Hindawi
Journal of Electrical and Computer Engineering
Volume 2019, Article ID 7374287, 14 pages
https://doi.org/10.1155/2019/7374287

*Research Article*

# Optimal Connection of Offshore Wind Farm with Maximization of Wind Capacity to Power Systems considering Losses and Security Constraints

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Received 8 August 2018; Revised 12 February 2019; Accepted 18 February 2019; Published 11 March 2019

Guest Editor: Mustafa I. Fadhel



The technical, economic, and environmental constraints related to the construction of new transmission lines are complex issues related to the definition of points for connecting new offshore wind farms (OWFs) to the grid. In this context, it has become an important research topic to choose the best OWF connection point to a power system, among some geographically close to each other within a given region, aiming at ensuring maximum generation capacity of the wind farm and safe use of existing transmission network. The objective of this work is to present a methodology to determine the optimal OWF connection point in a power system, with maximum penetration of firm wind power and minimum loss, considering security constraints related to the "$N-1$" contingency criterion, exchange limits between areas, and a strategy to reduce the number of constraints in the optimization problem. The algorithm is modeled using a Mixed Integer Nonlinear Programming (MINLP), and it is evaluated in a tutorial system and three well-known other networks from literature: IEEE 14-Bus, IEEE RTS-79, and Southern Brazilian System.

## 1. Introduction

Renewable energy is receiving more attention due to growing concerns about the environment and the depletion of conventional energy sources based primarily on fossil fuels. In this sense, wind energy is one of the most prominent options in renewable sources investment scenarios. Moreover, many countries are planning ambitious scenarios with this energy for the future [1, 2].

Onshore wind energy is one of the cheapest types of renewable options. It is a good choice for investors in many countries due to its relatively short installation time, government incentives, and easy operation procedures. However, in most cases, regions with high wind generation potential are far from the load centers. In some cases, it justifies the installation of wind farms in a marine environment, which is known as offshore wind farms (OWFs). On the other hand, this option needs a suitable transmission system to inject the wind power into the existing network. The problem is to determine the best network point for connecting these farms to the main onshore grid, considering that they are installed in places with high energy potentials. Building a new structure for OWF requires not only investment but also regulatory issues and environmental barriers. Also, for remote wind farms, the produced wind energy may not be fully usable due to constraints of transmission lines as, for instance, their thermal limits.

Optimal strategies for connecting wind farms to the grid should be studied to overcome all the mentioned barriers. However, a comprehensive analysis is required over an extended period to find the ideal connection points to the main grid. The aforementioned analysis should consider the load profile, existing energy sources, transmission lines' infrastructure, and wind speed scenario of all potential regions under study.

This paper proposes a novel methodology to determine the optimal connection point of a transmission system for injecting the power from OWF with the purpose of maximizing the wind energy penetration with minimum network loss, among some candidate buses "$k$" geographically close to each other within a given region, connected or not by a "$n$" possibilities of switches "$sw_k$," as illustrated by Figure 1. The proposed approach considers important aspects and constraints related to the problem and uses Mixed Integer Nonlinear Programming (MINLP) for the decisions about the connection points within a given region. The approach is assessed through studies using three well-known networks besides a tutorial case.

*1.1. Contributions of This Paper.* The main contributions of the present work can be summarized as follows:

(i) A novel and efficient approach based on MINLP to determine the best network connection point for injecting OWF power that maximizes the wind energy penetration and minimizes the transmission losses

(ii) The proposal of a strategy for representing the transmission line constraints in the optimization problem, which allows the efficient incorporation of the "$N - 1$" contingency criterion to the problem for security analysis

*1.2. Paper Organization.* The research work is structured as follows. Section 2 shows a brief overview of the literature about the themes related to this paper. Section 3 presents the proposed approach explaining in details the strategies used in each step of the optimization process. Section 4 gives a tutorial case for explaining the steps of the proposed algorithm, whereas other results for practical systems are shown in Section 5. Finally, Section 6 gives the main conclusions.

## 2. Background and Related Works

In this section, a brief overview is made on the maximum penetration of wind power in electric power systems (EPSs) (Section 1.1) and optimal allocation and connection of wind power generation (Section 1.2). Besides, it is highlighted how this paper relates to these issues.

*2.1. Maximum Penetration of Wind Power in Electric Power Systems (EPS).* An optimization cost function is defined in [3] to minimize an economic cost criterion for wind turbine farm, comprising the choice of the best wind resource regions. A specific target related to wind energy penetration is initially assumed to be feasible for a firm wind capacity connection. However, it would not be realistic in most of the energy systems with current transmission limitations. As an

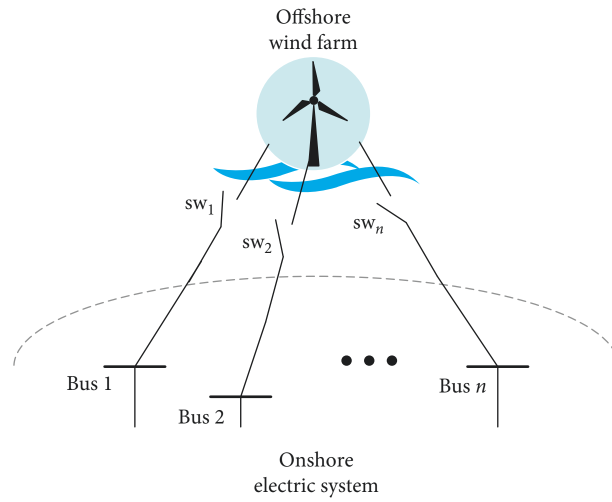


Figure 1: Scheme of the proposed methodology.

improvement of [3], the problem described in [4] attempts to maximize the wind power potential of an existing system in the short term, before the transmission expansion in the long run. Incremental penetration targets of firm wind energy are applied from a lower initial level to a threshold when the optimization model becomes unfeasible.

Reference [5] analyzes the possibility of considering the wind as a nonfirm power source, where historical wind data are used to model wind energy variations and spatial interdependence. The Benders decomposition method was applied to explore the structure of the large-scale constraint diagonal matrix. The wind and load demand profiles, as well as fuel price and contingency management sensitivities, are also evaluated for demonstrating the importance of an ideal wind power capacity allocation solution.

In [3–5], the "$N - 1$" contingency criterion is considered and the thermal limits of the existing transmission lines and transformers are observed. These aspects are also addressed in the approach proposed in the present paper. Moreover, this paper proposes the inclusion of transmission losses in the economic dispatch model and an efficient strategy to include only the active constraints into the optimization problem.

*2.2. Optimal Allocation and Connection of Wind Power Generation.* As previously discussed, wind power is site dependent, and in many cases, good wind locations are far from the grid. Additionally, the connection of wind power to a power system can be hampered by transmission capacity limitations. In this scope, reference [6] presents a methodology for finding optimal positions in an existing transmission system to connect firm wind capacity for achieving desired renewable and secure penetration targets.

Following this line, paper [7] addresses the problem of optimal allocation of wind capacity and determines the capacity of the transmission line to connect the wind farm to the grid. In [8], a network reinforcement model incorporating the optimal integration of wind farms (WFs) into power systems is proposed. Based on the reinforcement model, transmission lines are added to eliminate congestion issues.

Considering the diverse interests of investors and power systems' operators in wind farms, Zeńczak [9] presents issues related to the choice of the best location for connecting wind farms. In [2], it is presented a robust planning model to determine the optimal allocation of wind farms in a multiarea power system, so that the expected energy not supplied (EENS) is minimized under uncertain wind power and unit forced outages.

In this scenario, a MINLP is introduced in the present paper to handle the nonlinear nature of the problem and the integer binary variables that are proposed to represent switches' statuses, which are associated to the options for connecting OWF to a candidate bus of a power system.

## 3. Proposed Methodology

It is required a feasibility technical study to verify if the wind energy connection does not congest the transmission network after possible network contingencies. Note that a firm wind connection does not observe wind reduction due to system limitations. However, when a connection is nonfirm, the system operator can reduce the wind in case of contigencies [7]. As mentioned before, the present work considers a firm wind power connection.

In this sense, it is assumed initially that the transmission system is decongested (not violating the established limits) and that the addition of new wind generating capacity must preserve this situation. Thus, a low target for wind energy penetration is defined to assess the system feasibility. As the optimization problem gives a feasible solution for this condition, the wind energy is increased through small discrete steps until the connection of additional wind power to any of the candidate buses is not possible without congestion in the system.

