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Artículo Original

A new method for wind power limit calculation using P-V curves and continuation power flow routine

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Abstract

Wind generation can have a significant impact on the power flow, voltage profile and the power quality for customers and electricity suppliers. This paper presents a new method for calculate the wind power limit for each node with the connection of a wind farm. The method considers the static security constrains and voltage system stability using P-V curve and analyzing the distance to voltage collapse. The method was applied and validated on the IEEE 30 bus test system and the results are very close to those obtained in a previous work from other authors. Further evaluation to analyze the influence of the load and interconnection point characteristics in the wind power limit was carried out. In all cases, the system remains voltage stable and increases the distance to voltage collapse.

Keywords: Wind power limit, continuation power flow, P-V curves, voltage collapse

1. Introduction

The world faces a global crisis: a crisis due to the fast and high consumption of fossil fuels and its impact on the environment due to greenhouse gas emissions. In order to fight this crisis, humankind has been developing science and technology. One of main solutions is the developing and use of renewable energies. Among them, one of the most used path ways is wind energy, saving fossil fuels and reducing greenhouse emissions.

The size of wind turbines and wind farms are increasing quickly; a large amount of wind power is integrated into the power system. As the increasing number of large-scale wind farms begins to access the grid, the influence on the power quality and voltage stability is becoming more and more significant. A high penetration of wind energy in a power system may cause important problems due to the random nature of the wind and the characteristics of wind generators. Because of this, people began to pay more attention to wind power integration with the static security constraints. Some examples can be found in literature [1-5].

Static techniques are very useful to determine the load margin or how close the actual system operating state is from the point of voltage collapse point. The majority of this work deals with the determination of the maximum active and reactive power, which is possible to be connected on a system load bus, until the voltage at that bus reaches the voltage collapse point when an additional generation, in particular, wind power is connected to a power system. Generally, this is done through traditional methods of P-V and Q-V curves [6-10]; and few using a P-Q plane [11-13]. In these cases, a wind farm capacity (fixed value) is considered, but not from the point of view of the wind power limit.

For wind power penetration limit calculation, having into account a static security constrains, a method was developed in the literature using a DC power flow algorithm [14]. This method calculates the wind power based on tide constrains, but they despise the line resistance. Thus, the method cannot be applied, for example, in a distribution system.

The aim of this paper is to propose a new method for calculate the wind power limit in the interconnection point of a wind farm with the power system, using continuation power flow routine and taken into account system static security constrains.

2. Materials and Methods

The wind power limit can be defined as the maximum value of wind power connected in the point of common coupling without losing system stability in any aspect and maintaining all the parameters within the limits. For a better comprehension of the concept, a two bus system is shown in Figure 1.

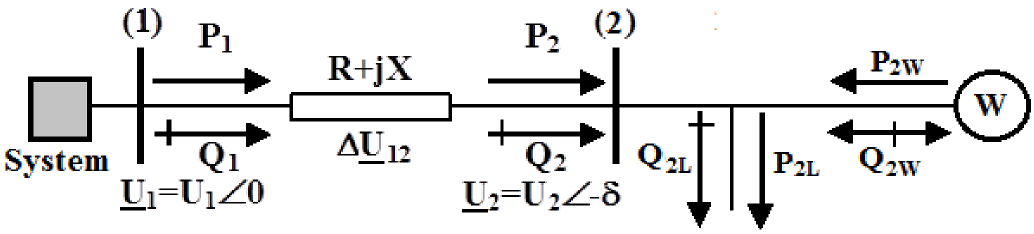

Fig.1 Two bus system

The general expression for calculate the voltage drop ($\Delta \underline{U}$) in the transmission line is given by equation 1:

$$\Delta \underline{U}_{1-2} = \underline{I}\underline{Z} = \underline{I}(R + jX)\ Volt \quad (1)$$

