate line k (MW)
ce_{kij}	Investment cost of candidate line k in branch ij ($)

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N_W Number of wind scenarios
N_L Number of operational states, including the base case and contingencies

Sets

B System buses
E Existing lines
C Candidate lines
Ω_i^E Existing lines connected to bus i
Ω_i^C Candidate lines connected to bus i
L Operational states
W Wind scenarios

1 Introduction

The goal of the Transmission Expansion Planning (TEP) is to guarantee the best electricity service to consumers with minimal investment considering technical, environmental and social criteria. There are recent challenges for TEP (Lumbreras and Ramos 2016b): deregulation of electrical markets; massive penetration of renewable energy; large-scale generation projects; market integration; regional planning; and long permitting process. Due to the necessity of a diversified energy matrix and the reduction in the use of fossil fuels, renewable energy sources are growing in the world as they are less polluting and have a low environmental impact (Qazi et al. 2019).

From the modeling point of view, TEP has been performed by using AC and DC models. The AC model is able to incorporate voltage limits, stability constraints, reactive power profile and transmission losses (Gomes and Saraiva 2016). However, AC problem is commonly relaxed by using approaches based on the DC model to avoid nonlinearities through the linearization of the second Kirchhoff's law; however, the standard linearized approach does not include transmission losses. dos Santos and Diniz (2011) present a new Dynamic Piecewise Linear Model (DPLM) to represent DC transmission losses during the optimization process; however, the DPLM cannot be used in TEP problems because it requires high computational burden. Also, authors compare the DPLM with a faster iterative process widely used in TEP problems (Assis et al. 2018; Poubel et al. 2015), and conclude that the global solution of a schedule problem may not be found if the iterative process is considered. Moreover, neither the DPLM nor the commonly used iterative process in the literature are able to ensure the flow limit in both directions of a line. In de la Torre et al. (2008) TEP is modeled as a Mixed-Integer Linear Programming (MILP) problem considering active transmission losses; however, the model also presents the problem associated with the flow limit. In order to overcome it, the present paper introduces a modified iterative process to solve the Optimal Power Flow (OPF) problem in reasonable computational time considering transmission losses and respecting the capacity of lines.

Uncertainties have been considered in TEP problems in order to model demand growth, production capacity increase, equipment availability, and variability of demand and renewable power sources. Deterministic approaches are unable to deal with uncertainties once all problem variables are modeled as known values; thus, stochastic and robust approaches have been employed to deal with uncertainties.

Stochastic TEP approaches obtain expansion plans that reach the optimal average of all sampled scenarios from probability distributions or uncertainty sets. Orfanos et al. (2013) merge the Benders Decomposition (BD) and Monte Carlo algorithms to solve the TEP considering forced outages of transmission lines, future load scenarios and correlated wind power generation capacities. These approaches accurately measure the system energy quality and random variables but imply high computational effort once, generally, a large number of scenarios is needed.

Non-deterministic robust optimization approaches have the advantage of considering the uncertainties with a simple polynomial uncertainty set (namely as robust sets), which is more simple to be modeled when the complete information about the probability distributions are not available. Robust optimization is a branch of optimization formulations that deal with problems in which the solution robustness level is sought. Examples of approaches based on robust optimization applied to the TEP problem can be found in Zhang and Conejo (2018) and Dehghan et al. (2018). However, these papers do not consider outage of lines or active line losses. Also, methodologies based on robust optimization applied to TEP problem, in specialized literature, only consider linear models.

In Moreira et al. (2015), a robust contingency-constrained TEP under generalized joint generation and transmission N-k security criteria is proposed and the model is approached by a tri-level methodology based on BD, but did not consider wind or load uncertainties. The deterministic security criterion, also known as N-k, ensures proper system operation even if k equipment interrupts simultaneously. The N-1 security criterion is commonly used in TEP models and guarantees system adequacy to any single equipment outage (Alizadeh-Mousavi and Zima-Bočkarjova 2016; da Silva et al. 2017).

A hybrid method is proposed in Baringo and Baringo (2018), in which authors presented a stochastic adaptive robust optimization approach to solve the TEP problem. On the one hand, short-term uncertainties (variability of demand and production of stochastic generation units) are modeled in a stochastic way. On the other hand, long-term uncertainties (future demand level and generation costs) are modeled by robust sets.

Authors in Yu et al. (2011) and Li et al. (2016) achieve robust TEP without using robust optimization concepts (Gomes and Saraiva 2019) or the commonly applied min–max–min cost model introduced in Jabr (2013). In these works, the robustness of the network is verified through a Monte Carlo Simulation to stress the grid with a wide range of scenarios. Yu et al. (2011) presented a robust TEP by using scenarios of wind and load generated by Taguchi's Orthogonal Array Testing (TOAT). However, the scenarios generated by TOAT are extreme and do not consider the correlation between stochastic variables. To overcome these issues, a scenario-based robust TEP is presented in Li et al. (2016) using Heuristic Moment Matching method to generate correlated wind power generation output; then, the results presented better performance in trade-offs between robustness and economy. All aforementioned papers model the robust TEP as a MILP problem without considering the electrical losses of the grid.