The flow chart of the proposed algorithm, based on [4], is presented in Figure 2.

In Step 1, the initial wind generation time series are generated, which are considered as being from historical data for the candidate regions. These series are used in Step 2 for the economic dispatch of conventional and dispatchable generation in the system, aiming at minimum losses. In Step 3, a direct current power flow (DCPF) model [10] uses these wind power series to obtain a simplified power flow solution that allows identifying the lines that have their active power capacity violated. Then, the violated lines define linear inequality constraints related to transmission limits for a MINLP problem in Step 4.

The purpose of Step 4 is to determine the connection point in the power system for the offshore wind farm, aiming at maximizing the wind power utilization through a feasible connection solution for the current wind power penetration level. In this step, the decision variables of the optimization problem are the wind power capacity ($C_k$) for each candidate bus $k$. If the MINLP finds a feasible solution, the wind power time series are updated in Step 5 as described in the next section. Notice that the updated series cannot fit the corresponding series that were introduced in the economic dispatch. In this case, Steps 2 to 5 are carried out again until the power wind time series of Step 5 are close to the input series of Step 2. The difference between these series is further described in the next section. When it occurs, the convergence criterion is achieved.

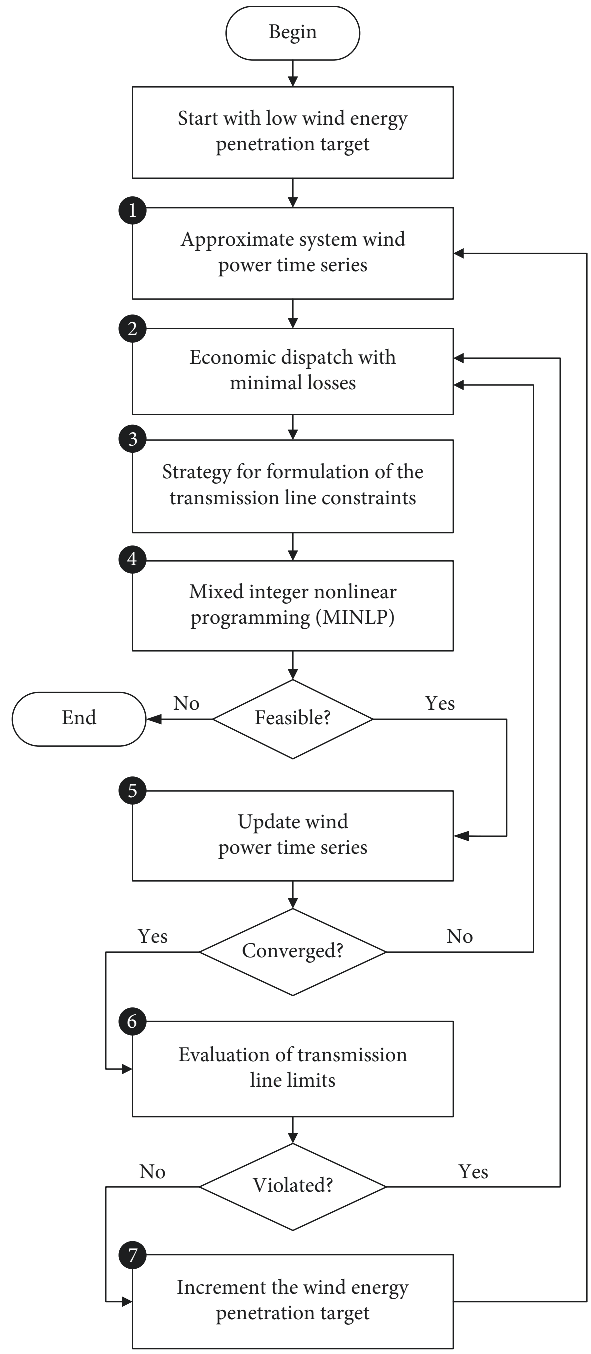


Figure 2: Flow chart of the proposed algorithm.

After obtaining the convergence of the process that comprises Steps 2 to 5, if the solution is feasible, an evaluation is made to check the presence of violated transmission lines in Step 6. If a violation is identified, the aforementioned iterative process is repeated until no violation occurs. Otherwise, the wind energy penetration is increased in Step 7, and the whole process is repeated until a no feasible wind penetration level is achieved. At this infeasible point, the previous point is identified as that presents the optimal connection of the OWF, associated with maximum bearable wind power capacity for the system under analysis.

In the following topics, each step of the methodology proposed in this paper is discussed in detail.

*3.1. Approximate System Wind Power Time Series (Step 1).* In order to carry out the economic dispatch of the conventional generations, it is necessary to have information about the time series of wind generation of the system. Each potential location candidate for the wind farm installation has its capacity factor ($\lambda$) and individual variations in its wind power generation series. Therefore, the system wind power time series that are introduced in the Economic Dispatch Step cannot be precisely defined before completing the Optimization Step (Step 4, MINLP), where the individual wind power capacities are defined. However, it can initially be assumed that the system wind power series converges to a geographically smoothed or approximate time series, denoted by $t_h^{\mathrm{APR}}$. The calculation of the value of $t_h^{\mathrm{APR}}$ is presented in detail in [4]. $t_h^{\mathrm{APR}}$ satisfies the goal of wind energy penetration $\delta$ respecting hourly wind variations and, therefore, this is suitable for Step 2.

*3.2. Economic Dispatch with Minimal Losses (Step 2).* The connection of a wind power to a transmission system not only affects the power flows due to the corresponding power injections, but also impacts on the entire operational dispatch of the system. Thus, the interdependence between load, existing and new, wind generation, and present conventional generation must be determined with the task of finding optimal locations for penetration of wind power. The increase in wind energy penetration changes the load demand requirements, which needs a dispatch response from conventional plants.

The geographically smoothed time series of wind power (Step 1) is subtracted from the system load, and the resulting net load time series serve as input data for the Economic Dispatch Step (Step 2). In this step, the economic dispatch for minimum losses corresponds to the lowest cost for conventional generation powers $G_i$, considering the current wind energy penetration target.

A relevant technical issue of system operators regarding energy efficiency consists of trying to impact as little as possible the transmission losses due to generation redispatches, with no violation of lines limits, which justifies the loss minimization problem proposed in this paper. In this scope, the transmission losses are included in DC Economic Dispatch as shown by equations (1) and (2), according to methodology introduced by [11]:

$$P_j^{\mathrm{loss}} = g_j \cdot \theta_j^2, \tag{1}$$

$$P_j = \frac{\theta_j}{x_j} + \frac{P_j^{\mathrm{loss}}}{2} = \frac{\theta_j}{x_j} + \frac{g_j \cdot \theta_j^2}{2}, \tag{2}$$

where $P_j^{\mathrm{loss}}$ is the loss of the branch $j$ (MW), $x_j$ is the reactance of the branch $j$, $g_j$ is the conductance of the branch $j$, and $\theta_j$ is the angular difference between buses of the branch $j$.

Thus, the inclusion of the loss of line $j$ in each iteration $t$ of the DCPF is done as in [11]:

$$P_j^{(t)} = \frac{\theta_j^{(t)}}{x_j} + \frac{g_j \cdot \theta_j^{(t-1)} \cdot \theta_j^{(t)}}{2}, \tag{3}$$

where $\theta_j^{(t-1)}$ indicates the value of $\theta_j$ obtained in the previous iteration. This procedure is needed to avoid the inclusion of the nonlinearities related to losses in the DCPF.

The proposal of the economic dispatch, instead of the unit commitment, given in [4], is justified by the focus of the present paper on the medium- or long-term planning, as well as by the adopted context of the Brazilian system, whose profile is mostly hydraulic.

*3.3. Strategy for Formulation of the Transmission Line Constraints (Step 3).* After the DCPF, the obtained power injections $P_i$ in each bus $i$, except at the reference bus $r$, are used to calculate the power flows $f_j$ in each line $j$, as a linear combination of a set of linear coefficients $\alpha_{j,i}$ ("power transfer distribution factors" or "distribution displacement generation factors") [12], equation (4). An important advantage of the DCPF is that linear constraints can be formulated to represent network power flow safety criteria in the optimization (MINLP) stage; this advantage stands out by reducing the complexity of the optimization problem.

$$f_j = \sum_{i \neq r} \alpha_{j,i} \cdot P_i. \tag{4}$$

The factor $\alpha_{j,i}$ can be calculated according to the reactance parameters of the system [12], as shown in the following equation:

$$\alpha_{j,i} = \frac{X_{ki} - X_{mi}}{x_j}, \tag{5}$$

where $X = B'^{-1}$ ($B'$ is the nodal admittance matrix, $X_{ki}$ is the element referring to the row $k$ and column $i$ of the matrix $X$, $X_{mi}$ represents the element in the position $mi$ of the matrix $X$, and $x_j$ is the reactance of line $j$) [13].

