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Coordination of power reactive management considering variations in wind speed from wind farms and power transmission limits

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Abstract. This paper presents a methodology that allows performing the optimized and coordinated management of reactive power injection in power systems with wind farms and other sources of reactive injection, such as capacitor banks or static voltage compensators, minimizing the losses in the transmission power system. The variation in wind speed is characterized by the Weibull distribution. The values of this distribution are used as input data for the optimal power flow model whose output provides a sample of values for defining the confidence intervals of the injected reactive power, as well as the voltage values in each bus of the electrical system. The proposed methodology was tested using a real 140 buses system to determine the dispatch of reactive sources available in the power system. The results found by the proposal can help to make a better management of the available reactive sources in the real-time operation.

Keywords: optimal power flow, reactive power, wind farms, DFIG, active power losses, voltage stability.

1 Introduction

The increase in intermittent generation sources in the power networks makes the coordination of injected reactive power more complex to maintain the voltage profile within operating voltage limits [1], [2]. In recent years, the injection of reactive power by wind farms (WF) has been analyzed to avoid installing other sources of injection of reactive in the power system [3]. In general, this farms has a doubly-fed induction generator (DFIG), which can inject certain range of reactive power [4], [5]. The reactive power provided by DFIG depends on the power converter devices [6]. The dispatch of this reactive power is important for maintaining the voltage level and minimizing apparent power of the network losses [7], [8].

Another source of reactive power is the Static Var Compensator (SVC) that presents good results in the control and stability of the voltage in power networks [9]. Adequate coordination of SVC and other reactive injection sources can result in lower operating cost of the power transmission systems [10], [11]. To operate the reactive power management of WF and SVC, some techniques can be used, such as the optimal power flow (OPF), which determines the optimal operating point of electrical systems, considering the physical and operational restrictions of the electrical network.

The OPF can adjust to all the reactive power control elements available in the electrical system [12]. In the specialized literature, several OPF have been presented with more than one objective [13]. However, the variation in wind resource have been little explored [14]. In most of the studies that explore such variation, they consider deterministic scenarios taking into account a single value for each operation value [15]. In some other studies, probability curves for wind variation [16], [17] have been considered, but without carrying out confidence intervals for the values found for reactive power. These confidence intervals can help decision makers of the electrical system to adjust the reference values of the controllers of the reactive sources. Such adjustment has been considered in some works as a secondary control performed by the operator of the control center to improve the local voltage in several regions of the power system [18], [19].

In the specialized literature, several methodologies are available for determining the optimal operating point considering the physical restrictions of the reactive injection sources, operational restrictions of the electrical system and different objectives for optimal operation.

In Amaris and Alonso [12], a genetic algorithm was presented to solve a multi-objective problem considering SVC devices and wind farms. However, this study did not analyze the variation in reactive power injection due to changes in wind speed. In Da Rosa and Belati [20], it is considered changes in wind speed within the OPF, but disregarding other reactive injection devices, such as SVC devices that can collaborate in reducing losses active power and improving the stability of the voltage profile. Nevertheless, a verification of the total current flow in the transmission lines must be analyzed, due to an increase in the reactive power injection could bring their operation close to their thermal capacity.

The contribution of this work is a methodology that allows performing the optimized and coordinated management of reactive power injection in power systems with wind farms and other sources of reactive injection, minimizing the total losses in the transmission system. Wind speed's variations are characterized by the Weibull distribution. The values of this distribution are input data for the OPF model whose output provides a sample of values for defining the confidence intervals of the injected reactive power and the voltage values in each bus of the electrical system.

2 Proposed Methodology

The proposed methodology uses the electrical parameters of the transmission lines, a daily load profile and the generation dispatch values as input data. The proposed methodology is based on a OPF that minimizes the objective function composed by apparent power of the network losses. The following are the main modeling equations considered in the OPF.