After this background, the present paper introduces a scenario-based robust static transmission expansion planning considering transmission losses, N-1 security criterion and wind generation fluctuation. The problem is modeled as a mixed-integer nonlinear programming (MINLP) problem and is solved by a bi-level formulation which consists in a MILP problem and a sequence of linear programming problems. In order to model the short-term uncertainties associated with the intermittent behavior of wind, it is applied in the k-means clustering algorithm in historical series of active wind power dispatch. The use of k-means is also applied in Baringo and Conejo (2013) and Zhang and Conejo (2018) and can accurately represent the correlation between the stochastic variables. Then, the main contributions of the paper are identified as follows:

– The introduction of a framework suitable to find a scenario-based robust static TEP considering the N-1 security criterion, uncertainties over wind generation, as well as the active transmission losses.
– The introduction of a modified iterative linearized optimal power flow that meets the active flow limit constraints in both directions of transmission lines.
– The analysis of the impact of renewable resources considering a realistic model of wind power generation, intermittent behavior and the correlation between different geographical regions through scenarios obtained by real historical data of wind farms operation.

The performance of the proposed scenario-based robust static TEP is verified by using the IEEE-RTS (Subcommittee 1979) and Brazilian southern (Monticelli et al. 1982) systems that are modified to include wind scenarios.

2 Scenario-Based Robust Static TEP Formulation

The complete formulation of the proposed methodology is presented in Eqs. (1)–(11). A static TEP (STEP) model is, in mathematical terms, a multi-objective, probabilistic, mixed non-convex search space and combinatorial problem with integer variables. These characteristics lead to a huge set of possible solutions and scenarios that, due to the required computational effort, make it impractical to evaluate them all within the acceptable time.

$$\min \left(\sum_{kij \in C} ce_{kij} X_{kij} + \sum_{i \in B} \sum_{w \in W} \sum_{c \in L} (rd_{iwc} + rw_{iwc}) \right) \tag{1}$$

subject to ($\forall\ i \in B,\ c \in L$ and $w \in W$):

$$f^E_{kijwc} = -b_{kij}\theta_{ijwc} + g_{kij}\frac{(\theta_{ijwc})^2}{2} \tag{2}$$

$$f^C_{kijwc} = X_{kij}\left(-b_{kij}\theta_{ijwc} + g_{kij}\frac{(\theta_{ijwc})^2}{2}\right) \tag{3}$$

$$\Phi_{iwc} = \sum_{kij \in \Omega^E_i} f^E_{kijwc} + \sum_{kij \in \Omega^C_i} f^C_{kijwc} \tag{4}$$

$$pg_{iwc} - \Phi_{iwc} + rd_{iwc} - rw_{iwc} = d_i - pw_{iw}\,[\lambda_{iwc}] \tag{5}$$

$$\left| f^E_{kijwc} \right| \le \bar{f}^E_{kij}, \quad \forall\, kij \in E \tag{6}$$

$$\left| f^C_{kijwc} \right| \le \bar{f}^C_{kij}, \quad \forall\, kij \in C \tag{7}$$

$$0 \le pg_{iwc} \le \overline{pg}_i \tag{8}$$

$$0 \le rd_{iwc} \le d_i \tag{9}$$

$$0 \le rw_{iwc} \le pw_{iw} \tag{10}$$

$$X_{kij},\ \text{binary}, \quad \forall\, kij \in C \tag{11}$$

Objective function (1) aims at minimizing load shedding and wind curtailment for all wind scenarios and operational states. The active power flows in existing and candidate lines for each state are evaluated by (2) and (3). The active power flow coming out from bus i through connected lines (existing and candidates) is represented by Φ_{iwc} in (4). The constraint in (5) models the active power balance at bus i related to the Kirchhoff's first law. The dual variable λ_{iwc}, associated with (5), is obtained through the iterative DC-OPF solution (see Sect. 2.1). The active power flow limit for existent and candidate circuits is limited, respectively, by (6) and (7). The limits of active generation, load shedding and wind spilled variables are modeled, respectively, by (8), (9) and (10). Finally, the constraint in (11) models the binary investment decision for every candidate line k of branch ij. In this formulation, the outage of any line is done by replacing it by a pseudo-line. A pseudo-line does not provide path for the power flow; it only guarantees the mathematical convergence of the optimization problem.

Considering the difficulty to solve such kind of complex programming as one problem, the proposed framework solves the MINLP using the BD approach, dividing it into two interconnected mathematical models. Also, to avoid the nonlinearities, the framework also considers the proposed iterative DC-OPF. The following subsections describe in detail the proposed framework.