With the information of the conventional generations coming from the economic dispatch of Step 2, the partial flows $\gamma_{j,h,s}$ are calculated (for branch $j$, hour $h$, contingency scenario $s$) considering no injection of wind power. In this context, the inequality constraints of equation (6) are defined for every hour to ensure that the wind power penetration does not overwhelm any transmission line by violating its thermal capacities. Notice that these constraints are defined both in the direct and reverse flow directions.

$$\forall_{h,j,s} = \left[ -L_j \leq \sum_k \alpha_{k,j,s} \cdot t_{k_h} \cdot \mathrm{sw}_k \cdot C_k + \gamma_{j,h,s} \leq L_j \right], \tag{6}$$

where for every hour $h$, every branch $j$, every contingency scenario $s$, and considering $k$ as the bus index of the wind farm in the network, $L_j$ (MW) is the thermal limit of line $j$,

$t_{k_h}$ (MW) is the wind power time series (normalized in 1 MW) in hour $h$, $\gamma_{j,h,s}$ (MW) is the predefined partial flow, $\mathrm{sw}_k$ represents the switch that connects (1) or not (0) the wind farm to the grid, and $C_k$ (MW) is the optimization variable of wind capacity.

The inequalities on both sides of equation (6) can be manipulated algebraically and represented by (6a) and (6b). Equation (6c) ensures that the turbine capacity optimization variables are positive.

$$\forall_{h,j,s} = \left[\sum_k \alpha_{k,j,s} \cdot t_{k_h} \cdot \mathrm{sw}_k \cdot C_k - \left(L_j - \gamma_{j,h,s}\right) \le 0\right], \tag{6a}$$

$$\forall_{h,j,s} = \left[\sum_k -\alpha_{k,j,s} \cdot t_{k_h} \cdot \mathrm{sw}_k \cdot C_k - \left(L_j + \gamma_{j,h,s}\right) \le 0\right], \tag{6b}$$

$$\forall_k \left(C_k \ge 0\right). \tag{6c}$$

The computational requirements of the optimization algorithm are sensitive to both the number of variables and the number of constraints in the applied mathematical model [14]. In this sense, the present paper proposes to include only the active constraints, i.e., the constraints for lines whose thermal limits are violated in the economic dispatch, to the MINLP of Step 5. This procedure seeks to obtain computational efficiency in the optimization process avoiding a large and unnecessary number of constraints. The strategy proposed in the present paper significantly reduces the percentage of the number of constraints that are active in the optimization problem, as will be seen in the case studies in items 3 and 4.

*3.4. Mixed Integer Nonlinear Programming (MINLP) Formulation (Step 4).* In the proposed approach, the MINLP model is applied to determine the connection point for offshore wind farm that makes the wind power penetration level feasible with its highest utilization as possible. For this task, the wind power generation capacity $C_k$ for the current incremental wind energy penetration target $\delta$ is defined as the objective function (OBF), equation (7a), which is minimized. It can be highlighted that the minimization of $C_k$ implies in the choice of the best place for wind farm, i.e., with the best capacity factor $\lambda$, which means the best utilization of the wind resource. Considering the possibilities for connection of OWF, the proposed optimal connection model for maximum penetration of wind power capacity is formulated by the following equations:

$$\mathrm{OBF} = \min\left(\sum_k C_k\right), \tag{7a}$$

$$\sum_{k=1}^{n} \mathrm{sw}_k \cdot C_k \cdot \lambda_k = D^{\mathrm{AVG}} \cdot \delta, \tag{7b}$$

$$\sum_{k=1}^{n} \mathrm{sw}_k = 1, \tag{7c}$$

$$\mathrm{sw}_a \cdot \mathrm{sw}_b = 0, \quad \forall a \ne b, \tag{7d}$$

$$\forall_{h,j,s} = \left[\sum_k \alpha_{k,j,s} \cdot t_{k_h} \cdot \mathrm{sw}_k \cdot C_k - \left(L_j - \gamma_{j,h,s}\right) \le 0\right], \tag{7e}$$

$$\forall_{h,j,s} = \left[\sum_k -\alpha_{k,j,s} \cdot t_{k_h} \cdot \mathrm{sw}_k \cdot C_k - \left(L_j + \gamma_{j,h,s}\right) \le 0\right], \tag{7f}$$

$$\forall_k \left(C_k \ge 0\right), \tag{7g}$$

where $n$ defines the total number of possible switches to connect the wind farm to the grid.

The output of the MINLP model (7a)–(7g) is the optimal connection of OWF considering the maximum capacity of wind power that guarantees the feasibility of the wind power penetration target, i.e., so that the wind power goal is achieved and no line is overloaded for all contingency scenarios ("$N-1$" criterion).

In theory, the feasibility of each firm wind penetration target $\delta$ is defined only by the constraints and should not be sensitive to the applied cost function. However, the choice of the cost function can affect the convergence of the general methodology and the allocation of wind generation capacity.

The energy contribution of a wind farm is defined by its capacity factor value. The optimal connection of OWF with maximum wind power capacity in the MINLP should fit the total wind energy penetration $\delta$. This is ensured by including equation (7b) where each switching devices $\mathrm{sw}_k$ and wind capacity $C_k$ are the optimization variables.

The equality constraints (7c) and (7d) are inserted into the mathematical model to ensure the optimal connection of one of the OWF connection options. Equation (7d) has two at a time combination of $n$ switches that results in a set of $n \cdot (n-1)/2$ constraints, where $a$ and $b$ represent distinct OWF connections.

*3.5. Update Wind Power Time Series (Step 5).* The formulation of the economic dispatch problem, in Step 2, uses as input a time series of geographically smoothed wind power. However, this may not necessarily correspond precisely to the time series of wind power resulting from the MINLP. Thus, to preserve the energy balance of the power system and correct dispatch of the conventional units at each operating time, Steps 2 to 5 are performed until the input series of Step 2 is equivalent to the output of Step 5.

*3.6. Evaluation of Transmission Lines Limits (Step 6).* The purpose of this step is to determine whether or not the thermal limits of the network lines are violated after the solution found in the optimization process. If any line has been violated, Steps 2 to 6 are reiterated aiming at adding to the optimization model constraints for such line, to ensure that the solution found is feasible at the current penetration target. If no line is overloaded at all periods and contingency scenarios, the process moves to Step 7.

*3.7. Increment the Wind Energy Penetration Target (Step 7).* After the wind power series have been updated and the power flows have met the thermal lines' limits, the wind energy penetration $\delta$ is increased in small discrete steps $\Delta\delta = 1\%$. Thus, as in Figure 1, Steps 1 to 7 of the methodology are reiterated until a feasible solution is obtained for the optimum connection of OWF with maximum firm wind power capacity. In this point, the algorithm ends and the optimal results are from the last feasible connection obtained.

## 4. Tutorial Example

*4.1. General System Information.* Figure 3 shows the unifilar diagram of the tutorial system used to illustrate the application of the proposed approach for maximizing the wind power generation. This system is inspired by the 11-Bus described in [13]. To consider wind generation, buses "12" and "13" are inserted into the system, where the reactances and resistances of the lines connecting these buses to the original system are equal to 0.01667 p.u. and 0.00100 p.u., respectively. The values of the active power demanded PL as well as the behavior of the wind power time series $t_{k_h}$, normalized in 1 MW, for a period of three hours under study are shown in Figure 4. The conventional generation capacity of the generators connected in buses "1," "2," "3," and "4" are 2100, 2100, 2154, and 2100 MW, respectively. The peak load demanded by the system is 3007.4 MW. The average load over the period under analysis is 2734 MW. The thermal limits of the lines are shown in Table 1.

The analysis of optimal connection of OWF with maximum wind energy penetration is performed considering two options to connect the wind farm: at bus "12" or bus "13." The capacity factor $\lambda_k$ of the offshore wind farm is 28.37%.

