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Wind Generation Impact in Transmission Expansion Planning

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Abstract
This research proposes a post-stage investment analysis in the transmission expansion network planning problem considering the intermittence of renewable energy sources, especially wind power sources. The main goal of this study is to analyze the voltage profiles in all the system buses and the level of electrical losses in the lines using AC flow for impact evaluation of renewable energy insertion. This research also performs an additional analysis considering wind energy insertion during the planning stage. This analysis is to demonstrate the effect in the stage of investment in transmission lines. The variability of these sources is represented through scenarios obtained by the K-means classification algorithm that allows the preservation of the correlation among generating stations. The methodology performance is tested using the IEEE 24-bus system, which is modified to include a significant share of wind energy.

Keywords Transmission expansion planning · Renewable energy sources · Voltage profiles · DC network model · AC network model

List of Symbols

Sets and Subscripts

E	Set of branches with existing transmission lines
C	Set of branches with candidate transmission lines
F	Set of branches with fictitious transmission lines
B	Set of load buses
Z	Set of generation buses
R_{ij}	Set of candidate reinforcements of branch ij
E_{ij}	Set of existing transmission lines of branch ij
F_{ij}	Set of fictitious transmission lines of branch ij
ΩE_i	Set of existing lines connected to bus i
ΩC_i	Set of candidate lines connected to bus i
k	Index for existing or reinforcement transmission line
w	Index for wind generation scenario

Variables

$\mathrm{pg}_{i,w}$	Active power generation at bus i and wind generation scenario w (MW)
$\mathrm{pw}_{i,w}$	Active wind power generation at bus i and wind generation scenario w (MW)
$\mathrm{pd}_{i,w}$	Active power deficit at bus i and wind generation scenario w (MW)
$\mathrm{EP}_{k,ij}$	Expansion binary 0/1 parameter for reinforcement k in branch ij
$\theta_{ij,w}$	Angular difference between terminal buses i and j at wind generation scenario w
$fE_{k,w}$	Active power flow (MW) of transmission line k in branch ij, at wind generation scenario w
$fC_{k,w}$	Active power flow (MW) of candidate transmission line k for branch ij, at wind generation scenario w
$fF_{k,w}$	Active power flow (MW) of fictitious line k for branch ij, at wind generation scenario w

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Parameters

dc_i Specific deficit generation cost at bus i ($/MW)
pg_i^{min} Inferior limit of $pg_{i,w}$ (MW)
pg_i^{max} Superior limit of $pg_{i,w}$ (MW)
$d_{i,w}$ Demand at bus i (MW) at wind generation scenario w
fE_k^{max} Active power flow limit of an existing transmission line k (MW)
fC_k^{max} Active power flow limit of a candidate transmission line k (MW)
ce_k Investment cost of a candidate transmission line k ($)
b_k Susceptance of line k
γ_k Susceptance of fictitious line k, considered as 0.001 per unit (pu)
g_k Conductance of line k
K Number of clusters to the K-means method

1 Introduction

Contemporary society faces challenges to supply the growing demand for electrical energy. The evolution of the supply depends on aspects like the available generation capacity, alternatives to expand transmission, technological innovations, associated costs, and environmental issues (Moghaddam 2019). Therefore, there is an increasing search for investments identification in transmission lines with a proper cost–benefit ratio. Thus, the generation and transmission capacities need to be expanded to satisfy the increasing demand of electrical grid.

The central purpose of the TEP is the determination of an optimal transmission planning to ensure that the increase in electricity demand can be served throughout a planning horizon without any violation of planning criteria. The classical TEP optimization problem has a few characteristics: (1) a non-convex solution space, i.e., several solutions make some algorithms converge toward a locally optimal point; (2) combinatorial nature related to the investment alternatives resulting in a high computational effort; (3) the existence of disconnected electrical systems and isolated buses; and (4) the presence of nonlinear constraints and integer variables.

The TEP can be classified according to the planning horizon. In this sense, electrical companies must individually choose when [i.e., dynamic view (De Oliveira et al. 2017)] and where [i.e., static view (De Mendonça et al. 2016)] must invest into this highly complex business environment during a given horizon with fair conditions and lowest possible cost.