2.1 Modeling power polynomial of the DFIG

For modelling the characteristics of the DFIG wind turbine, we considered that the injection of active (P_{GW}) and reactive (Q_{GW}) per unit (p.u.) are determined for each wind speed (v) considering the modelling described in Rather and Chen [21]. Equations (1) and (2) represent respectively the active and reactive power polynomials with respect to wind speed.:

$$P_{GW} = -7.69\times10^{(-5)}v^6 + 4.31\times10^{(-3)}v^5 - 9.83\times10^{(-2)}v^4 + 1.17v^3 - 7.60v^2 + 2.56\times10v - 3.5\times10. \quad (1)$$

$$Q_{GW} = -2.53\times10^{(-5)}v^6 + 1.42\times10^{(-3)}v^5 - 3.23\times10^{(-2)}v^4 + 3.84\times10^{(-1)}v^3 - 2.50v^2 + 8.42v - 1.15\times10. \quad (2)$$

In general, the Weibull distribution is used to represent wind speed characteristics. In the proposed methodology, the Weibull distribution is used to describe the uncertainty of wind speed, being defined by eq. (3).

$$f_v(v) = (k/c)(v/c)^{k-1} exp(-v/c)^k. \quad (3)$$

Where k is the shape parameter and c is the scale parameter, obtained from historical wind data.

2.2 Modeling SVC Devices

In principle, SVC is considered as an adjustable reactance with threshold values for the trip angle or limits on the reactance [22].In the model, the total susceptance of the SVC is determined by the parallel equivalent susceptances of the separately controlled modules. Thus, the susceptibility has a lower limit ($BSVC_{min}$) and an upper limit ($BSVC_{max}$). The power supplied by the SVC to the system is calculated by:

$$Q_{SVC} = V_{SVC}{}^2 \times B_{SVC}. \quad (4)$$

Where:
Q_{SVC} reactive power reduced by SVC for the system;
V_{SVC} voltage at the SVC connection bar;
B_{SVC} susceptance equivalent to SVC.

We used a reactive OPF for the management of reactive power on the transmission network. The reactive OPF is a particular case with fixed active power and the optimization is performed considering the reactive power variables. The mathematical model being that:

$$minF(x) = min(\sqrt{\sum_{l=1}^{Nl}(P^2{}_{Losses,l} + Q^2{}_{Losses,l}})). \quad (5)$$

s.t.:

$$P_k = (P_{Gk} + P_{GkW}) - P_{Lk} = V_k \sum_{m \in k} V_m (G_{km} \cos\theta_{km} + B_{km} sen\theta_{km}). \quad (6)$$

$$Q_k = (Q_{Gk} + Q_{GkW}) - Q_{Lk} + Q_k{}^{sh} = V_k \sum_{m \in k} V_m (G_{km} sen\theta_{km} - B_{km} cos\theta_{km}). \quad (7)$$

$$V_{k\min} \le V_k \le V_{k\max}. \quad (8)$$

$$Q_{Gk\min} \le Q_{Gk} \le Q_{Gk\max}. \quad (9)$$

$$B_{SVC\min} \le B_{SVC} \le B_{SVC\max}. \quad (10)$$

$$Q_{Gkw\min} \le Q_{Gkw} \le Q_{Gkw\max}. \quad (11)$$

$$\sqrt{P_{Losses,l} + Q_{Losses,l}} \le S_{Losses,l,\max}. \quad (12)$$

Where:

$P_{Losses,l}$	Active power losses in branch *l*
$Q_{Losses,l}$	Reactive power losses in branch *l*
$S_{Losses,l,max}$	Maximum flow limit on the branch *l*
g_{km}	Line conductance between bus *k* and *m*;
V_k	Bus voltage module *k*;
V_m	Bus voltage module *m*;
θ_{km}	Phase angle between bus *k* and *m*;
κ	Set of all buses *m* adjacent to bus *k,* including bus *k* itself*;*
N	Number of buses;
P_k	Liquid value of injection of active power in bus *k*;
P_{Gk}	Generation of active power in the bus *k*;
P_{GkW}	Generation of active power from the wind turbine in bus k;
P_{Lk}	Active load on bus *k*;
Q_k	Liquid value of injection of reactive power in bus *k*;
Q_{Gk}	Generation of reactive power in bus *k* by other reactive sources;
Q_{Gkw}	Reactive power of the wind turbine in bus *k*;
Q_{Lk}	Reactive load on bus *k*;
$Q_k{}^{sh}$	Reactive power injection due to *k*-bus shunt elements;
V_{kmin}	Minimum voltage limit in the System;
V_{kmax}	Maximum voltage limit in the System;
B_{SVCmin}	Minimum susceptibility limit of the SVC connected to bus *k*;
B_{SVCmax}	Maximum susceptibility limit of the SVC connected to bus *k*;
Q_{Gkmin}	Minimum limit of reactive power that can be inserted by the generator connected to bus *k*;
Q_{Gkmax}	Maximum limit of reactive power that can be inserted by the generator connected to bus *k*;
Q_{GkWmin}	Minimum limit of reactive power that can be inserted by the wind turbine connected to bus *k*;
Q_{GkWmax}	Maximum limit of reactive power that can be inserted by the wind turbine connected to