*4.2. Optimal Connection of Offshore Wind Farm with Maximum Wind Generation Capacity.* The MINLP model applied to determine the connection point among buses "12" and "13" is written for this tutorial system in (8a)–(8d). The inequality constraints follow the formulation presented in (7e)–(7g):

$$\text{FOB} = \min\left(C_{12} + C_{13}\right), \tag{8a}$$

$$\text{sw}_{12} \cdot C_{12} \cdot \lambda_{12} + \text{sw}_{13} \cdot C_{13} \cdot \lambda_{13} = D^{\text{AVG}} \cdot \delta, \tag{8b}$$

$$\text{sw}_{12} + \text{sw}_{13} = 1, \tag{8c}$$

$$\text{sw}_{12} \cdot \text{sw}_{13} = 0. \tag{8d}$$

As described in Section 1, it is initially considered the system operating with a low wind power penetration target, equal to 1%. In this case, the active power flows in the lines are within the respective thermal limits with no wind energy penetration. Then, this penetration is increased in small steps of 1% until the target of 11% makes the system operation not feasible. Thus, penetration increments of 0.1% are performed from the 10% level to find the maximum penetration value of wind power that respects the thermal line limits. Table 2 shows the values of the allocated wind power capacity $C_k$ for each penetration level and each candidate connection point.

As it can be observed, the OWF connected to bus "12" is the optimal option to obtain the maximum penetration ($\delta_{\max} = 10.3\%$) and maximum wind generation capacity ($C_{12_{\max}} = 992.67$ MW), with the switches being arranged as follows: $\text{sw}_{12} = 1$ and $\text{sw}_{13} = 0$.

The infeasible level identified by the proposed optimization model for this case is given by $\delta = 10.4\%$. At this point, the power flow in Lines 7–12 violates the corresponding thermal limit (1000 MW) in all contingency scenarios, making it unfeasible for an additional injection of wind energy into the system. Any increase in penetration is also not supported by bus "13."

The described results for this tutorial case are the same found by using the linear programming optimization presented in [4], considering only bus "12" as option for the OWF, which can validate the proposed approach in the present paper.

*4.3. MINLP Inequality Constraints Used in Step 5.* For each penetration target, the insertion of line constraints, equations (7e) and (7f), is considered to ensure that their thermal limits are not violated. In this sense, for the base case (without contingency), there are "14" limit constraints for the forward direction, equation (7e), added by "14" constraints for the inverse direction, equation (7f), by hour of the period under analysis. It should also be taken into account that a number of "12" "$N-1$" contingencies are analyzed (contingencies for all lines except lines 7–12 and 9–13 because they would generate conflicting constraints for the optimization process). Thus, for the period of three hours considered, there is a total number of constraints by each penetration level given in the following equations:

$$N_{\text{constrains}} = \left(N_{\text{lines}_{\text{base}}} \cdot \text{hours} \cdot 2\right) + \left(N_{\text{lines}_{\text{“}N-1\text{”}}} \cdot \text{hours} \cdot 2\right) \cdot N_{\text{contingencies}}, \tag{9a}$$

$$N_{\text{constrains}} = (14 \cdot 3 \cdot 2) + (13 \cdot 3 \cdot 2) \cdot 12 = 1020, \tag{9b}$$

where $N_{\text{constrains}}$ is the total number of constraints, $N_{\text{lines}_{\text{base}}}$ is the number of transmission lines existing in the base case, $N_{\text{lines}_{\text{“}N-1\text{”}}}$ is the number of transmission lines in a "$N-1$" contingency scenario, and $N_{\text{contingencies}}$ is the number of contingencies under analysis.

However, with the proposed strategy of selecting only the constraints related to lines that have their thermal limits violated, only "52" inequality constraints are added in this case throughout the optimization process, in which only the constraints concerning the lines 7–12 and 9–13 are violated, in the first hour, in both directions of the power flow. Then, obtaining a percentage reduction of 95.67% thus improves the computational efficiency in the process.

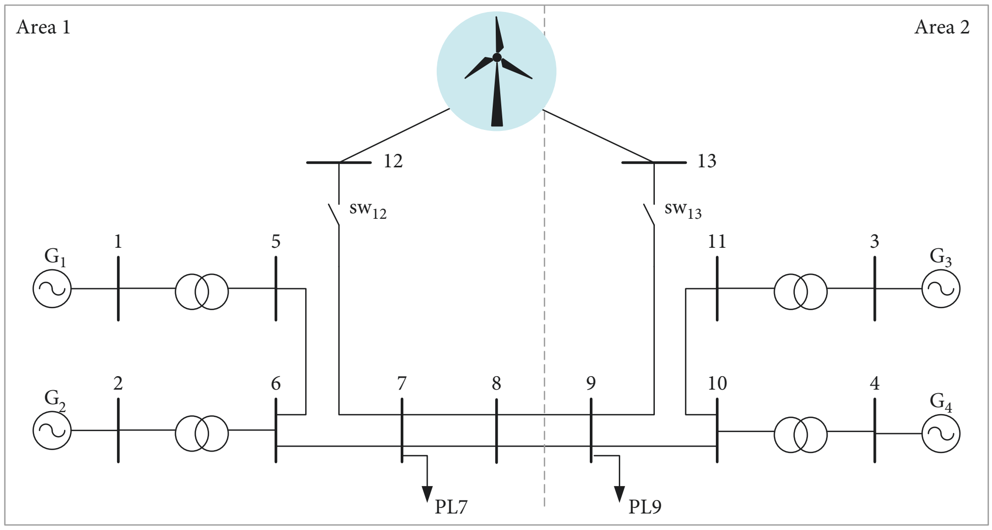


Figure 3: Unifilar diagram of the 11-Bus system.

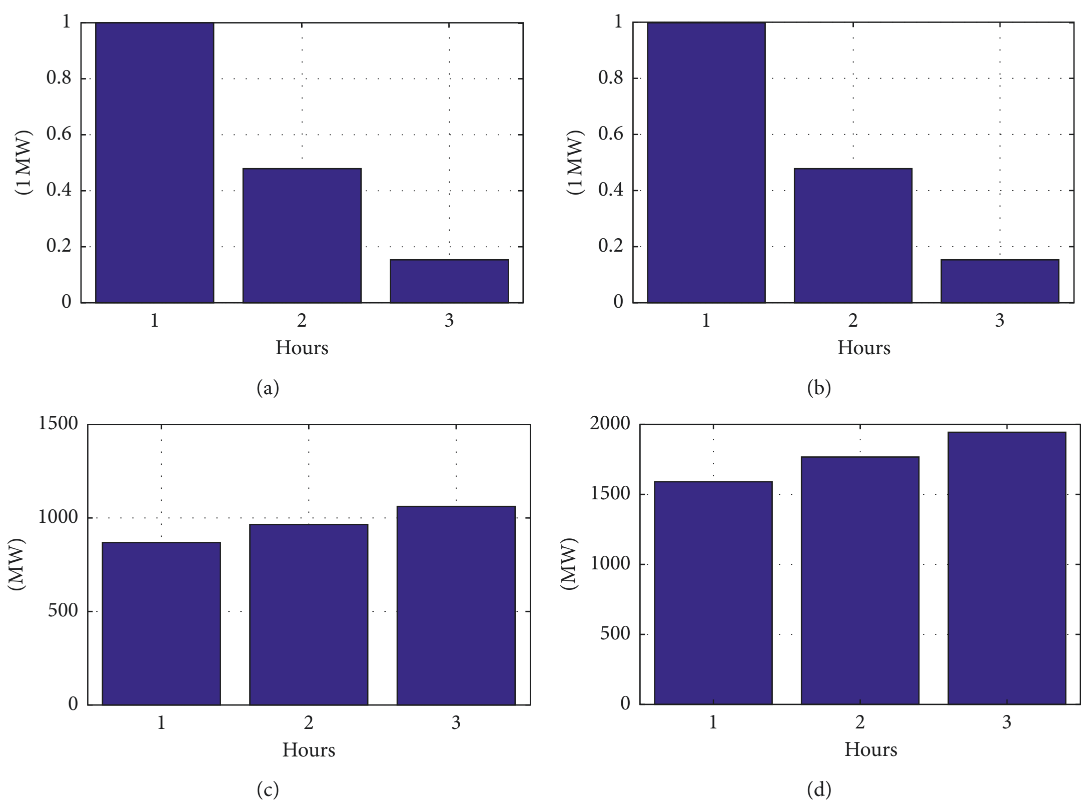


Figure 4: Hourly behavior of the wind power time series (1 MW) and the load. (a) $T_{12\text{h}}$ (1 MW). (b) $T_{13\text{h}}$ (1 MW). (c) $PL_7$. (d) $PL_9$.