Concerning the formulation model, power systems can be modeled by DC and AC models for TEP studies. The AC load flow formulation, in addition to high computational effort, may encounter risks of infeasibility or divergence. Commonly, the expansion planning obtained by the DC model cannot be implemented directly in practice. It should be verified and reinforced using the simulation of the AC model. Generally, the optimum cost reinforcement is not adequate to operate the real system, since several existent and built lines present active power flow near the line bounds. Therefore, there is a necessity for new studies for modeling TEP with uncertainties that are concerned with verifying operation on the AC network model. This paper aims to be a starting point for this analysis.

There is a considerable number of recently proposed planning models to solve TEP problem through deterministic models that do not consider the uncertainties, such as in De Oliveira et al. (2017), De Mendonça et al. (2016) and Mendonça et al. (2017). However, recently, many works have been proposed to tackle the inherent uncertainty characteristics of TEP. The work of Zavadil et al. (2005) studied the intermittent generation resources connected to the grid. A formulation of chance constrained to address uncertainties of load and wind generator in TEP is proposed by Yu et al. (2009). The authors in Gao and He (2009) developed a planning model considering wind energy exploitation indexes and energy-saving indexes. A literature review regarding the generation expansion planning and wind power plant is presented in Schenk and Chan (1981). As can be seen, there are a considerable number of studies about TEP and uncertainties inherent in renewable generation. However, these studies generally do not analyze the effects on the AC network model of renewable generation insertion.

The most used methodologies to deal with uncertainties are stochastic programming and robust optimization. A set of scenarios represents the uncertainty in the robust optimization approach (Jabr 2013). In case that the number of scenarios grows, the problem keeps a moderate size. In the stochastic programming context, the scenario describes the uncertainty. The objective is to achieve optimally on average considering all scenarios (De La Torre et al. 2008). The stochastic programming advantage is the ability to find the detailed distribution of parameters, such as wind and load variation. The deficiencies of some stochastic models include the computation complexity when applied to large-scale systems. However, the robust optimization models issues are the lack of ability to quantify the overall expected cost. Besides, the scenario construction to balance model accuracy and complexity is still an active research topic for both categories of methods (You et al. 2016).

The uncertainties related to TEP can be classified as internal and external. Internal uncertainties have to do with the availability of equipment over a period of time. External uncertainties are linked to energy market transactions, the availability of energy, for example, from renewable sources, such as precipitation, wind and solar incidence (Kim et al. 2018).

In addition to the uncertainties engaged in loads modeling and security constraints (De Oliveira et al. 2018), power systems have been experiencing an even higher level of uncertainty, which is also associated with the increase in renewable energy sources (RES) connected to the grid, such as wind, solar and biomass sources (Munoz et al. 2012; Loureiro et al. 2018; Majumder et al. 2017).

The volatility presented by renewable energy sources influences in an operational and financial way the system functioning. Therefore, the transmission planning stage should consider it. These types of sources play a prominent role in sustainable development. The reason relies on the fact that they are, in principle, inexhaustible and less harmful to the environment when compared to generators using fossil fuels (Luo et al. 2015).

In recent years, due to the worldwide energy crisis, wind farms have been developed to generate electric power from renewable wind power. Many large-scale wind farms are connected to transmission networks directly. However, as a drawback, this generation source introduces extra uncertainties for the power system operation and planning due to its intermittence (Ma and Zhou 2012; Gomes et al. 2019).

In general, wind farms are in considerably distant areas from the large demand centers. Consequently, a transmission infrastructure that allows wind farms to send their power output to the consumer nodes is a determining factor in the successful development of this type of generation. Increased transmission capacity helps to improve access to flexible energy sources (Morales et al. 2013).

The transmission expansion planning for the power system with the insertion of renewable energy from wind farms is a significant problem but has not been thoroughly analyzed (Gomes and Saraiva 2019). Due to its complex nature, its practical implementation requires the consideration of a wide range of aspects including economic, environmental, regulatory, technical, operational, social and potential interdependencies with other complementary sectors (Koltsaklis and Dagoumas 2018).

The flexibility and adequacy of current transmission systems have been widely discussed. The generation plants installation based on this type of source has been feasible, and the forecast is that this amount increases over time (Da Silva et al. 2012). Thus, it is necessary to identify expansion plans to enable a more flexible operation for greater use of this energy resulting in a network capable of dealing with the intermittent effects of renewable sources.