Where the voltage drop depends of the characteristic impedance ($\underline{Z}$) of the line and the circulating current ($\underline{I}$). The expression can be modified substituting the current as function of active power (P) and reactive power (Q). If the voltage (U) and powers in bus1 are known, the current is calculated using equation 2:

$$\underline{I} = \frac{S_1^*}{\underline{U}_1^*} = \frac{P_1 - jQ_1}{U_1} \quad Ampere \quad (2)$$

U_1 is the reference and the absolute value in the sending end of the line; the voltage angle is 0^o. Substituting equation (2) in equation (1) and separating the real and imaginary parts, the voltage drop can be calculated as is show in equation 3:

$$\Delta \underline{U}_{1-2} = \frac{P_1 R + Q_1 X}{U_1} + j\frac{P_1 X - Q_1 R}{U_1} kV \quad (3)$$

Then, the voltage in the receiving end is obtained using equation 4:

$$\underline{U}_2 = \underline{U}_1 - \Delta \underline{U}_{1-2} \quad (4)$$

For calculate the active and reactive losses in the transmission line, is used equation 5:

$$\Delta S = 3I^2 Z10^{-6} = \Delta P + j\Delta Q MVA \tag{5}$$

Substituting the absolute value of the current as function of active, reactive power, and voltage, the expression for losses should be written as is shown in equation 6:

$$\Delta \underline{S}_{1-2} = \frac{P_i^2 + Q_i^2}{U_i^2}(R + jX) = \Delta P_{1-2} + j\Delta Q_{1-2} MVA \tag{6}$$

Where ¨i¨ depends of line side where knowing voltage and power values, and its value, are 1 or 2.

In the analyzed system, the expressions to obtain P_2 y Q_2 are function of the load and the wind power, and they are calculated using the equations 7 and 8:

$$P_2 = P_{2L} - P_{2W} \tag{7}$$
$$Q_2 = Q_{2L} \pm Q_{2W} \tag{8}$$

The active power is always delivered to the system via wind power, but the reactive power may be consumed or supplied, depends of wind turbine technology and operation mode.

To simplify the analysis, the reactive power due to wind turbine is considered zero. So, only active power is supplied from wind turbine. In this case, when the wind power is disconnected, the active and reactive power depends only on the load. Therefore, the losses of the line, its voltage droop and the voltage in the receiving end are depending of P2L and Q2L. The active power transfer for the line went for sending end to receiving end; this is shown in the voltage angles in Figure 2.

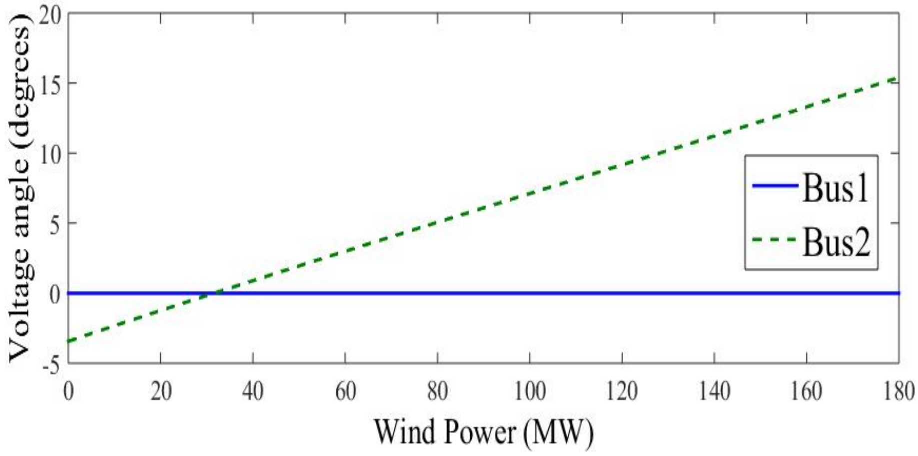

Fig.2 Voltage angle for wind power increase

When the wind power is gradually increased, the active power generated by the wind turbine is consumed by the load, and the system ‘‘see’’ a reduction in load. So, it is possible to treat the wind power as negative load. The P-V curve for this analysis is shown in Figure 3.