## 5. Results and Discussion

This section presents the results obtained by applying the proposed methodology for optimal connection of OWF with maximum penetration of wind energy in well-known systems in the literature: IEEE 14-Bus [15], IEEE RTS-79 (a 24-Bus system), [16] and a Southern Brazilian system [17, 18]. The IEEE 14-Bus system has originally 14 Buses and 20 lines, the total load demand of 259 MW and the maximum generation capacity as 2021.6 MW. The IEEE RTS-79 consists of a 24 buses system and 38 candidate lines for expansion, widely used in studies of transmission systems expansion, in which each branch can receive a maximum of three reinforcements; the total load demand is 2850 MW, and the maximum generation capacity is 3405 MW. The Southern Brazilian system has a basic network topology with

Table 1: Capacity (MW) of transmission lines, tutorial case.

| Branch $j$ | Capacity (MW) |
|---|---|
| 1–5 | 4000 |
| 2–6 | 4000 |
| 3–11 | 3800 |
| 4–10 | 2000 |
| 5-6 | 4000 |
| 6-7 | 5000 |
| 7-8 ($x_2$) | 2000 |
| 8-9 ($x_2$) | 2000 |
| 9-10 | 5000 |
| 10-11 | 3800 |
| 7–12 | 1000 |
| 9–13 | 1000 |

Table 2: Allocated capacity (MW) for each penetration level and candidate connection, tutorial case.

| $\delta$ (%) | Allocated capacity | |
|---|---|---|
| | $C_{12}$ | $C_{13}$ |
| 1.0 | 96.376 | 0.00 |
| 2.0 | 192.75 | 0.00 |
| 3.0 | 289.13 | 0.00 |
| 4.0 | 385.50 | 0.00 |
| 5.0 | 481.88 | 0.00 |
| 6.0 | 578.25 | 0.00 |
| 7.0 | 674.63 | 0.00 |
| 8.0 | 771.00 | 0.00 |
| 9.0 | 867.38 | 0.00 |
| 10.0 | 963.76 | 0.00 |
| 10.1 | 973.39 | 0.00 |
| 10.2 | 983.03 | 0.00 |
| 10.3 | 992.67 | 0.00 |

46 buses and 79 branch candidates for expansion, where each branch can receive a maximum of three reinforcements; the total demand is 6880 MW, and the maximum generation capacity is 10545 MW.

For all the systems, it was considered that the behavior of the wind power series (1 MW) for the offshore wind generator in the 3-hour study period is similar to that shown in Figure 4; and that the load behavior followed the guideline of light, medium, and heavy load scenarios in the three hours under analysis (it can be extended to a larger situation of hours, without impairing the efficiency and robustness of the proposed model). Besides that, the capacity factor ($\lambda_k$) of the offshore wind farm is 28.37%.

It is important to note that the proposed approach and analyses focus on the optimal connection of OWF, among some candidate buses geographically close to each other within a given region. The regions and respective buses are chosen at random and assuming that such regions are potential for wind energy, a strategy that is similarly used in [19], to obtain maximum penetration of wind power on a network whose structure is already consolidated. The network reinforcements required to achieve a higher penetration rate of wind power is not addressed in the present paper.

The proposed methodology presents robustness, both for smaller systems, e.g., IEEE 14-Bus and IEEE RTS-79, and for large systems, e.g., the Southern Brazilian system that is a more complex network.

The algorithm used to implement the methodology was developed in MATLAB [20], version R2016a, and utilized the FMINCON solver to solve the problems of Nonlinear Programming, using the "Sequential Quadratic Programming (SQP)" simulation model in the optimization algorithm configuration. The simulations were performed on a computer with an Intel Core i7-4500U, 2.40 GHz processor.

*5.1. Case 1: System IEEE 14-Bus.* The first test system used to evaluate the methodology proposed in this work is a modified version of the IEEE 14-Bus system, similar to [3], presented in Figure 5. In this case, the candidate connection points for an OWF are the original buses "12," "'13," and "14," which are considered in a region with high wind potential, and the respective terminal buses of the OWF are buses "15," "'16," and "17." The "$N-1$" contingency criterion is adopted.

Initially, it is considered the system operating with a low target of penetration of wind energy, $\delta = 1\%$. The active power flows in the lines are within the thermal limits with no wind energy penetration. The values of the generation capacity of the conventional generators and the thermal limits of the lines are presented in Tables 3 and 4, respectively.

The wind energy penetration is increased in steps of 1% until a target whose the system operation is unfeasible, given by 22% in this case. Thus, penetration increments of 0.1% are performed from the target of 21% to find the maximum feasible penetration value. Table 5 shows the allocated wind generation capacities $C_k$ for each penetration level and candidate connection point. As it can be observed, the OWF connected to bus "16" is the best option, since this leads to the maximum penetration ($\delta_{\max} = 21.3\%$) and maximum wind generation capacity ($C_{16_{\max}} = 194.47$ MW). For this optimal solution, the switching devices are $\text{sw}_{15} = 0$, $\text{sw}_{16} = 1$, and $\text{sw}_{17} = 0$.

The maximum penetration level obtained in this case is given by $\delta = 21.3\%$. Beyond this point, the power flow in Lines 13-14 violates its limit (90 MW), in the first hour, for the contingency of Lines 9–14. Any increase in penetration is also not supported by buses "15" and "17."

By adding all inequality constraints in Step 5 of the proposed optimization algorithm for both power flow directions, the number of hours in analysis, the number of lines ($N_{\text{lines}_{\text{base}}} = 23$ and $N_{\text{lines}_{“N-1”}} = 22$) and the number of contingencies ($N_{\text{contingencies}} = 20$), the resulting number of inequality constraints is given by

$$N_{\text{constrains}} = (23 \cdot 3 \cdot 2) + (22 \cdot 3 \cdot 2) \cdot 20 = 2778. \tag{10}$$

On the other hand, by using the proposed constraint selection strategy for transmission lines whose thermal limits are violated, the number of constraints is significantly reduced to 44, obtaining a percentage reduction of 98.42%, thus demonstrating the computational efficiency improvement through the proposed methodology.

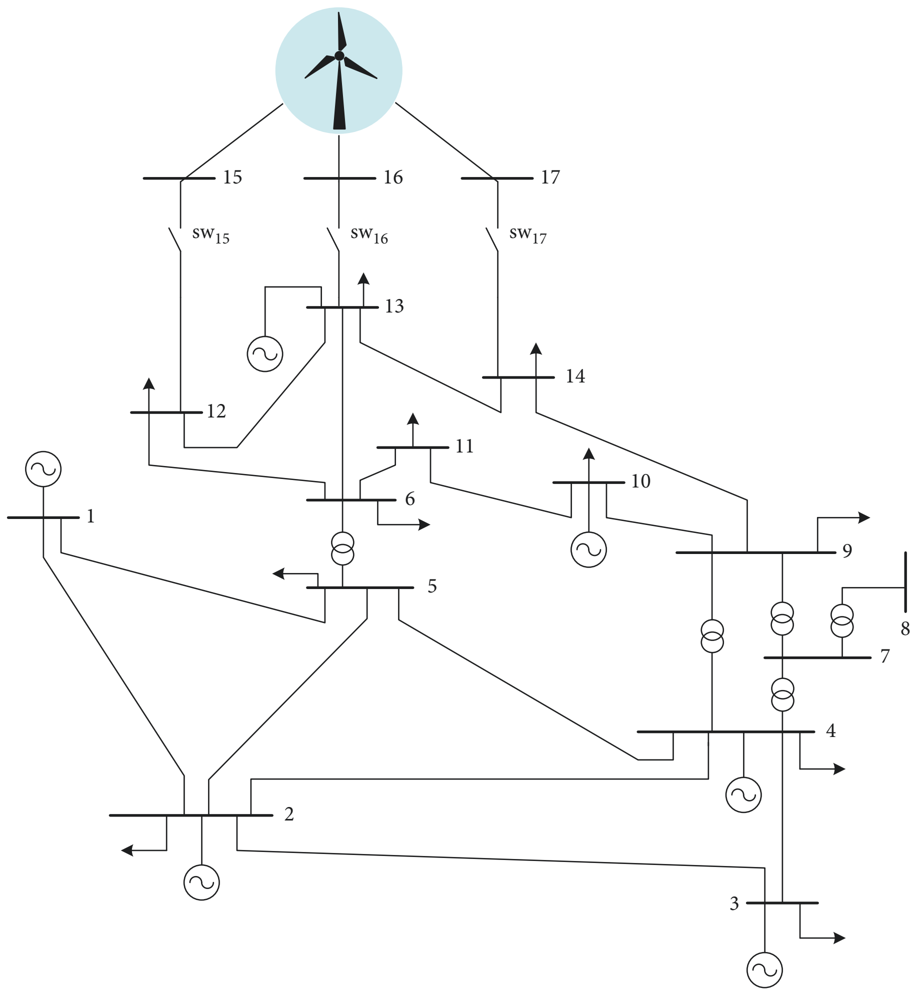


FIGURE 5: Unifilar diagram of the modified IEEE 14-Bus system.