2.1 Iterative DC Optimal Power Flow

The modified iterative DC-OPF in (12) aims to minimize the load shedding and the wind curtailment in the grid by the redispatch of controllable generators given an operational state c and a wind scenario w. The optimization process in (12) is repeated until $\theta^{(s)}_{ijwc}$ and $\theta^{(s-1)}_{ijwc}$ are close enough, where s is the current iteration number.

$$\text{OBF}_{wc} = \min \sum_{i \in B} (rd_{iwc} + rw_{iwc}) \tag{12}$$

subject to (4)–(5), (8)–(10) and:

$$L_{kijwc} = 0.5 \cdot g_{kij} \left(\theta^{(s)}_{ijwc} \cdot \theta^{(s-1)}_{ijwc} \right), \quad \forall\, kij \in E \cup C \tag{13}$$

$$f^{E}_{kijwc} = -b_{kij}\theta^{(s)}_{ijwc} + L_{kijwc}, \quad \forall\, kij \in E \tag{14}$$

$$f^{C}_{kijwc} = X_{kij} \left(-b_{kij}\theta^{(s)}_{ijwc} + L_{kijwc} \right), \quad \forall\, kij \in C \tag{15}$$

$$f^{E}_{kijwc} \le \bar{f}^{E}_{kij}, \quad \forall\, kij \in E \tag{16}$$

$$f^{C}_{kijwc} \le \bar{f}^{C}_{kij}, \quad \forall\, kij \in C \tag{17}$$

$$-f^{E}_{kijwc} + L_{kijwc} \le \bar{f}^{E}_{kij}, \quad \forall\, kij \in E \tag{18}$$

$$-f^{C}_{kijwc} + X_{kij} \cdot L_{kijwc} \le \bar{f}^{C}_{kij}, \quad \forall\, kij \in C \tag{19}$$

The active line loss is calculated in the linear constraint (13), which is obtained by multiplying the variable $\theta^{(s)}_{ijwc}$ and the parameter $\theta^{(s-1)}_{ijwc}$ obtained in the previous iteration. Thus, the linearized active power flow is calculated by (14) and (15), and limited by (16) and (17), respectively, for existent and candidate lines. The opposite flow in the lines is then limited by constraints (18) and (19), respectively, for existent and candidate lines.

The main advantage of using the iterative DC-OPF presented in (12) is to consider, in a more realistic way, the capacity of transmission lines with the power losses, in addition to avoiding the nonlinearities of (2) and (3) in the complete STEP formulation.

2.2 Bi-level Formulation

The BD (Benders 1962; Rahmaniani et al. 2017) has been used to decompose the TEP into a Master Problem (MP), representing the planning stage and several subproblems. Thus, the TEP approached by BD commonly involves a recursive and iterative procedure where the subproblems feed the MP with linear constraints, known as Benders' cuts. Then, the MP defines a new expansion plan that will be again evaluated by the subproblems. Several reports have made improvements to the BD technique for the TEP problem. In Majidi-Qadikolai and Baldick (2018), a decomposition framework is proposed to link the BD and the progressive hedging decomposition method to consider the N-1 criterion. In (Alizadeh-Mousavi and Zima-Bočkarjova 2016), new Benders' cuts are proposed to reduce the computational time and improve the solution considering the N-1 criterion. In Lumbreras and Ramos (2016a), several accelerations techniques applied to BD are revised and tested. In the present paper, an approach based on BD is applied that divides the MINLP problem presented by (1) into MP and a sequence of subproblems, consisting of linear programming problems related to the modified iterative DC-OPF and several operative states and wind scenarios. Also, the decomposed problem avoids the nonlinearities present in (1) by using the previously described iterative DC-OPF in (12).

The MP formulation is presented in (20) and determines the reinforcement decisions (X_{kij}), which form the expansion plan, through the minimization of the investment cost (IC).

$$\text{IC} = \min \sum_{kij \in C} ce_{kij} X_{kij} \tag{20}$$

The optimization problem in (20) is also constrained by (11) and by the set of Benders' cuts. The set of Benders' cut is composed by linear constraints calculated by (21) and will be better explained hereinafter.

The expansion plan, obtained by solving the MP, is evaluated by several modified iterative DC-OPF subproblems, one for each combination of an operational state (c) and a wind scenario (w), aiming to minimize the system load shedding and wind spill. Thus, each unfeasible solution generates a Benders' cut formulated as the linear constraint in (21). The solutions which return an OBF_{wc} greater than zero are considered unfeasible.

$$\text{OBF}_{wc} - \sum_{kij \in C} S_{kijwc} \left(X_{kij} - X^{*}_{kij} \right) \le 0 \tag{21}$$

where X^{*}_{kij} is the value obtained from the decision variables X_{kij} regarding the problem modeled in (20), and S_{kijwc} is a sensitivity index.