If the wind power increases more, it may produce reverse power flow when the wind power is higher than the local load power, so the transfer power is from bus2 to bus1. This change is observed in Figure 2 when the voltage angle in bus2 changes the angle for negative to positive. The reduction in power transfer leads to a reduction in line losses and voltage droop. As a consequence, voltage in bus2 rises. The inflection point is presented when the power transfer is minimum. In this point the losses and voltage droop had minimum values and voltage in bus2 reach its maximum value. A higher value of wind power means that the power losses and voltage droop rise again and voltage in bus2 begins to reduce its value. The entire process is shown in Figure 4.

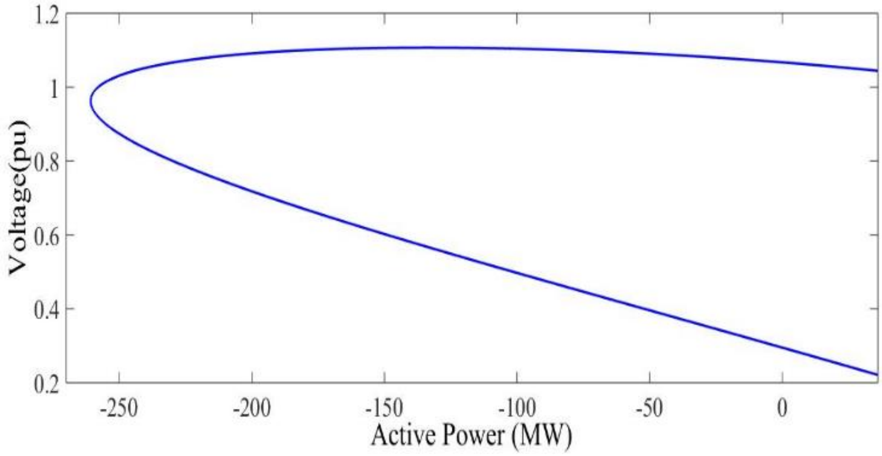

Fig.3 P-V curve in bus1 for increasing wind power

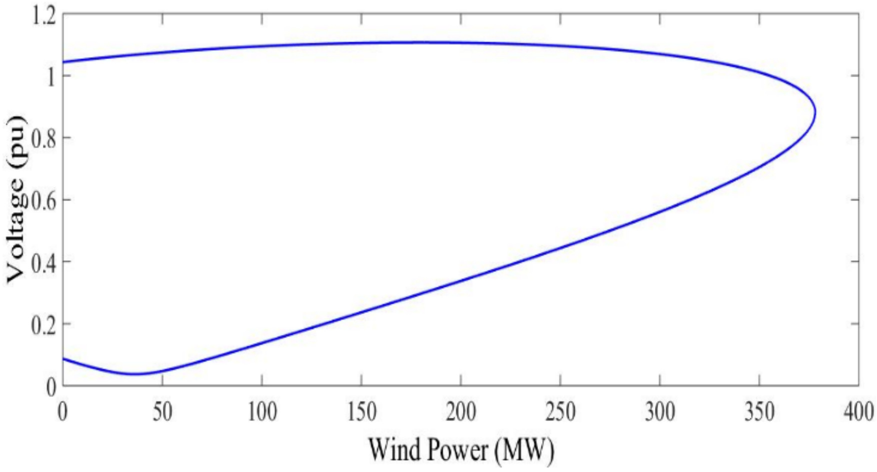

Fig.4 P-V curve in bus2 for increasing wind power

In this case, the wind power limit is not the noose of the curve because the system must operate without violate any static security constrains. Therefore, the wind power limit is the last value of wind power when the system operates within static security limits; in this case scenario, transfer power limits trough the transmission line or voltage in bus2. In the example, the wind power limit is 120 MW, for an upper value of wind a maximum voltage in bus2 is violated.