		bus k;
G_{km}		is the real part of the admittance matrix element Y_{BUS} corresponding to row k and column m;
B_{km}		is the imaginary part of the admittance matrix element Y_{BUS} corresponding to row k and column m.

Constraint in eq. (7) shows that the methodology considers the power that can be injected by any reactive source installed in the system. Constrain in eq. (9) considers the physical limitations of electrical energy conversion devices, as explained in Ghaljehei [19]. Additionally, the values of P_{GkW} and Q_{GkW} are calculated using eq. (1) and eq. (2), and the wind value (v) from eq. (3) must be informed. From eq. (3) it is possible to create a set of speed values in order to create a sample and obtain a confidence interval for the values injected by the wind turbines.

2.3 Creation of the Confidencial Interval PDF for each Wind Range

According to Vidica [23], with smaller samples equal to 25, confidence intervals can be calculated using the expressions in eq. (13) and eq. (14).

$$I_{Low} = \mu - t(K-1.005)\frac{\sigma}{\sqrt{K}}. \tag{13}$$

$$I_{High} = \mu + t(K-1.005)\frac{\sigma}{\sqrt{K}}. \tag{14}$$

Where: μ is the arithmetic mean of the sample and σ the standard deviation of the sample obtained by k executions of the OPF. The $t(K-1.005)$ is obtained from the t distribution table. Considering $K=25$, we have $t(K-1.005)=2.060$, for 95% confidence interval. Considering that it is desired to have information for the operation in real time, it was decided to work with speed ranges and within each speed range obtain 25 samples. This criterion can get a quick response as shown in the following section. Figure 1 shows the sequence of steps of the proposed methodology. Such sequence of steps must be performed for each speed range defined by the operator and for each operating point of the system under study.

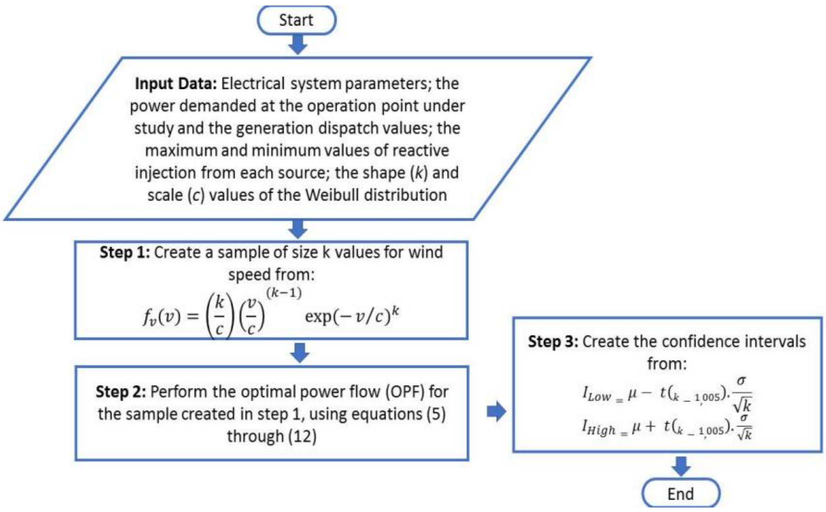

Figure 1. Main Steps of the proposed methodology

3 Results and Discussions

The 140 buses network chosen for the analysis represents an area of the Spain's transmission system 140 buses with five voltage levels of 380 kV, 132 kV, 45 kV, 15 kV and 380V as explained in Amaris and Alonso

[12] and illustrated in Figure 2. This system has three wind farms and two SVC devices. The third wind farm, of 10 MW, is connected to bus 21, together with a local compensator of 8 Mvar to correct the power factor. Finally, the two SVC are connected to bus 19 and 57 with installed powers of 7 and 5 Mvar, respectively. The optimal allocation of WF and SVC is outside the scope of this work.