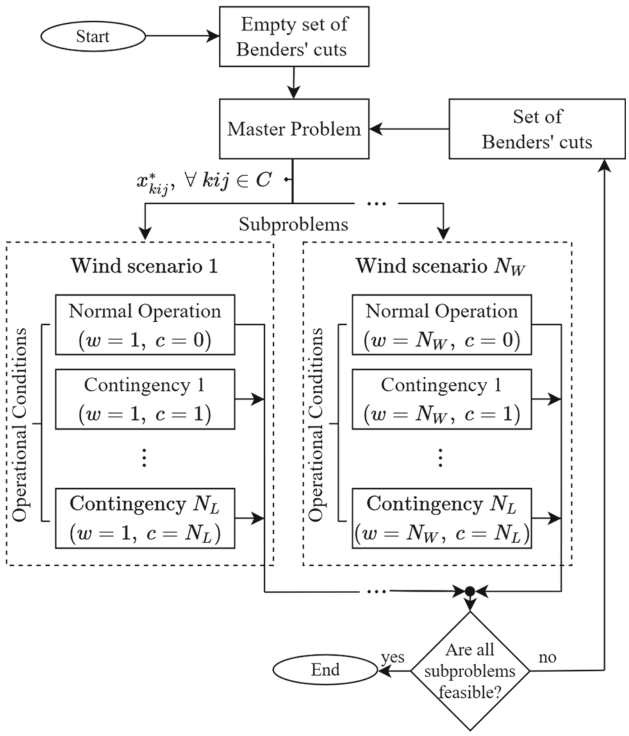

Fig. 1 Flowchart of the proposed framework

The sensitivity index varies according to the characteristics of each candidate line kij following a heuristic approach widely used in the literature (Orfanos et al. 2013). At first, the sensitivity index is calculated by (22).

$$S_{kijwc} = b_{kij} \left|\theta_{ijwc} \left(\lambda_{iwc} - \lambda_{jwc}\right)\right| \tag{22}$$

However, if the candidate line kij connects an isolated bus, the index is calculated by (23). The isolated bus in the system is connected by a dummy network formed by pseudo-lines. For this reason, the voltage angle of an isolated bus has no physical relationship with the electrical system and cannot be used.

$$S_{kijwc} = \bar{f}^{C}_{kij} \left(\lambda_{iwc} - \lambda_{jwc}\right) \tag{23}$$

The proposed bi-level formulation is illustrated in Fig. 1. Summarizing, the formulation starts solving the MP with an empty set of Benders' cuts. Thus, the MP returns the trivial solution without reinforcements. The case base grid is then evaluated by $(N_L \cdot N_W)$ subproblems. Each unfeasible subproblem generates a Benders' cut with (21) and is aggregated with the set of Benders' cut. In sequence, the set of Benders' cut constrains the MP producing a more robust expansion plan that will be re-evaluated by the subproblems until all result in feasible solutions.

2.3 Scenarios Generation

The formulation in this paper employs wind scenarios obtained from grouped wind capacity series by using the k-means algorithm as in Assis et al. (2018). The k-means method (MacQueen 1967) is an optimization heuristic that aims to divide a number of observations into groups in which each observation belongs to the group with the nearest mean.

In this paper, each group represents a set of wind observations which have similar characteristics. The number of observations belonging to one group defines the probability of the wind scenario, and the group mean defines the wind availability of the scenario. The use of k-means becomes interesting when there is more than one historical series representing the correlation between the regions of the system. Thus, the k-means has the advantage of reproducing the correlation between the wind power of different regions with great diversity in their wind series through a few scenarios, making the transmission system capable of transferring surplus energy from one region to another depending on the wind scenarios characteristic. In this paper, heavy load level is used in the simulations to check candidate planning schemes in the robust STNEP formulation.

2.4 Robustness of Planning Schemes

Once the generated scenarios from the k-means algorithm do not cover all possibilities of wind, the robustness of obtained expansion scheme is verified through (24). The confirmation method consists in a Monte Carlo Simulation, sampling a considerable number of points from the historical series, and for each point, the expansion scheme is evaluated for all contingencies considered in the N-1 security criterion. A similar robustness metric is applied in Yu et al. (2011) without consider the N-1 security criterion.

$$\beta = \frac{K_1}{K} \cdot 100\% \tag{24}$$

where K_1 is the number of observations that meet the N-1 security criterion; K is the total of observations evaluated; and β is the robustness metric.

3 Tutorial Case: Garver System

This section presents a tutorial case to exemplify the STEP under the N-1 security criterion and wind availability in a modified Garver 6-bus test system (Garver 1970). The existent topology is illustrated in Fig. 2. The system is composed of five interconnected and one isolated buses; the data of buses containing thermal and wind generators are described in Table 1. The data of existent and candidate circuits of

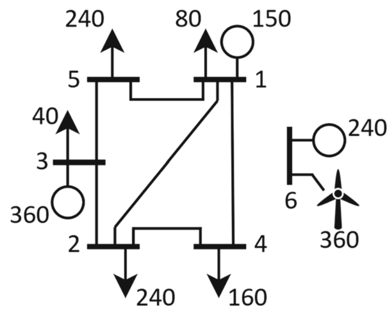

Fig. 2 Modified Garver test system

Table 1 Bus data of modified Garver test system

Bus	Demand (MW)	Thermal generation (MW)	Wind generation (MW)
1	80	150	–
2	240	–	–
3	40	360	–
4	160	–	–
5	240	–	–
6	-	240	360

the expansion planning can be found in Garver (1970). The robust expansion planning considers two scenarios of wind availability: with total wind capacity and without wind. Also, the N-1 security criterion considers only the outage of the existent circuit at the branch "3–5" in order to simplify the analysis of the tutorial. Under each contingency, flexibility is considered for the system operation through a permissible overload of up to 10% in each line. The tolerance of the framework was set to 1 MW of load shedding and wind curtailment.