In this sense, the works related to transmission planning has been increasingly concerned with the high participation of renewable energy sources in the systems (Mortaz and Valenzuela 2019; Dehghan and Amjady 2016). For instance, similar works considering the problem of Generation Expansion Planning (GEP) with the insertion of renewable energy can be found in Dagoumas and Koltsaklis (2019). This paper aims at providing a review of the models employed to integrate RES in the GEP and classifies models in three generic categories: optimization models, general/partial equilibrium models and alternative models, not adopting the optimum integration of RES in the GEP. It provides insights on the characteristics, advantages and disadvantages of the theoretical approaches implemented, as well on their suitability for different aspects of the problem, contributing in the better understanding on the expected outcomes of each methodology.

The most significant impact caused by renewable energy insertion is the considerable increase in the number of random variables and the complexity of the system operation. Another problem is that the demand for wind energy and wind power production is not statistically correlated in the case of wind power generation. For example, wind power production is generally high during the night when load demand is low and vice versa (Baringo and Conejo 2013).

In light of this context, this research work uses the wind energy to represent renewable sources connected to the grid. The historical series of wind generation capacity is converted into possible generation scenarios employing the *K*-means classification method. Each of these scenarios has an associated probability of occurrence. Thus, the problem solution considers the stochasticity characteristic of renewable sources. A post-stage investment evaluation of renewable energy insertion is also carried out by analyzing the stress profiles in all system buses, verifying the performance when the operation occurs in the AC network model. Besides, an analysis of wind energy insertion during the investment stage is considered to show the importance of an appropriate modeling choice of wind power generation insertion in TEP, which is evident by comparing the results obtained when wind power is inserted in the post-investment stage or during the investment stage.

So, the present research proposes a new approach to solve the TEP problem with renewable energy insertion in the power system. The main contributions can be summarized as follows:

- The *K*-means stochastic model as clustering technique to generate scenarios of wind energy production through real data of the wind history of a Brazilian region;
- A post-stage investment evaluation of renewable energy insertion through analysis of the stress profiles in all the system buses and the level of electrical losses by AC network model;
- An additional analysis considering wind energy insertion during the investment stage. The goal is to evaluate the impact on the step of investment in transmission lines and, then, the stress profiles in all the system buses and the level of electrical losses by AC network model.

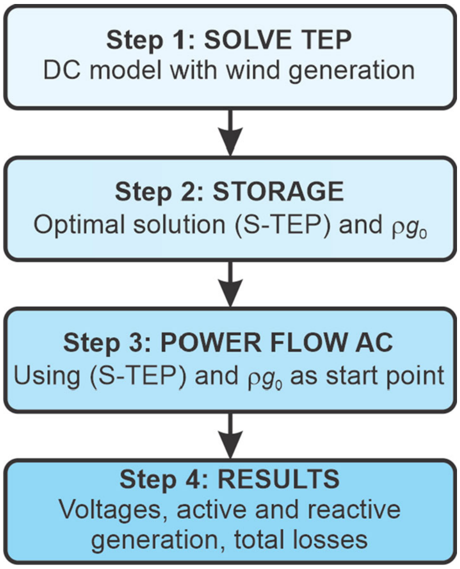

Fig. 1 Flowchart of the methodology for wind generation insertion in TEP

2 Methodology for Renewable Energy Sources Insertion in TEP

In this paper, the proposed methodology was applied considering the active power generation data related to a wind energy source. However, it can be extended to any active power source represented by a random variable as well as solar energy. Figure 1 details the proposed methodology for wind generation insertion in TEP along with its four main stages, represented by steps 1–4.

Step 1 This first step solves the TEP using the DC network model considering the active transmission losses. This problem is mixed-integer nonlinear programming (MINLP). This research work uses the efficient hybrid algorithm (EHA) proposed by the authors in De Oliveira et al. (2018), which consists of a search space reducer (SSR) and a modified bat-inspired algorithm (MBA) to solve the TEP. The MBA handles discrete variables, and optimal power flow is used to evaluate the fitness function as well as the planning options. It should be emphasized that the wind generation is taken into account as described in a subsequent item.

Step 2 This step is a storage process. Hence, this step stores the solution of TEP (S-TEP) obtained by Step 1, considering the expansion plan added to the base topology of the system, also storing the point of operation, i.e., saving the dispatches of the conventional generators (pg_0) in MW taking into account the insertion of wind generation.

Step 3 This stage is responsible for simulating the AC power flow using the storage values obtained in the Step 2. At this stage of the proposed methodology, the capacity limit of reactive power generation of synchronous machines is not considered. On the other hand, the unit power factor of wind power generation is adopted equal to one.

Step 4 This last step analyzes the voltage in the buses and electrical losses in the lines with and without wind generation. It is desired to check the stress profiles in all the system buses and the active power loses in the lines using the AC power flow.