2.1. Summary description of proposed method

The proposed method for finding the wind power limit using continuation power flow routine in a power system is divided in three steps and can be summarized as follows:

1. First step: System analysis without wind power integration.

a) Set the wind power interconnection point with the power system.

b) Run a power flow routine to establish the initial system conditions.

c) Run a continuation power flow routine in order to construct a P-V curve for finding the distance to voltage collapse in the point of common coupling without the wind power.
   - The active power increment of all loads of the system is 10% at bus load.
   - The reactive power increment of all loads of the system is 10% at bus load.

2. Second step: Wind power limit calculation.

a) Set the wind power conditions in the selected interconnection point.
   - Set the active power increase of wind generator; corresponding with the nominal capacity of the wind turbine.
   - Set the reactive power increase, which depends of wind turbine technology and characteristics.

b) The increment in all loads is zero for active and reactive power. Therefore, the wind power is the only change in the system for generator.

c) Run a power flow routine to establish the initial system conditions.

d) Run a continuation power flow routine in order to obtain the wind power limit in the point of common coupling.

e) The wind power limit is reached when overpass one static security constrain. This constrains are:
   - Transfer power flow through transmissions power lines.
   - Minimum and maximum bus voltages.
   - Reactive power limits in the system conventional generators.

3. Third step: Check system stability with the wind power limit integration.

a) Set the wind power limit value in the point of common coupling.

b) Run a power flow routine to establish the initial system conditions.

c) Run a continuation power flow routine in order to obtain a P-V curve for finding the distance to voltage collapse in the point of common coupling with the wind power.
   - The active power increase of all loads of the system is 10% at bus load.
   - The reactive power increase of all loads of the system is 10% at bus load.

d) Analyse the results and compare with the first step. Check if in the system remains voltage stable using P-V curve and what is the new distance to voltage collapse.

2.2. Method validation

In this section, the validation of the proposed method is carried out. First, the wind power limit is calculated using the second step of the method. Then, the result is compared with the obtained in [15]. A graphical method for estimating network limits for wind power integration is in this reference used; the capability chart gives a clear indication of the permissible wind farm size. The method is applied in the IEEE 30-bus system, presenting the capability chart and the limit for wind power integration in the bus30.

The active and reactive power increments for wind power limit calculation in bus30 are fixed. In this case, the active power increment was fixed in 0.5 MW with a power factor nearly to one, and its increments simulate a variable speed wind turbine. A power flow is running to check that all variables compliment the limits and initial conditions; if these conditions are cover, a continuation power flow is running to find the wind power limit.

The wind power limit for this case was 31.5 MW and the first static constrains violated was the maximum voltage in the bus30. The maximum wind power in [15] was 32.35 MW. The validation is observed once the difference is 2.6%.

3. Results and Discussion

With the method validated is possible to run several simulations for a wind power limit analysis in the IEEE 30-bus system. The purpose is to calculate and analyse the wind power limit for different load conditions and interconnection point locations.

To analyse load condition, it is necessary to take into account different active and reactive power in the selected bus. The bus30 is chosen for the study and five load cases are considered. Case 1 is the base case scenario; in case 2 and 3 the active power is reduced with the same power factor. Finally, case 4 and 5 are maintaining the active power of case 3 and change the reactive power consumption, decreasing the power factor of the load. Only the load on bus30 is changed, the rest of the loads maintain the same value.

The procedure is as follows: wind power limit (step two of the proposal method) is calculated first and P-V curve (to analyse system stability with and without wind power) is presented later. Active and reactive power for wind turbine is setting in 0.5 MW with a power factor nearly to one, according to a variable speed wind turbine. After running a power flow, it is checked that all variables are within limits (without wind power) and the initial conditions have been established. Them, the continuation power flow routine is running for calculate the wind power limit in each case. The results are shown in Table 1. For base case scenario, the large value of wind power limit with 31.5 MW is obtained. The maximum voltage at the bus30 was the first constraint violated in all cases, being an important aspect and consequence of the system condition with all voltage buses, near to maximum allowed level.