TABLE 3: Capacity of the conventional generators, case 1.

| Bus number | Capacity (MW) |
|---|---|
| 1 | 572.00 |
| 2 | 400.00 |
| 3 | 540.00 |
| 4 | 207.60 |
| 10 | 219.00 |
| 13 | 83.00 |

In order to validate the solution found about the choice of the optimal connection point for the OWF, the solutions for each of the possible connection paths were realized individually, wherein the maximum penetration targets found are equal to $\delta_{15_{\max}} = 17.0\%$, $\delta_{16_{\max}} = 21.3\%$, and $\delta_{17_{\max}} = 11.3\%$, associated with the OWF connected through switches $sw_{15}$, $sw_{16}$, and $sw_{17}$, respectively, validating the optimal solution found through the proposed methodology.

*5.2. Case 2: System IEEE RTS-79 (24-Bus System).* The second test system is the modified version of IEEE RTS-79 (24-Bus system) [16] presented in Figure 6. In this system, buses "10," "6," and "8" are the candidates to receive power from OWF, through terminal additional buses "25," "'26," and "27," respectively.

The active power flows in the transmission lines are within the thermal limits with no wind energy penetration. The values of resistances and reactances of the circuits of this system, as well as the generating capacity of the conventional generators and the lines active power flow, can be found in [16]. For Lines 10–25, 6–26, and 8–27, the values of resistance and reactance are equal to $r_j = 0.0023$ p.u. and $x_j = 0.0839$ p.u., respectively, and the transmission limit is equal to 400 MW.

In this case, the wind power penetration is not feasible for a target of 4%. Thus, penetration increments of 0.1% are performed from the 3% to find the maximum wind power penetration that meets the line limits. Table 6 shows the values of the wind capacity allocated $C_k$ for each penetration level and candidate connection point.

As it can be observed, the bus "25" is the best option with the maximum penetration ($\delta_{\max} = 3.9\%$) and maximum wind generation capacity ($C_{25_{\max}} = 391.81$ MW). The corresponding switches decision is given by $sw_{25} = 1$, $sw_{26} = 0$, and $sw_{27} = 0$. Beyond the wind penetration limit ($\delta \geq 4.0\%$), the power flow in Lines 10–25 overcome its limit (400 MW) in all "$N-1$" contingencies, thus making additional wind

Table 4: Thermal limits of transmission lines, case 1.

| Branch $j$ | Capacity (MW) |
|---|---|
| 1–2 | 600 |
| 1–5 | 300 |
| 2-3 | 250 |
| 2–4 | 300 |
| 2–5 | 350 |
| 3-4 | 300 |
| 4-5 | 150 |
| 4–7 | 400 |
| 4–9 | 250 |
| 5-6 | 700 |
| 6–11 | 90 |
| 6–12 | 250 |
| 6–13 | 250 |
| 7-8 | 200 |
| 7–9 | 200 |
| 9-10 | 300 |
| 9–14 | 200 |
| 10-11 | 200 |
| 12-13 | 150 |
| 13-14 | 90 |
| 12–15 | 200 |
| 13–16 | 200 |
| 14–17 | 200 |

Table 5: Allocated capacity (MW) for each penetration level and candidate connection, case 1.

| $\delta$ (%) | Allocated capacity | | |
|---|---|---|---|
| | $C_{15}$ | $C_{16}$ | $C_{17}$ |
| 1.0 | 0.00 | 9.13 | 0.00 |
| 2.0 | 0.00 | 18.26 | 0.00 |
| 3.0 | 0.00 | 27.39 | 0.00 |
| 4.0 | 0.00 | 36.52 | 0.00 |
| 5.0 | 0.00 | 45.65 | 0.00 |
| 6.0 | 0.00 | 54.78 | 0.00 |
| 7.0 | 0.00 | 63.91 | 0.00 |
| 8.0 | 0.00 | 73.04 | 0.00 |
| 9.0 | 0.00 | 82.17 | 0.00 |
| 10.0 | 0.00 | 91.30 | 0.00 |
| 11.0 | 0.00 | 100.43 | 0.00 |
| 12.0 | 0.00 | 109.56 | 0.00 |
| 13.0 | 0.00 | 118.69 | 0.00 |
| 14.0 | 0.00 | 127.82 | 0.00 |
| 15.0 | 0.00 | 136.95 | 0.00 |
| 16.0 | 0.00 | 146.08 | 0.00 |
| 17.0 | 0.00 | 155.21 | 0.00 |
| 18.0 | 0.00 | 164.34 | 0.00 |
| 19.0 | 0.00 | 173.47 | 0.00 |
| 20.0 | 0.00 | 182.60 | 0.00 |
| 21.0 | 0.00 | 191.73 | 0.00 |
| 21.1 | 0.00 | 192.64 | 0.00 |
| 21.2 | 0.00 | 193.55 | 0.00 |
| 21.3 | 0.00 | 194.47 | 0.00 |

power unfeasible. Any increase in penetration is also not supported by buses "26" and "27."

For this system, the number of transmission lines are given by $N_{\text{lines}_{\text{base}}} = 41$ and $N_{\text{lines}_{\text{“}N-1\text{”}}} = 40$, whereas the number of contingencies is $N_{\text{contingencies}} = 38$, resulting in a number of inequality constraints given by equation (11). On the other hand, the proposed strategy that consists of considering only the active constraints leads to the significantly reduced number of 1530, obtaining a percentage reduction of 83.66%, as expected for the computational efficiency.

$$N_{\text{constrains}} = (41 \cdot 3 \cdot 2) + (40 \cdot 3 \cdot 2) \cdot 38 = 9366. \tag{11}$$

In order to validate the solution found about the choice of the optimal connection point for the OWF, the solutions for each of the possible connection paths $sw_{25}$, $sw_{26}$, and $sw_{27}$ were realized individually, wherein the maximum penetration targets found are equal to $\delta_{25_{\max}} = 3.9\%$, $\delta_{26_{\max}} = 2.9\%$, and $\delta_{27_{\max}} = 2.3\%$, respectively.

*5.3. Case 3: Southern Brazilian System.* The third test system is the modified version of the Southern Brazilian System [17, 18], presented in Figure 7. This system is widely used for transmission expansion planning studies, so the thermal limits of the lines are very close to the values of the active power flows found in the base case. In this sense, it is not possible to penetrate wind energy in the base topology without violating the limits of some transmission lines, even at shallow levels. Due to such characteristic, it is considered, in this case, that the system is expanded by adding to it some candidate transmission lines, as shown in Figure 7 (dashed lines). It is important to note that this measure does not interfere in the efficiency of the methodology proposed in this paper since the proposal is to evaluate the maximum penetration of wind energy into a system whose structure is previously defined. The values of resistances and reactances of the circuits, as well as the generating capacity of the conventional generators and line limits can be found in [17, 18]. For Lines 44–47, 43–48, and 34–49, the resistance and reactance values are equal to $r_j = 0.01250$ p.u. and $x_j = 0.08205$ p.u., respectively, whereas their limits are equal to 600 MW. Buses "47," "48," and "49" are the candidate points to connect an OWF and the "$N-1$" contingency criterion is also considered.

For this practical system, an increase of 3% in wind energy penetration is already infeasible. Thus, the penetration increments of 0.1% are performed from the level 2% to find the maximum feasible penetration target. Table 7 shows the values of the wind capacity allocated $C_k$ for each penetration level and candidate connection point.