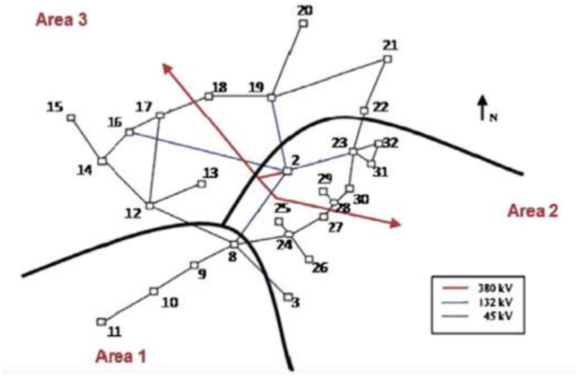

Figure 2. Real 140 buses test system

The system has a maximum load of 1.4 p.u and voltage limits are in 0.95 to 1.05 p.u. The proposed model was implemented in the AMPL programming environment [24], using the Knitro solver. The simulations will be carried out considering the variable wind speed, in order to reduce the apparent power of the network losses. Using the Rstudio software to create the intervals, it takes 2.5 seconds to read the AMPL files and show the intervals. And with 25 AMPL runs on Knitro for each range, it took 25 seconds to get the AMPL files, so the average time is 30 seconds to find the values for a range.

Table 1 shows the reactive power injection and active power losses values calculated by the proposed methodology for a speed range between 8 m/s and 14 m/s. This speed range is considered due to that in this range there is injection of reactive power by the wind turbines, as explained in Souza [22].

Table 1. Reactive power injection and active power losses for 8 to 14 m/s wind speed

Wind Speed (m/s)	WF1		WF3		WF2		SVC1		SVC2		Active Power Losses (MW)	Reactive Power Losses (Mvar)
	Bus	Q(Mvar)	Bus	Q(Mvar)	Bus	Q(Mvar)	Bus	Q(Mvar)	Bus	Q(Mvar)		
8	9	0.95	21	7.84	32	1.70	19	6.89	57	4.66	2.93	21.56
9	9	0.95	21	7.60	32	1.70	19	6.89	57	4.66	2.79	20.29
10	9	0.95	21	7.54	32	1.70	19	6.62	57	4.67	2.67	19.15
11	9	0.95	21	7.39	32	1.70	19	6.12	57	4.67	2.58	18.10
12	9	0.95	21	7.38	32	1.70	19	5.55	57	4.68	2.48	16.85
13	9	0.95	21	7.23	32	1.70	19	4.94	57	4.69	2.41	15.49
14	9	0.95	21	7.18	32	1.70	19	4.74	57	4.70	2.39	15.03

According to the results shown in Tab. 1, it is possible to see that the variation of reactive power injection in some buses is little influenced by the wind speed, that is the case of bus 32 where the injected value from WF2 was 1.7 Mvar for all speed values. However, in bus 21 the injected power values of WF3 vary from 7.18 to 7.84 Mvar, which helps to reduce the total electrical losses in the electrical system. The results shown in Tab. 1 reinforces the proposal of this work to determine confidence intervals for the values of reactive power injected per bus because of these intervals can help to achieve the objectives defined by the operator.

The effectiveness of the proposal is demonstrated when comparing the values of losses and injected reactive power determined by the model explained in Amaris and Alonso [12]. The active power losses obtained by [12] are in the range between 3.39 and 2.38 MW, considering the maximization of voltage stability and minimization of electrical losses, with a variation of reactive power injection from 17 to 12 Mvar provided by SVC 1 and 2. With the proposal, the active power losses are lower than 2.93 MW, within the speed range of 8 to

14 m/s, with a maximum reactive injection of 6.89 Mvar by SVC1.