Table 1. Wind power limit for different load conditions at bus30

Study case	Load condition		Wind power limit (MW)
	Active power (MW)	Reactive Power (MW)	
Case 1	10.6	1.9	31.5
Case 2	7.95	1.44	26.5
Case 3	5.30	0.96	22
Case 4	5.30	1.92	26
Case 5	5.30	2.57	29

When the value of active power of the load is reduced the wind power limit reduces its value. For case 3 the lower value of wind power with 22 MW is obtained, representing 30% reduction compared to case 1.

From case 3 to case 5 the violated constrains was the maximum voltage at bus30. Is the power factor of the load reduce his value the consumption of reactive power increase, so the initial voltage condition is far from the maximum voltage limit. Therefore, the wind power limit for case 4 and case 5 is higher respect the case 3. For case 5 the wind power limit rise a 31.8% compared with case 3. After the obtaining of wind power limit, the power system stability is cheeked for each case. The criterion to analyze is the distance to voltage collapse using P-V curves. The P-V curves for cases 1, 3 and 5 with and without wind power are showed in Figure 5(a,b,c).

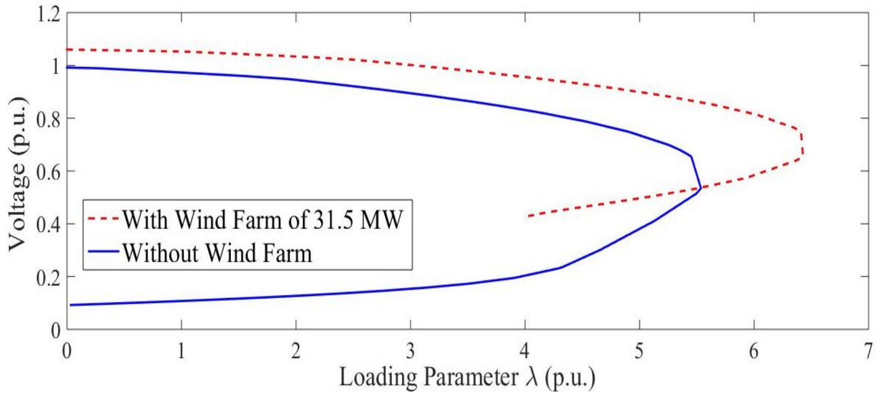

Fig.5 a) P-V curves at bus30 with and without wind integration. Case 1

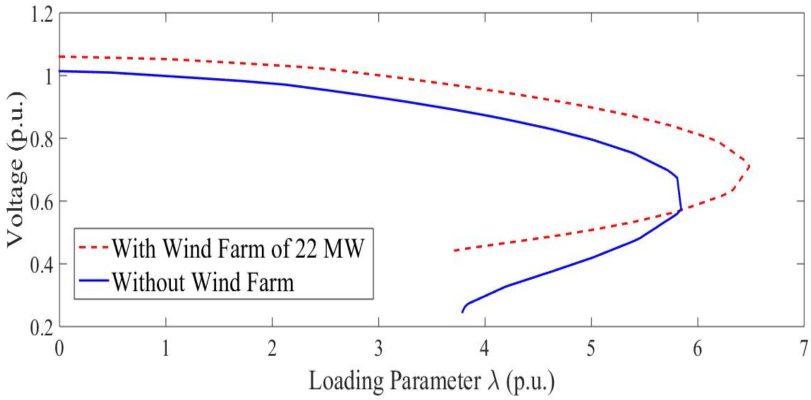

Fig.5 b) P-V curves at bus30 with and without wind integration. Case 3

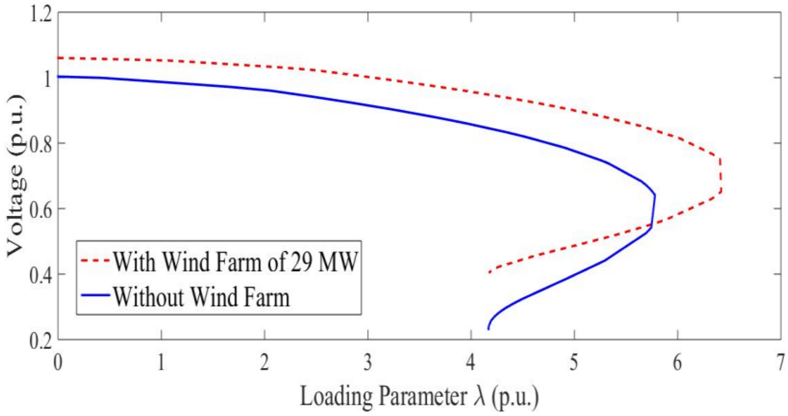

Fig.5 c) P-V curves at bus30 with and without wind integration. Case 5

When the wind farm is connected to the power system, the distance to voltage collapse is raised. For case 1 the distance to voltage collapse is raised in 16%, and until 11% for case 3 and 5. It is interesting to see that as wind power is increased, the stability region increases and the bifurcations move away, i.e., lambda also increases. However, there is a point where this trend reverses, as which corresponds to a “maximum” bifurcation point; for these cases, the maximum bifurcation points are obtained at case 1, with a wind farm of 31.5 MW.

For analyzing the influence of interconnection point, the procedure described below must be followed. It is considering a connection of a wind farm with type C wind turbine, the integration of a wind power is done in one bus at a time. The results are shown in Table 2.