2.1 Proposed TEP Formulation Considering Wind Generation

There are three types of lines: (1) the existing ones in the base topology; (2) the candidate reinforcement lines for expansion; and (3) fictitious lines that seek to avoid mathematical issues related to unconnected networks. The static planning problem of electrical power systems considering the wind generation and electrical losses can be defined as (1)–(11):

$$\mathrm{OBF} = \mathrm{Min} \sum_{k\in R_{ij}} \sum_{ij\in C} (\mathrm{ce}_k \mathrm{EP}_{ij}) + \sum_{i\in B} \sum_{w\in S} (\mathrm{dc}_i \mathrm{pd}_{i,w}) \tag{1}$$

subject to:

$$\mathrm{EP}_{k,ij} \in [0,1], \quad \forall k \in R_{ij}, \quad ij \in C \tag{2}$$

$$\mathrm{pg}_{i,w} + \mathrm{pd}_{i,w} - \sum_{k\in\Omega E_i} fE_{k,w} - \sum_{k\in\Omega C_i} fC_{k,w} = d_{i,w} - \mathrm{pw}_{i,w}, \quad \forall i \in Z, \quad w \in S \tag{3}$$

$$\mathrm{pd}_{i,w} - \sum_{k\in\Omega E_i} fE_{k,w} - \sum_{k\in\Omega C_i} fC_{k,w} = d_{i,w} - \mathrm{pw}_{i,w}, \quad \forall i \in B, \quad w \in S \tag{4}$$

$$|fE_{k,w}| \le fE_i^{\max}, \quad \forall k \in E_{ij}, \quad ij \in E, \quad w \in S \tag{5}$$

$$|fC_{k,w}| \le fC_k^{\max}, \quad \forall k \in R_{ij}, \quad ij \in C, \quad w \in S \tag{6}$$

$$\mathrm{pg}_i^{\min} \le \mathrm{pg}_{i,w} \le \mathrm{pg}_i^{\max}, \quad \forall i \in Z, \quad \forall w \in S \tag{7}$$

$$fE_{k,w} = -b_k\theta_{ij,w} + g_k\frac{\theta_{ij,w}^2}{2}, \quad \forall k \in E_{ij}, \quad ij \in E, \quad w \in S \tag{8}$$

$$fC_{k,w} = \mathrm{EP}_{k,ij}\left(-b_k\theta_{ij,w} + \frac{g_k\theta_{ij,w}^2}{2}\right), \quad \forall k \in F_{ij}, \quad ij \in F, \quad w \in S \tag{9}$$

$$fF_{k,w} = -\gamma_k\theta_{ij,w}, \quad \forall k \in F_{ij}, \quad ij \in F, \quad w \in S \tag{10}$$

$$\gamma_k \ll b_k, \quad \forall k \in F_{ij} \tag{11}$$

Equation (1) is the objective function (OBF). The first term corresponds to the investment related to the transmission system expansion, and the last term is related to the minimization of the energy deficit, which has a high operational cost. The deficit flexibility associated with a penalization makes the problem feasible even when the expansions do not meet the demand.

Equation (2) shows the decision of building the line k in the branch ij, which is represented by a nonzero value of $\text{EP}_{k,ij}$. On the other hand, when $\text{EP}_{k,ij}$ is zero, it means that line k is not selected to be built.

The active power balance is given by the well-known Kirchhoff's first law, as shown in (3) and (4). These equations include the network losses in an indirect way as described hereinafter and the different wind scenarios. Due to the wind power generation intermittency and the fact that it is not dispatchable, this generation will enter by dropping the demand value in those equations. So, wind generation in this study is modeled as an active power injection with a unity power factor as well used in the literature (Correa-Florez et al. 2016; Wen et al. 2015). Therefore, the voltage is not controllable in wind generation buses.

Moreover, positive values for $fE_{k,u,c}$ and $fC_{k,u,c}$ mean power flows from bus i, whereas negative values mean flow to bus i. Constraints (5) and (6) represent the limits of active power flow in the existing and candidate lines, respectively, according to their capacities. The generation limits are given by (7).

Then, the power flows through the existing candidate and fictitious lines are modeled by (8), (9) and (10), respectively, corresponding to the Kirchhoff's second law. The second terms of (8) and (9) represent half of the active power losses that introduce a nonlinear quadratic term. Constraints (10) and (11) are added to mathematically avoid problems related to unconnected networks in the OPF model, as in Mendonça et al. (2017), where the value adopted is equal to 0.001 pu.