As it can be observed, the offshore wind park connected to the bus 48 was chosen as the optimal connection site to obtain maximum penetration ($\delta_{\max} = 2.4\%$) and maximum wind generation capacity ($C_{48_{\max}} = 581.94$ MW), with the switches being arranged in the optimum configuration: $sw_{47} = 0$, $sw_{48} = 1$, and $sw_{49} = 0$. Any increase in penetration is also not supported by buses "47" and "49."

$$N_{\text{constrains}} = (123 \cdot 3 \cdot 2) + (122 \cdot 3 \cdot 2) \cdot 120 = 88578. \tag{12}$$

Above the maximum feasible penetration ($\delta \geq 2.5\%$), the power flow in Lines 43–48 overcomes the respective limit

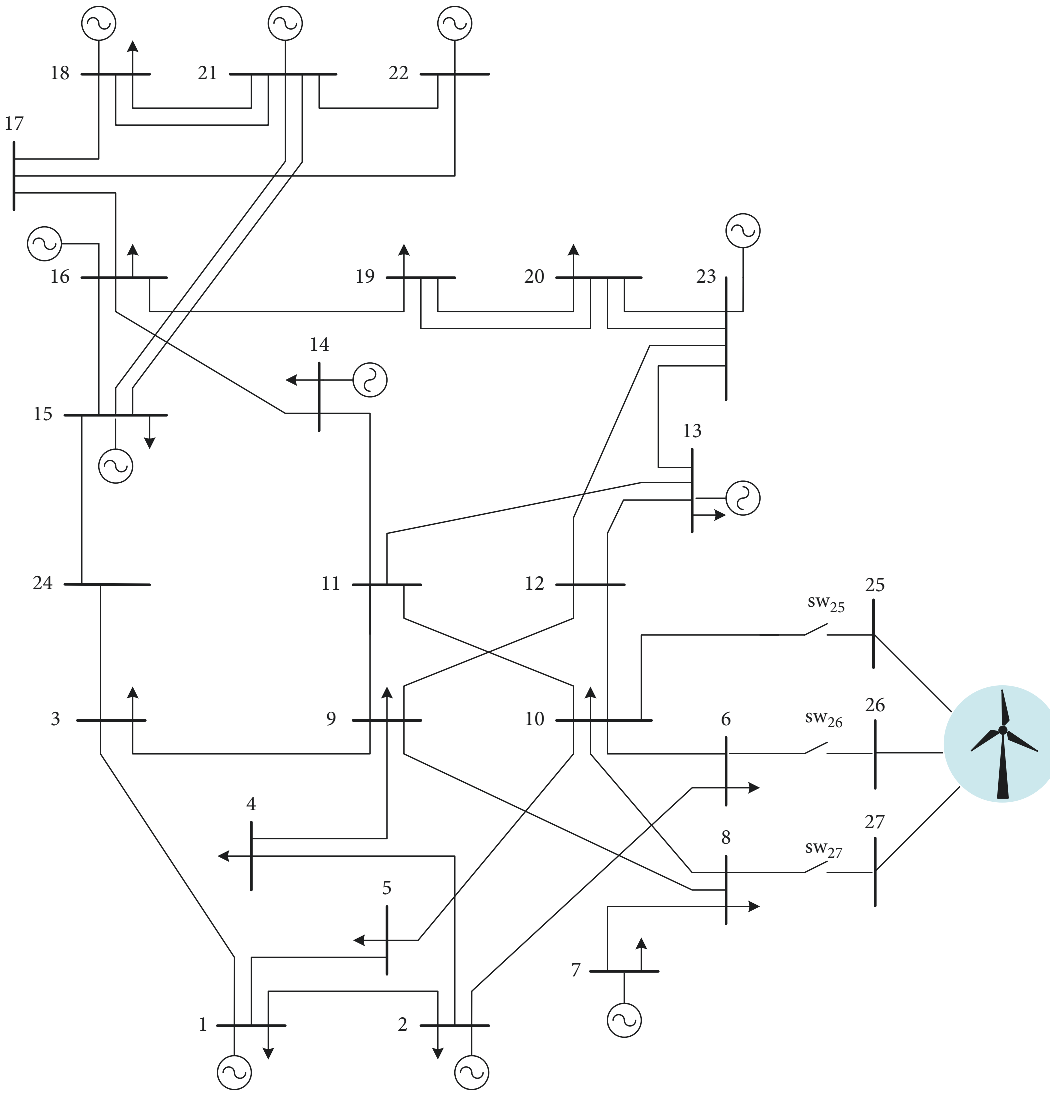


Figure 6: Unifilar diagram of the modified IEEE RTS-79 system.

Table 6: Allocated capacity (MW) for each penetration and candidate connection, case 2.

| $\delta$ (%) | Allocated capacity | | |
|---|---|---|---|
| | $C_{25}$ | $C_{26}$ | $C_{27}$ |
| 1.0 | 100.46 | 0.00 | 0.00 |
| 2.0 | 200.93 | 0.00 | 0.00 |
| 3.0 | 301.39 | 0.00 | 0.00 |
| 3.1 | 311.44 | 0.00 | 0.00 |
| 3.2 | 321.49 | 0.00 | 0.00 |
| 3.3 | 331.53 | 0.00 | 0.00 |
| 3.4 | 341.58 | 0.00 | 0.00 |
| 3.5 | 351.63 | 0.00 | 0.00 |
| 3.6 | 361.67 | 0.00 | 0.00 |
| 3.7 | 371.72 | 0.00 | 0.00 |
| 3.8 | 381.77 | 0.00 | 0.00 |
| 3.9 | 391.81 | 0.00 | 0.00 |

(600 MW) for all "$N-1$" contingency cases, thus making an additional injection of wind power into the system unfeasible.

In Case 3, there is $N_{\text{lines}_{\text{base}}} = 123$, $N_{\text{lines}_{\text{"}N-1\text{"}}} = 122$, $N_{\text{contingencies}} = 120$, and when the strategy for selecting only the active line constraints is not applied:

On the other hand, when only the active lines are selected as the proposed approach, the resulted number of constraints is reduced to 3232 for increasing the computational efficiency.

The solutions found for each OWF connection possibility, when they are realized individually through the $\text{sw}_{47}$, $\text{sw}_{48}$, and $\text{sw}_{49}$ switches, are $\delta_{47_{\max}} = 2.1\%$, $\delta_{48_{\max}} = 2.4\%$, and $\delta_{49_{\max}} = 1.5\%$, respectively. With these results, the solution found through the proposed approach is validated.

*5.4. Runtimes.* The typical runtimes for the evaluated test systems by using the proposed methodology are presented in Table 8.

## 6. Conclusions

In this paper was proposed a novel approach for determining the optimal connection of an offshore wind farm to the