The investment decision, load shedding and wind curtailment obtained during the planning process are presented in Table 2. At each iteration, the SP is formed by four subproblems:

$w = 1$ and $c = 0$: no wind power and intact grid;
$w = 2$ and $c = 0$: full wind power and intact grid;
$w = 1$ and $c = 1$: no wind power and outage in 3–5;
$w = 2$ and $c = 1$: full wind power and outage in 3–5.

At the first iteration, the MP results in the trivial solution of no investments in the network once the set of Benders' cuts is empty (see Fig. 1). As bus 6 is isolated, the sensitivity index for each candidate line that gets connected with it is calculated by (23), and the others are calculated by (22). From Table 2, shows that until the third iteration occurred wind curtailment once the wind power generation at the second scenario (full wind power) could not be consumed. Finally, the search process ends after the fifth iteration since there was no load shedding or wind curtailment.

4 Results

This section presents the results of the proposed bi-level framework for the IEEE-RTS and Brazilian Southern systems. From these systems, the following are derived: IEEE-RTS (Original IEEE), RTS-WIND (IEEE modified by adding wind power), BS (Original Brazilian Southern) and BS-WIND (Brazilian Southern modified by adding wind power). The following Simulation Cases (SC) are performed:

- SC-A STEP without both contingency and wind scenarios;
- SC-B STEP with contingencies, but without wind scenarios;
- SC-C STEP without contingencies, but wind scenarios;
- SC-D STEP considering contingencies and wind scenarios.

All single contingencies of the existing lines are considered for the tested systems. Under each contingency, as in the tutorial case, flexibility is considered for the system operation through a permissible overload of up to 10% in each line. Every branch with candidate circuits could receive a maximum of three reinforcements. It is considered a long-term STEP of 10 years of planning horizon.

The methodology was implemented in the MATLAB® numerical computing environment. The CPU times refer to an AMD Ryzen™ 5 2400G processor with 3.6GHz of clock speed. The MILP MP problem is solved by Branch & Bound algorithm using the CPLEX 12.9.0 (Copyright© IBM Corp.) optimization package in parallel using six threads and the iterative DC-OPF is solved by Primal-Dual Interior Point Method.

4.1 The IEEE-RTS 24-Bus System

The IEEE-RTS system (Subcommittee 1979) has 24 buses and 34 branches containing existent and candidate lines. The system receives a modification widely used in the literature, consisting of doubling its demand and generation capacity in order to reduce its reliability and increase the STEP difficulty. At the end of the 10 years planning horizon, all demand and generating capacities increase by 50%. A second modification derives the RTS-WIND system as in Assis et al. (2018), which defines wind power for buses 1 and 15. More specifically, the two 152 MW coal plants at bus 1 are replaced by 524 wind turbines of 2 MW each, whereas the 130 MW coal plant at bus 15 is replaced by 396 wind turbines also having capacity of 2 MW. The wind capacities with their respective probabilities are given in Table 3. The investment costs data were obtained from Fang and Hill (2003).

Table 2 Progress of the proposed framework

Iteration	Investment (million $)	Lines added (million $)	w/c (MW)	Load S. (MW)	Wind C. (MW)
1	0	–	$w = 1$ and $c = 0$	307.8	–
			$w = 2$ and $c = 0$	309.6	360.0
			$w = 1$ and $c = 1$	404.3	–
			$w = 2$ and $c = 1$	407.2	360.0
2	120	2–3, 2–6, 2(3–5), 4–6	$w = 1$ and $c = 0$	13.6	–
			$w = 2$ and $c = 0$	13.6	108.3
			$w = 1$ and $c = 1$	16.4	–
			$w = 2$ and $c = 1$	16.4	108.3
3	130	2–3, 3–5, 3(4–6)	$w = 1$ and $c = 0$	–	–
			$w = 2$ and $c = 0$	–	59.8
			$w = 1$ and $c = 1$	50.0	–
			$w = 2$ and $c = 1$	50.0	59.8
4	160	1–5, 2(2–6), 3–5, 2(4–6)	$w = 1$ and $c = 0$	14.9	–
			$w = 2$ and $c = 0$	–	–
			$w = 1$ and $c = 1$	66.7	–
			$w = 2$ and $c = 1$	–	–
5	160	2(2–6), 2(3–5), 2(4–6)	$w = 1$ and $c = 0$	–	–
			$w = 2$ and $c = 0$	–	–
			$w = 1$ and $c = 1$	–	–
			$w = 2$ and $c = 1$	–	–