Moreover, although unconnected networks are possible to be obtained, they imply in high deficit costs, as shown in the third term of (1) if load buses are isolated. Therefore, these solutions are avoided in the OPF model. It can be emphasized in (9) that the decision parameter $\text{EP}_{k,ij}$ multiplies the power flow of the candidate line k. Moreover, it implies that the multiplication of a discrete parameter $\text{EP}_{k,ij}$ and the nonlinear term is related to the losses.

The representation of wind generation scenarios provides a more realistic solution because of the characteristic flashing of the wind energy source. The constraints of the problem must meet the operating conditions for all wind power scenarios.

The problem relies on a decomposition scheme that proposes splitting the global problem (1)–(11) into two subproblems defined as master and slave to obtain an efficient approach for solving the TEP by avoiding nonlinear integer program (De Oliveira et al. 2018). Note that the master or investment subproblem performs the lines expansion decisions by optimizing the discrete $\text{EP}_{k,ij}$ variables only in constraint (2).

On the other hand, in the slave or load shedding subproblem, $\text{EP}_{k,ij}$ is not variable. However, this one is set as the corresponding value obtained in the master subproblem. As a consequence, the slave subproblem consists of a nonlinear programming with only continuous variables in constraints (3)–(11).

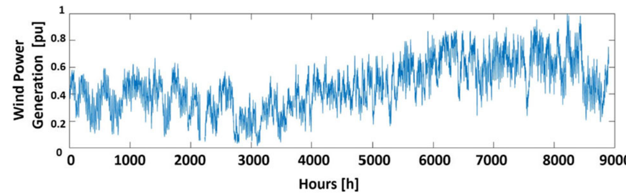

Fig. 2 Brazilian northeast system normalized wind generation data

2.2 Stochastic Model for Renewable Energy Representation

For the tests, this research has used a year of data with an hourly frequency of wind generation referring to the Brazilian Northeast system regarding the year of 2015, specifically from January to December. These data were used to analyze the wind energy generation model. They are available in the Brazilian Agency National Electric System Operator (ONS) (ONS 2018).

Although the doubly fed induction generator (DFIG) is the type commonly used for large-scale wind generators in Brazil (Agência Brasileira de Desenvolvimento Industrial 2017), this study when using directly the actual generation data (MW) from northeastern Brazil system, which are obtained by summing different wind turbines installed in the region, in a clustered way by K-means, has as a consequence that the proposed methodology is suitable for every type of turbine.

Since the data correspond to all northeastern Brazil wind generation in different geographical locations (i.e., wind regions), looking at these real data, it is possible to see that there is not a time when all the turbines are off. Thus, the wind generation curtailment of some turbines is already embedded in the included data.

First, the generation data are normalized, and, then, the values of the series are divided by the highest generation value found in the sample. Thus, all the values were framed in the interval (0, 1), as in Fig. 2.

The clustering method used to compose the probabilistic scenarios of wind generation, based on the actual data history provided by ONS, is the K-means method. This method is an iterative algorithm for data clustering presented for the first time in MacQueen et al. (1967). There are in general three stages involved in this clustering procedure, as illustrated in Fig. 3. Namely, 1. initialize K cluster centroids; 2. assign each sample to its closest centroid; 3. recompute cluster centroids with assignments produced in Stage 2 and go back to Stage 2 until convergence. This is known as *Lloyd* iteration procedure (Kulis and Jordan 2011). The iteration repeats Stage

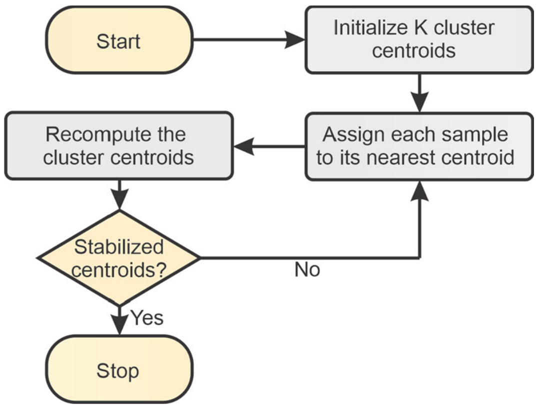

Fig. 3 *Lloyd* iteration procedure

Table 1 Wind generation scenarios and their occurrence probability

Wind Generation (pu)	Probability of occurrence (%)
0.1807	14.59
0.3458	26.62
0.4779	28.02
0.6176	19.37
0.7788	11.39

2 and Stage 3 until the centroids do not change between two consecutive rounds.