Figure 3 shows the voltage profile of electrical systems for the wind speed of 8, 11and 14 m/s. This figure shows that the reactive power improves the voltage profile. When this figure is compared with the power losses minimization profile scenarios presented in Amaris and Alonso [12], we can be observed that the proposal allows to obtain a greater number of bars with a voltage close to 1 p.u. and with lower values of electrical losses in the system.

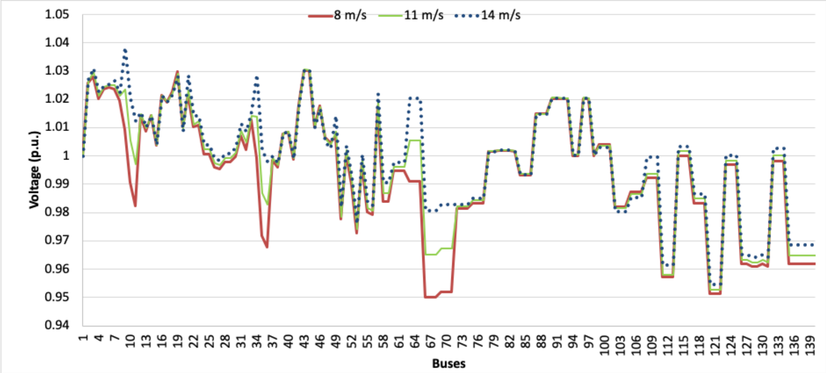

Figure 3. Voltage profile for best case with lower value of apparent power of the network losses

In order to determine the reactive power injection confidence intervals, the speed range between 8 m/s to 14 m/s was subdivided into 3 ranges, with bandwidth of 1 m/s for the first two ranges and a 4 m/s bandwidth for the last range. Within each range, 25 speed values are generated that follow a Weibull distribution, with a shape and scale parameter equal to 1.27 and 2.78 k, respectively, using eq. (3). Table 2 presents the values of the confidence interval for reactive power Q and voltage V in the buses with WF and SVC, according to eq. (13) and eq. (14), considering the minimization of apparent power of the network losses. In this table, the lower and upper limit are represented by I_l and I_u, respectively. Likewise, the confidence intervals are in Mvar and p.u. for the values of Q and V, respectively. It is observed that in the first speed range, the WF3 in bus 21 has a little variation in reactive power to maintain the voltage at 1.02 p.u., compared to other sources of reactive injection that do not show variation. In the second and third speed range, this WF3 and SVC1 are the only reactive sources that have an injected reactive power variation. These results reinforce the proposal of this work to determine confidence intervals for the reactive power values injected per buses, as these intervals can help the operator to define which should be the most critical bar with wind variation.

Table 2. Confidence interval considering the minimization of power losses

Range	Bus	9	21	32	19	57
8 to 9 m/s	I_u Q	0,95	7,61	1,70	6,71	4,64
	I_l Q	0,95	7,60	1,70	7,33	4,64
	I_u V	1,01	1,02	1,00	1,03	1,02
	I_l V	1,01	1,02	1,00	1,03	1,02
9 to 10 m/s	I_u Q	0,95	7,57	1,70	6,87	4,64
	I_l Q	0,95	7,55	1,70	6,87	4,65
	I_u V	1,02	1,02	1,00	1,03	1,02
	I_l V	1,02	1,02	1,00	1,03	1,02
10 to 14 m/s	I_u Q	0,95	7,19	1,70	6,91	4,68
	I_l Q	0,95	7,17	1,70	6,91	4,69
	I_u V	1,04	1,03	1,01	1,03	1,02
	I_l V	1,03	1,03	1,01	1,03	1,02

4 Conclusions

This Work presented a methodology to optimally manage reactive power injection in power system with wind farms and other reactive power sources. The variation in wind speed, used in the OPF input, was characterized by the Weibull distribution. Using the Weibull distribution, a set of speed values was created forming a sample and obtaining a confidence interval for the wind generators. The proposed methodology was tested on a real 140 buses system to determine the dispatch of the reactive sources. The results found by OPF were confronted with a methodology using genetic algorithms highlighting that the proposal obtained superior results. Using the methodology, the confidence intervals of the buses with reactive power injection were obtained, showing the maximum and minimum values of the Q and V variables. Finally, the methodology can be applied considering load variations and other objectives.

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