The interconnection point that allows a higher value of wind power was the Bus10 with 86.5 MW. Otherwise, Bus14 and Bus26 have the lowest values of wind power with 18.5 MW, almost 5 times less than Bus10. Bus10 has lower voltage than other buses and more interconnection lines, so it’s possible to deliver more active power through the lines, keeping the system among the limits. Note that the most common constrains violated are the maximum voltage in the interconnection point or the thermal limit of the line which connects the wind farm with the power grid. However, it is possible that other constrains are violated first, such as the Bus21. In this case, the first constrains violated is the thermal line between Bus22 and Bus24.

In all cases the distance to voltage collapse with wind power is increased. The lower value is obtained for the wind power limit connected to Bus26. In this case, the loading parameter rises from 5.54 to 6.09, increasing the distance to voltage collapse in only 0.19 MW. The largest value of lambda is obtained at Bus10 when 86.5 MW of wind power is connected. Under this condition, the maximum loadability point increases 34% compared to the value of lambda for the base case scenario.

Table 2. Wind power limit for different interconnection points

Interconnection point	Wind power limit (MW)	First constrains violated
Bus10	86.5	Imax in the line from bus 16 to bus 17
Bus12	20	Umax at bus12
Bus14	18.5	Umax at bus14
Bus15	22.5	Umax at bus15
Bus16	28	Imax in the line from bus16 to bus17
Bus17	53.5	Imax in the line from bus10 to bus17
Bus18	32	Imax in the line from bus18 to bus19
Bus19	42	Umax at bus19
Bus20	42.5	Umax at bus20
Bus21	57	Imax in the line from bus22 to bus24
Bus23	35	Umax at bus23
Bus24	43	Imax in the line from bus22 to bus24
Bus26	18.5	Umax at bus26
Bus29	31.5	Umax at bus29
Bus30	31.5	Umax at bus30

4. Conclusions

This work presents a method for determining the wind power limit in the interconnection point with the power system using P-V curves and continuation power flow routine. The proposal method takes into account the wind power characteristic, active and reactive power conditions, power system static security constrains and distance to voltage collapse. The accuracy of the proposed method was validated through comparing information obtained from other method applied in the IEEE 30-bus test system. From the last analysis on the test system, it is possible to conclude that the wind power limit depends of system conditions, value of the load and the wind farm interconnection point. The distance to voltage collapse is increased in all cases when the wind farm is connected to the power system.

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Conflict of Interests

The authors attest that there is no conflict of interest between them or with other colleagues or any external entity to this research.

Credit author's statement

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