The K-means classification method aims at partitioning the series of wind power generation within a predefined number of clusters K. Each group K receives a reference value called centroid of K. This value of the series is classified according to its proximity to the centroids.

This study defines the number of divisions equal to 5. Thus, the stochasticity presented by renewable sources is taken into account for solving the problem. Table 1 represents the possible wind generation scenarios with their respective occurrence probabilities adopted in this work. It can be emphasized that the TEP solution results in five operation points for each wind scenario. So, to reach the unique operation point, the weighted average is used for each variable.

This study analyzes wind power insertion in the system. Thus, the system with power equal to 20% of the total system load will be applied, i.e., when all wind generators are producing their maximum capacity at 20% of the full demanded load. This analysis considers a significant amount of renewable generation insertion in the system.

For this work, two load buses are randomly chosen to allocate two wind generation units. Notice that in a real case it is necessary to connect the wind power where this natural resource is available, i.e., the wind power placement is, in principle, not defined according to the best points for the system operation. In the present paper, it is supposed that the load center is a place where the wind source is available. In

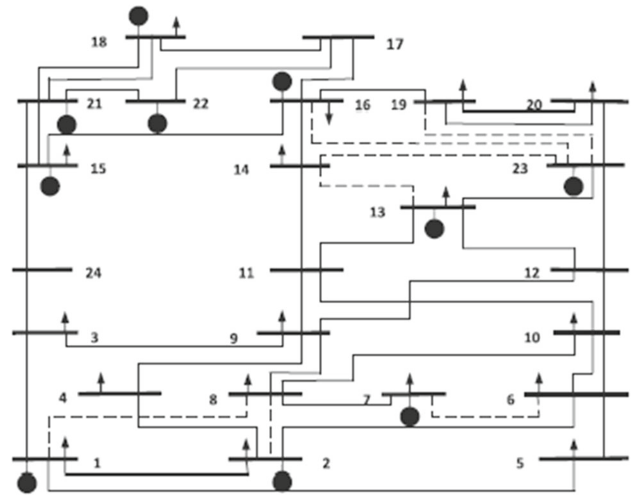

Fig. 4 IEEE 24-bus System

this case, the wind penetration is beneficial to the system due to the counter-flow. However, other places could be considered by the proposed approach for the wind penetration, even if they are not good for the system.

The combination of equal weights of these two generating units is equivalent to 20% of the total system load. A weighted average is made to achieve the final result of the conventional generators. In this way, the generations obtained through the consideration of each scenario of wind power are weighted by their respective probabilities of occurrence given by Table 1.

2.3 IEEE 24-Bus System

The IEEE 24-bus system (Romero et al. 2005) has 38 existing lines, ten generators and 41 candidate branches for expansion. Each one can receive a maximum of three reinforcements. The total demand is 8550 MW. Figure 4 shows the system topology. The bus 13 is considered as swing bus for all simulation cases. In addition, the up limit of voltage magnitude is considered equal to 0.95. To avoid no convergence in a AC load flow, the lower limit of voltage magnitude is not considered.

3 Results and Discussion

All simulations were conducted using a computer presenting a core I7 with 2.1 GHz. Besides, all the algorithms were implemented using the platform MATLAB®. Three different simulation cases (SCs) are performed for the analyses. These cases are summarized as follows:

SC-A: TEP considers the IEEE 24-bus system (Romero et al. 2005) regardless of the wind generation.

Table 2 Proposed plan for the IEEE 24-bus

Branches	6–10	7–8	14–16	10–12	16–17	Cust-OBF (M$)
Lines	1	2	1	1	1	188

Table 3 Generation buses for Step 3 of the SC-A

Buses	pg_i^0 (MW)	pg_i (MW)	qg_i (MVAr)
1	569.03	569.03	218.73
2	575.36	575.36	131.73
6	0	0	132.37
7	898.09	898.09	303.36
13	1512.32	1556.65	634.51
14	0	0	448.45
15	216.58	216.58	740.09
16	458.34	458.34	336.40
18	1175.62	1175.62	237.67
21	792.70	792.70	48.05
22	841.27	841.27	15.80
23	1765.43	1765.43	319.42

SC-B: This case considers for the same expansion plan obtained in the SC-A the wind generation allocated randomly in two load buses of the system.