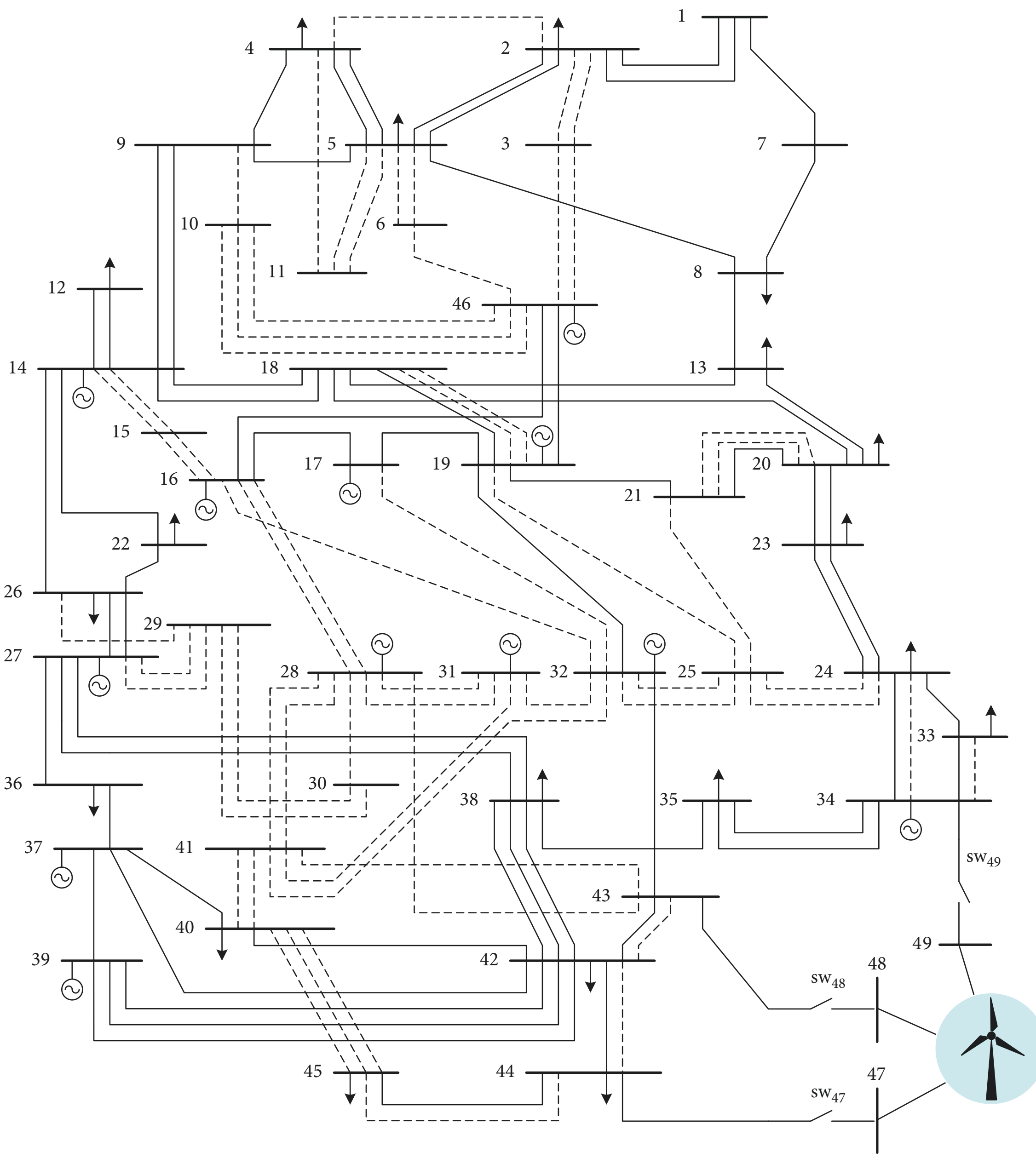


Figure 7: Unifilar diagram of the modified Southern Brazilian system.

Table 7: Allocated capacity (MW) for each penetration level and candidate connection, case 3.

| $\delta$ (%) | Allocated capacity | | |
|---|---|---|---|
| | $C_{47}$ | $C_{48}$ | $C_{49}$ |
| 0.1 | 0.00 | 24.25 | 0.00 |
| 1.1 | 0.00 | 266.72 | 0.00 |
| 2.1 | 0.00 | 509.20 | 0.00 |
| 2.2 | 0.00 | 533.45 | 0.00 |
| 2.3 | 0.00 | 557.69 | 0.00 |
| 2.4 | 0.00 | 581.94 | 0.00 |

onshore network, among some regionally close candidate points in a given region, aiming at obtaining the maximum wind power penetration, observing the network transmission

Table 8: Typical runtimes for the evaluated test systems.

| Case | Runtime (sec) |
|---|---|
| IEEE 14-Bus system | 503 |
| IEEE RTS-79 system (24-Bus system) | 216 |
| Southern Brazilian system | 5692 |

limits and the "$N-1$" contingency criterion. In addition, the formulation allows representing the stochastic nature of winds and the different behavior of the load, by using hourly time series. Network security criteria were analyzed for each hour of the time series, thus generating a large dimensionality of power flow constraints. For handling this feature, an efficient strategy is proposed to select only active line limit constraints for the optimization process, which leads to the computational efficiency of the proposed approach. Besides, the objective function of the model refers to minimum loss in the transmission network for an efficient and secure penetration of wind power.

Initially, the results are presented in an 11-Bus tutorial system with two potential offshore wind farm connection sites. Then, the proposed methodology was evaluated in three systems renowned in the literature: IEEE 14-Bus, IEEE 79-RTS, and Southern Brazilian system. With the analysis of these results, it was observed that the site of installation and connection of the OWF to the grid that provides the maximum penetration of wind power to the system is selected as the optimal point of connection. The results found through the proposed methodology are satisfactory for all the systems tested when compared with the solutions for each of the possible connection paths when they were realized individually.

Thus, the proposed approach can be considered efficient in the search for the optimum point of connection of an OWF to an onshore network, among some regionally close candidate areas, guaranteeing maximum penetration of wind power to the system, respecting the thermal limits of transmission lines and considering the all "$N-1$" contingency scenarios. Also, the method proposes to include the analysis of minimum losses in the study, thus ensuring that there is the least possible impact of losses in the operation of the system. Another proposed contribution is the selection of constraints that will compose the MINLP problem, an interesting and promising strategy since it significantly reduces the magnitude of the constraint vector, composed only of those referring to transmission lines whose limits have been violated, guaranteeing greater computational efficiency in the processing of the optimization problem under analysis.

## Nomenclature

*Indices*

$h$: Time series position index
$i$: Network bus position index
$j$: Network branch index
$k$: Potential wind farm network location index
$r$: DC load flow reference bus position index
$s$: Power flow contingency scenario index
$t$: Iteration of the DC power flow
$n$: Total number of possible switches to connect the wind farm to the grid
$a, b$: Distinct wind farm switches connections

*Constants and Variables*

$\alpha_{j,i}$: DC power transfer distribution factors for branch "$j$" with respect to bus "$i$"
$D^{\mathrm{AVG}}$: Average system power demand level (MW)
$L_j$: Thermal capacity for branch "$j$" (MW)
$G_i$: Conventional generation power in bus "$i$" (MW)
$P_j^{\mathrm{loss}}$: Transmission losses of the branch "$j$" (MW)
$x_j$: Reactance of the branch "$j$"
$r_j$: Resistance of the branch "$j$"
$g_j$: Conductance of the branch "$j$"
$\theta_j$: Angular difference between buses of the branch "$j$"
$P_i$: Active power injection in bus "$i$" (MW)
$f_j$: Power flow in the branch "$j$" (MW)
$B'$: Nodal admittance matrix
$\lambda_k$: Capacity factor of the wind farm "$k$"
$\delta$: Wind energy penetration target (%)
$\Delta\delta$: Discrete wind energy penetration target increment (%)
$t_h^{\mathrm{APR}}$: Geographically smoothed total system wind power production value in hour "$h$" (MW)
$t_{k_h}$: Nominal 1 MW wind power time series "$k$" in hour "$h$" (MW)
$\gamma_{j,h,s}$: Partial load flow solution of load/conventional plant in branch "$j$," hour "$h$" under contingency scenario "$s$" (MW)
$C_k$: "$k$" wind capacity optimization variables (MW)
$\mathrm{sw}_k$: "$k$"switch key that will connect (or not) the offshore wind farm to the onshore system candidate bus
$N_{\mathrm{constrains}}$: Total number of constraints
$N_{\mathrm{lines}_{\mathrm{base}}}$: Number of transmission lines existing in the base case
$N_{\mathrm{lines}_{\text{“}N-1\text{”}}}$: Number of transmission lines in a "$N-1$" contingency scenario
$N_{\mathrm{contingencies}}$: Number of contingencies.

## Data Availability

(1) The 11-Bus system (Tutorial Example) data used to support the findings of this study have been deposited in the repository [13] (ISBN-13: 978-0070359581; ISBN-10: 007035958X). (2) The IEEE 14-Bus system (Case 1) data used to support the findings of this study have been deposited in the repository [3] (https://doi.org/10.1109/psce.2009.4840126), or in the (Electrical Engineering Dept., University of Washington, Seattle, Washington, U.S.A.) available online in (http://www.ee.washington.edu/research/pstca/). (3) The IEEE RTS-79 (24-Bus system) (Case 2) data used to support the findings of this study have been deposited in the repository [16] (https://doi.org/10.1109/tpas.1979.319398). (4) The Southern Brazilian System (Case 3) data used to support the findings of this study have been deposited in the repository [17] (https://doi.org/10.1109/59.317588), or in the repository [18] (https://doi.org/10.1109/59.918294).

## Conflicts of Interest

The authors declare no conflicts of interest regarding this manuscript.

## Acknowledgments

The authors thank the Coordination for the Improvement of Higher Education Personnel (CAPES), Brazilian National Research Council (CNPq), Foundation for Supporting Research in of Minas Gerais (FAPEMIG), Electric Power National Institute (INERGE), Postgraduate Program in

Electrical Engineering of the Federal University of Juiz de Fora (PPEE/UFJF), and Federal Institute of Northern Minas Gerais (IFNMG) for supporting this work.

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