Where *w*/*c* indicates the wind scenarios w and operational state c

Table 3 Wind scenarios established for the RTS-WIND system

Scenario	Wind Capacity (%)		Probability (%)
	Bus 1	Bus 15	
1	5.320	6.990	24.75
2	9.680	18.88	16.44
3	13.32	33.06	11.05
4	22.32	48.89	9.160
5	51.09	74.16	8.230
6	33.06	66.47	6.670
7	65.95	88.68	6.500
8	27.82	32.61	6.410
9	41.23	52.44	6.020
10	88.05	97.82	4.720

The solutions obtained by the proposed framework for the IEEE-RTS are presented in Table 4, which gives the total investment cost calculated from (20). It can be viewed that N-1 security criterion demands an over-investment of 116.2% and 58.5%, respectively, for the IEEE-RTS and RTS-WIND systems. In this study case, a total of 434 MW of controllable generation capacity was replaced by 1.84 GW of wind power; this high insertion of renewable energy along with the removal of the non-renewable amount increases the need for investment as can be observed by comparing SC-A and SC-B (cases without renewable insertion) with SC-C and SC-D (cases with high insertion of renewable). The robustness metric of the expansion plans of SC-C and SC-D is 85.9% and 99.4%, respectively, showing the improvement in the robustness of the grid when the N-1 security criterion is considered in the planning task.

4.2 The Brazilian Southern System

The Brazilian Southern (BS) system (Monticelli et al. 1982) has 46 buses, 73 lines, besides 11 disconnected buses: 2 containing generators and 9 only for interconnection purposes. The modification that derives the BS-WIND test system adds three wind power farms of 700 MW containing 250 wind turbines each in buses 1, 21 and 43. The total renewable generation has a participation of 16.61% in the generation capacity. The wind capacities with their probabilities are given in Table 5; however, the deterministic worst-case planning does not take into account the probabilities of scenarios in its formulation. The capacities in Table 5 were obtained by using the *k*-means algorithm in the "*Scenario 1*" from the Netherlands historical series presented in da Silva et al. (2012).

The robust expansion plans obtained are presented in Table 6. Different from the RTS-WIND, which removes some non-renewable plants of the IEEE-RTS system, the

Table 4 Best solutions obtained for the IEEE-RTS system

SC	System	Branches	Cost (million $)	Time (min)
A	IEEE-RTS	6-10, 3(7-8), 10-12, 14-16, 16-17	2.04	0.6
B	IEEE-RTS	1-5, 3-24, 4-9, 2(6-10), 2(7-8), 10-12, 12-13, 14-16, 15-24, 16-17	4.41	0.5
C	RTS-WIND	2(1-2), 2(1-5), 3-24, 5-10, 2(6-10), 2(7-8), 9-12, 10-12, 12-13, 14-16, 16-17, 20-23	4.73	2.8
D	RTS-WIND	2(1-2), 1-5, 2-4, 3-24, 2(6-10), 2(7-8), 9-11, 2(10-12), 12-13, 2(14-16), 15-21, 15-24, 16-17, 20-23	7.50	4.3

Table 5 Wind scenarios established for the BS-WIND system

Scenario	Wind capacity (%)			Probability (%)
	Bus 1	Bus 21	Bus 43	
1	8.230	7.840	5.630	27.23
2	25.71	11.27	12.30	14.11
3	43.82	17.71	23.94	11.06
4	19.34	32.35	11.05	9.150
5	43.33	45.27	24.80	8.470
6	64.77	27.28	41.51	8.060
7	65.55	59.08	40.28	7.400
8	84.46	73.49	59.69	5.730
9	97.69	87.78	85.52	4.620
10	86.31	40.48	68.51	4.110

BS-WIND received 2.1 GW of wind farms in buses 1, 21 and 43 without reducing the non-renewable plants' capacity. As the transmission lines connected to the buses that received the renewable generation have enough capacity for the wind power, the SC-A and SC-C cases lead to the same expansion plan, as shown in Table 6. However, when the N-1 security criterion is considered, the SC-D case leads to an over-investment of 10% in comparison with SC-B to accommodate the renewable capacity.

The robustness metrics of the expansion plans of SC-C and SC-D are, respectively, 96.6% and 100%. Again, the consideration of N-1 security criterion during the planning task improves the robustness of the grid. To confirm the value 100%, the boundaries of the robust set were tested, and the expansion plan obtained in the SC-D showed to be feasible for any single outage and any wind scenario, even those from the boundaries.

Tables 4 and 6 also present the computational time spent in the simulation cases. It can be seen that a large number of isolated buses in BS systems introduce difficulties for the proposed methodology. Moreover, the costs obtained for SC-A and SC-B for both studied systems are comparable with the results presented in De Oliveira et al. (2018).