SC-C: This case considers the insertion of wind power generation in a TEP solution (Step 1).

The following subsection gives a detailed description of the three simulation cases.

3.1 SC-A

Table 2 presents the following expansion plan obtained by Step 1 as the best solution of SC-A, which determines one line in each one of the branches '6–10,' '14–16,' '10–12,' '16–17,' and two lines in the branch '7–8,' with a total cost of 188 M$ related to the OBF in Eq. 1. This solution is also found at the work (De Oliveira et al. 2018). This plan along with the conventional generators dispatch (pg_i^0) presented in the second column of Table 3 is stored in Step 2. Besides, these values are the input from Step 3 as a specified point.

The generators operation point obtained through Step 3 is given by the values of active power (pg_i) and reactive power (qgi), as shown in the third and fourth columns of Table 3, respectively. Note that the mentioned values along with the nodal voltages and the angle results are given in Table 4. The sum of total electrical losses corresponds to 299.07 MW. It can be emphasized that buses 3, 4, 9 and 24 have a voltage lower than 0.9 pu, as highlighted in bold values.

Table 4 V_i and θ_i in all buses for the SC-A

Buses	V_i (pu)	θ_i (°)	Buses	V_i (pu)	θ_i (°)
1	1.05	– 28.05	13	1.05	0
2	1.05	– 27.90	14	1.05	– 8.47
3	**0.77**	**– 40.00**	15	1.05	– 1.83
4	**0.87**	**– 39.06**	16	1.05	– 0.13
5	0.98	– 34.64	17	1.04	5.43
6	1.05	– 37.74	18	1.05	8.77
7	1.05	– 28.21	19	1.01	0.74
8	0.98	– 33.48	20	1.02	7.31
9	**0.86**	**– 33.26**	21	1.05	10.59
10	0.99	– 31.33	22	1.05	26.88
11	0.97	– 13.09	23	1.05	12.94
12	0.93	– 14.09	**24**	**0.89**	**– 13.07**

Table 5 Generation dispatch with wind generation for SC-B

Buses	pg_i^0 (MW)	pg_i (MW)	qg_i (MVAr)
1	494.88	494.88	162.37
2	499.24	499.24	121.16
3*	393.71	393.71	0.00
6	0	0	99.44
7	837.46	837.46	284.20
13	1470.20	1480.75	554.05
14	0	0	408.43
15	550.02	550.02	451.45
16	401.24	401.24	275.49
18	967.07	967.07	232.89
20*	393.71	393.71	0.00
21	854.06	854.06	– 54.08
22	471.01	471.01	– 33.41
23	1406.11	1406.11	253.70

3.2 SC-B

This simulated case considers the 393.71 MW insertion of wind energy into each of the load buses 3 and 20, taking into account the same expansion plane of Table 2. Then, Tables 5 and 6 indicate the generation buses results for Step 3 as well as voltages and angles in each system bus, respectively.

A significant improvement can be observed with the insertion of wind generation to the system concerning the results of the voltage presented in Table 6. Even with high levels of renewable generation insertion, the system maintains the maximum voltage levels in the buses within the established threshold of 1.05 pu using the conventional generators redispatch presented in the network. Note that the voltage increases in all buses that does not reach this maximum voltage limit.

Table 6 V_i and θ_i in all buses. For Step 3 of the SC-B

Buses	Vi (pu)	θ_i (°)	Buses	Vi (pu)	θ_i (°)
1	1.05	− 25.85	13	1.05	0
2	1.05	− 26.08	14	1.05	− 7.77
3	0.91	− 20.71	15	1.05	0.58
4	0.89	− 35.20	16	1.05	0.40
5	0.98	− 32.74	17	1.05	4.37
6	1.05	− 36.05	18	1.05	6.98
7	1.05	− 28.51	19	1.02	1.98
8	0.99	− 33.12	20	1.03	9.12
9	0.90	− 28.25	21	1.05	9.58
10	1.00	− 29.85	22	1.05	17.75
11	0.98	− 12.05	23	1.05	12.78
12	0.95	− 13.02	24	0.97	− 6.62

Table 7 Proposed plan for the IEEE 24-bus considering the wind generation during TEP

Branches	6–10	7–8	14–16	10–12	Cost-OBF (M$)
Lines	1	2	1	1	152

In particular, there was an improvement in the undervoltage in the buses where the wind units were allocated; for example in bus 3, the voltage goes from 0.77 to 0.91 pu, in bus 20 and the voltage variation goes from 1.02 to 1.03 pu, and also buses 4, 9 and 24, which in the SC-A had the voltages of 0.87, 0.86 and 0.89 pu, respectively, according to Table 4, have an improvement to 0.89, 0.90 and 0.97 pu, respectively, as shown in Table 6.

Note that there is a decrease in the sum of total electrical losses. The value of 299.09 MW obtained for the SC-A reached the amount of 209.14 MW. It can be inferred that the wind generation insertion in the system was beneficial in terms of nodal voltage improvement of the active power profile and losses in the transmission lines.

3.3 SC-C

In this simulation, the wind power units were included in the buses 3 and 20 during the planning stage. The purpose of this analysis is to verify the wind energy insertion impact in the investment in transmission lines, and, then, the stress profiles in all the system buses and the level of electrical losses. Table 7 shows the new obtained expansion plan when considering the two wind units in the planning stage. Note that this new plan is cheaper due to the wind penetration of 20% of the total system load.

Tables 8 and 9, respectively, indicate the generation buses results for Step 3 as well as the voltages and angles in each system bus. Note that the voltage levels were remarkably similar to the ones obtained by SC-B. However, the cost of line investment proposed in this simulation is considerably cheaper.

In this way, the importance of contemplating the insertion of wind power generation still in the stage of investment in the lines is clear. The reason relies on the fact that it contains all the information about the problems from the initial stage.

It is worth to mention that the sum of total electrical losses decreases. For instance, the value of 299.09 MW obtained for the SC-A or the value of 209.14 MW obtained for the SC-B reached the amount of 207.25 MW.

Table 8 Conventional and wind generation (3* and 20*) final results for Step 3 of the SC-C

Buses	pg_i^0 (MW)	pg_i (MW)	qg_i (MVAr)
1	495.03	495.03	160.96
2	504.78	504.78	119.91
3*	393.71	393.71	0.00
6	0	0	98.63
7	845.41	845.41	282.30
13	1485.07	1503.45	554.69
14	0	0	400.73
15	566.69	566.69	449.58
16	418.84	418.84	275.67
18	953.80	953.80	227.94
20*	393.71	393.71	0.00
21	837.87	837.87	− 56.50
22	381.85	381.85	− 37.44
23	1460.11	1460.11	263.24

Table 9 V_i and θ_i in all buses. For Step-3 of the SC-C

Buses	Vi (pu)	θ_i (°)	Buses	Vi (pu)	θ_i (°)
1	1.05	− 25.75	13	1.05	0
2	1.05	− 25.96	14	1.05	− 8.79
3	0.91	− 20.98	15	1.05	− 0.28
4	0.89	− 35.18	16	1.05	− 0.90
5	0.98	− 32.70	17	1.05	5.11
6	1.05	− 36.05	18	1.05	7.01
7	1.05	− 28.03	19	1.02	1.28
8	0.99	− 32.74	20	1.03	8.96
9	0.90	− 28.33	21	1.05	9.05
10	1.00	− 29.87	22	1.05	15.78
11	0.99	− 12.45	23	1.05	12.90
12	0.95	− 13.03	24	0.97	− 7.29

4 Conclusions and Future Work

This research proposed an analysis of the K-means clustering technique to generate wind power production scenarios. The wind energy insertion at a post-stage investment improves the voltage profiles in the buses where the wind power units were allocated as well as in other buses. The profile of total electrical losses was also improved.

Even with the considerable insertion of wind power generation, the system was able to maintain the voltage levels in the buses within the established maximum limit and to improve the buses voltage profile that does not reach this threshold through the dispatch of the conventional generators present in the network.

For the additional analysis performed in this work (i.e., SC-C), a new economically feasible investment plan is observed when considering the insertion of wind energy during the planning stage. This study justifies the importance of contemplating the addition of wind power generation in the stage of investment in lines.

A few extensions are foreseen for future works: first, an investment stage considering more complex scenarios and other kinds of uncertainties in the power system; second, a proposition of a new multi-objective model to optimize power systems reliability along with cost implementation; and third, although the reactive power limits were not taken into account in this paper, they are important to be considered in the future work because they require a reactive power support from another source that should be included in the total investment costs. So, it is also intended to study an efficient model for the TEP resolution considering the AC network model along with an optimal allocation of investment in reactive and consideration of the insertion of reactive generation limits control. At last, other electrical power systems are also considered to fully investigate the proposed methodology.

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