4.3 Modified Iterative DC-OPF

In order to verify the proposed modified iterative DC-OPF, Table 7 presents the solutions obtained for the IEEE-RTS system with the iterative DC-OPF commonly used to estimate line losses in the literature as in Assis et al. (2018) and Poubel et al. (2015).

It can be seen that the modified algorithm can make a big difference to find more robust networks, suggesting that the non-consideration of opposite power flow limit constraint in DC-OPF analyzes can lead to unfeasible solutions.

5 Conclusions

This paper presented a novel and efficient framework to obtain a robust STEP considering N-1 security criterion and wind availability uncertainties. From the results, some points can be emphasized:

– The security constraints and wind generation associated with isolated buses introduced more difficulties in STEP.
– The correlation between wind generation has brought more realistic results for the transmission planning.
– The modified iterative DC-OPF based on Benders Decomposition has shown to be able to find more robust expansion plans.
– The STEP problem was modeled as a mixed-integer nonlinear programming problem. The nonlinearities imply a non-convex optimization problem for which solvers cannot guarantee the global optima.
– The proposed methodology has been shown suitable to be applied in real systems where the computational time is not the main issue because transmission planning is solved offline.

Table 6 Best solutions obtained for the BS system

SC	System	Branches	Cost (million $)	Time (min)
A	BS	2(5-6), 18-20, 2(20-21), 20-23, 42-43, 46-6	75.9	0.7
B	BS	2-5, 2(5-6), 12-14, 19-21, 3(20-21), 2(20-23), 31-32, 32-43, 40-42, 40-45, 2(42-43), 46-6	189.5	47.8
C	BS-WIND	2(5-6), 18-20, 2(20-21), 20-23, 42-43, 46-6	75.9	1.5
D	BS-WIND	1-2, 2-5, 2(5-6), 12-14, 19-21, 3(20-21), 2(20-23), 24-25, 31-32, 32-43, 40-42, 40-45, 2(42-43), 46-6	204.7	667

Table 7 Comparison of solutions obtained for the IEEE-RTS system using the modified iterative DC-OPF and the approach used in Assis et al. (2018) and Poubel et al. (2015)

SC	System	Branches	Cost (million $)	Difference (million $)
A	IEEE-RTS	6-10, 2(7-8), 10-12, 14-16, 20-23	1.82	0.16
B	IEEE-RTS	1-5, 3-24, 4-9, 2(6-10), 2(7-8), 10-11, 10-12, 11-13, 14-16, 15-24, 16-17	4.41	0
C	RTS-WIND	3(1-2), 1-5, 3-9, 5-10, 2(6-10), 2(7-8), 9-12, 10-12, 12-13, 14-16, 16-17	4.05	0.68
D	RTS-WIND	3(1-2), 2(1-5), 2(3-24), 4-9, 3(6-10), 2(7-8), 9-12, 10-11, 10-12, 12-13, 2(14-16), 15-21, 15-24, 16-17, 20-23	7.30	0.20

As the proposed approach was tested in well-known power systems with isolated buses, uncertainties and contingencies, it cannot ensure global optimal solution as well as any method in the literature. However, the results have shown that the proposed methodology is suitable to be apply in real system with reasonable computational effort.

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References

Alizadeh-Mousavi, O., & Zima-Bočkarjova, M. (2016). Efficient benders cuts for transmission expansion planning. *Electric Power Systems Research*, *131*, 275–284.

Assis, F. A., Manso, L. A. F., da Silva, A. M. L., & Leon, J. E. A. (2018). Transmission expansion planning with wind sources based on constructive metaheuristics. In *2018 Simpósio Brasileiro de Sistemas Elétricos (SBSE)* (pp. 1–6) (**in Portuguese**)

Baringo, L., & Baringo, A. (2018). A stochastic adaptive robust optimization approach for the generation and transmission expansion planning. *IEEE Transactions on Power Systems*, *33*(1), 792–802.

Baringo, L., & Conejo, A. (2013). Correlated wind-power production and electric load scenarios for investment decisions. Sustainable Development of Energy, Water and Environment Systems. *Applied Energy*, *101*, 475–482.

Benders, J. (1962). Partitioning procedures for solving mixed-variables programming problems. *Numerische Mathematik*, *4*, 238–252.

da Silva, A. M. L., da Fonseca Manso, L. A., de Sousa Sales, W., Flávio, S. A., Anders, G. J., & de Resende, L. C. (2012). Chronological power flow for planning transmission systems considering intermittent sources. *IEEE Transactions on Power Systems*, *27*(4), 2314–2322.

da Silva, A. M. L., de Assis, F. A., Manso, L. A. F., Freire, M. R., & Flávio, S. A. (2017). Constructive metaheuristics applied to transmission expansion planning with security constraints. In *2017 19th international conference on intelligent system application to power systems (ISAP)* (pp. 1–7).

de la Torre, S., Conejo, A. J., & Contreras, J. (2008). Transmission expansion planning in electricity markets. *IEEE Transactions on Power Systems*, *23*(1), 238–248.

De Oliveira, E. J., Moraes, C. A., Oliveira, L. W., Honório, L. M., & Poubel, R. P. B. (2018). Efficient hybrid algorithm for transmission expansion planning. *Electrical Engineering*, *100*(4), 2765–2777.

Dehghan, S., Amjady, N., & Conejo, A. J. (2018). A multistage robust transmission expansion planning model based on mixed binary linear decision rules–part I. *IEEE Transactions on Power Systems*, *33*(5), 5341–5350.

dos Santos, T. N., & Diniz, A. L. (2011). A dynamic piecewise linear model for dc transmission losses in optimal scheduling problems. *IEEE Transactions on Power Systems*, *26*(2), 508–519.

Fang, R., & Hill, D. J. (2003). A new strategy for transmission expansion in competitive electricity markets. *IEEE Transactions on Power Systems*, *18*(1), 374–380.

Garver, L. L. (1970). Transmission network estimation using linear programming. *IEEE Transactions on Power Apparatus and Systems*, *PAS–89*(7), 1688–1697.

Gomes, P. V., & Saraiva, J. T. (2016). Hybrid discrete evolutionary PSO for ac dynamic transmission expansion planning. In *2016 IEEE International Energy Conference (ENERGYCON)* (pp. 1–6).

Gomes, P. V., & Saraiva, J. T. (2019). State-of-the-art of transmission expansion planning: A survey from restructuring to renewable and distributed electricity markets. *International Journal of Electrical Power and Energy Systems*, *111*, 411–424.

Jabr, R. A. (2013). Robust transmission network expansion planning with uncertain renewable generation and loads. *IEEE Transactions on Power Systems*, *28*(4), 4558–4567.

Li, J., Ye, L., Zeng, Y., & Wei, H. (2016). A scenario-based robust transmission network expansion planning method for consideration of wind power uncertainties. *CSEE Journal of Power and Energy Systems*, *2*(1), 11–18.

Lumbreras, S., & Ramos, A. (2016a). How to solve the transmission expansion planning problem faster: acceleration techniques applied to benders' decomposition. *IET Generation, Transmission Distribution*, *10*(10), 2351–2359.

Lumbreras, S., & Ramos, A. (2016b). The new challenges to transmission expansion planning. survey of recent practice and literature review. *Electric Power Systems Research*, *134*, 19–29.

MacQueen, J. (1967). Some methods for classification and analysis of multivariate observations. In *Proceedings of the fifth berkeley symposium on mathematical statistics and probability, volume 1: statistics* (pp. 281–297). University of California Press, Berkeley, CA.

Majidi-Qadikolai, M., & Baldick, R. (2018). A generalized decomposition framework for large-scale transmission expansion planning. *IEEE Transactions on Power Systems*, *33*(2), 1635–1649.

Monticelli, A., Santos, A., Pereira, M. V. F., Cunha, S. H., Parker, B. J., & Praca, J. C. G. (1982). Interactive transmission network planning using a least-effort criterion. *IEEE Transactions on Power Apparatus and Systems*, *PAS–101*(10), 3919–3925.

Moreira, A., Street, A., & Arroyo, J. M. (2015). An adjustable robust optimization approach for contingency-constrained transmission expansion planning. *IEEE Transactions on Power Systems*, *30*(4), 2013–2022.

Orfanos, G. A., Georgilakis, P. S., & Hatziargyriou, N. D. (2013). Transmission expansion planning of systems with increasing wind power integration. *IEEE Transactions on Power Systems*, *28*(2), 1355–1362.

Poubel, R. P. B., de Oliveira, E. J., de Mello, Honório L., de Oliveira, L. W., & da Silva Junior, I. C. (2015). A coupled model to multistage transmission expansion planning. *Journal of Control, Automation and Electrical Systems*, *26*(3), 272–282.

Qazi, A., Hussain, F., Rahim, N. A., Hardaker, G., Alghazzawi, D., Shaban, K., et al. (2019). Towards sustainable energy: A systematic review of renewable energy sources, technologies, and public opinions. *IEEE Access*, *7*, 63837–63851.

Rahmaniani, R., Crainic, T. G., Gendreau, M., & Rei, W. (2017). The Benders decomposition algorithm: A literature review. *European Journal of Operational Research*, *259*(3), 801–817.

Subcommittee, P. M. (1979). IEEE reliability test system. *IEEE Transactions on Power Apparatus and Systems*, *PAS–98*(6), 2047–2054.

Yu, H., Chung, C. Y., & Wong, K. P. (2011). Robust transmission network expansion planning method with taguchi's orthogonal array testing. *IEEE Transactions on Power Systems*, *26*(3), 1573–1580.

Zhang, X., & Conejo, A. J. (2018). Robust transmission expansion planning representing long- and short-term uncertainty. *IEEE Transactions on Power Systems*, *33*(2), 1329–1338.