Impact of Wind Turbine Generating Units on Power System Voltage Stability

Selma Hanjalić MSc, Vedad Bećirović, Dženita Bašić

Abstract-- The operation of a distribution system with a large amount of distributed generation raises a number of issues, for example, voltage profiles change along the network, depending on how much power is produced and consumed at that system level. This paper presents impact of wind turbine generating units to variations of voltage and power losses in distribution power system.

This steady state load flow analysis should be performed at different load situations in order to assess:
• The voltage profile in the power system
• The reactive power balance
• The losses in the system

At first, wind turbine generating units are modeled as P-Q bus. Next, this units behaves like a conventional generator connected to a (PV) bus.

Index Terms-- Wind Turbine (WT), Power System (PS), Load Flow (LF), Voltage variations, Power Losses, Wind speed, Capacitor bank.

I. INTRODUCTION

As Mediterranean country Bosnia and Herzegovina is having large wind potential. Unfortunately, wind atlas is still not prepared for whole territory, but available data are quite optimistic in that sense. Bosnia and Herzegovina is at the beginning of the integration process of wind power plants in power system. Fig. 1 shows the transmission system in Bosnia and Herzegovina together with nine potential sites for wind generation.

The main power system problems from this wind turbine technology come from the lack of control on the active and reactive powers. The active and reactive power control is very important to keep the frequency and voltage stable within limits. Lack of reactive power can lead to voltage problems and no control in the active power can cause frequency deviations.

Induction (or asynchronous) machines applied as generators demand reactive power from the network, which is partially compensated with shunt capacitor banks. The reactive power demanded to the wind farms is partially compensated by capacitor banks and the network supplies the rest of the reactive power. The demand of reactive power is the key factor on voltage stability from wind farms.

This paper investigates the importance of reactive power and voltage regulation on steady-state between WT and distribution networks. The impact of various reactive power control policies on network power losses and voltage profile is also investigated.

Fig. 1: Bosnia and Herzegovina transmission system with the nine wind sites

II. WT MODEL IN LF ANALYSIS

According to available information, investors are generally decide to initially cheaper option, then the wind in a performance with a constant angular speed and constant frequency, using asynchronous generators at the facility on solid network [1]. This fact is stated to analyze the behavior of PS in the conditions connected WT to the PS.

In this paper, impact of WT on PS voltage stability in
quasi-steady state, is analyzed. The analysis is carried out on WT with induction motor. It should be noted that the asynchronous machine in the generator regime consumes reactive power, so this article from these reasons, great attention dedicated flows of reactive power. As already known reactive power is in direct correlation with the voltage modules. Based on the previous two sentences can conclude that the presence of WT (with the induction motor) in the PS directly affects the voltage fluctuations in quasi-steady state.

The main objective of which is set to model the WT to the LF analysis. There are different approaches, but each of them is modeling WT over PQ or P | U | bus. If the WT is in the insular regime, then it modeled over | U | θ bus. For detailed analysis, complete asynchronous generator equivalent circuit can be integrated in LF calculation. Models are most often differing in what is to be analyzed and what information is available for WT.

Fig. 2. shows a model of wind turbines in the LF analysis with constant angular speed, which gives the distribution of power (wind) to the PS. Power electronics (e.g. AC / DC and DC / AC) can be ignored in the LF analysis.

![Fig. 2. WT asynchronous generator model for LF analysis](image)

Labels on the Fig. 2. have the following meaning:
- v – mean wind speed (m/s)
- h – the height where is installed WT (m)
- ρ(h) - density of air at a height h (kg/m³)
- A – area outlines blade (m²)
- Pw – wind power at the entrance to the turbine (W)
- Pt – turbine power (W)
- Pg – generator power (W)
- Qg – reactive generator power (VAr)
- Qc – reactive power on bus injected by capacitor bank (VAr)
- PS – Power System

Relations describing the connection between certain values (Fig. 1.) are given below. They describe the WT in the quasi-steady state. For this description it is necessary to understand the relation of conversion of wind power into electricity.

### A. Wind power

Wind power in the known wind speed v, area outlines blade A, temperature T and the height h is a data expression (1) [8].

\[
P_w = \frac{1}{2} \rho(h) \cdot A \cdot v^3 (W)
\]  

(1)

Where is:

\[
\rho(h) = \frac{\rho_0}{\alpha \cdot T} e^{-\frac{h}{k \cdot T}} (kg/m^3)
\]  

(2)

Where are:
- \(\rho_0\) – standard atmospheric density of air at sea level (1225 kg/m³)
- R - specific gas constant for air (287,05 J/kgK)
- g -gravitational constant (9,81 m/s²)
- T - temperature of environment (K)

### B. Turbine power

Turbine output power is directly proportional to turbine input power (3).[1]

\[
P_t = C_p(\beta, \lambda) \cdot P_w
\]  

(3)

Where are:
- \(C_p(\beta, \lambda)\) – characteristic coefficient of turbine
- \(\beta\) – turbine rotor blade pitch angle (°)
- \(\lambda\) – turbine rotor tip speed ratio
- \(\lambda = \frac{r \cdot \omega_T}{v}\)

(4)

Where are:
- r – blade radius (m)
- \(\omega_T\) – angular speed of the turbine (rad/s)

![Fig. 3. Blade pitch angle](image)

Each wind turbine has a coefficient \(C_p(\beta, \lambda)\) that can be experimentally determined. There are also analytical approximations of the coefficients, and one very well describes the behavior of wind turbines.

This coefficient is determined in dependence of wind turbine type.

If this is a wind turbine without pitch angle regulation, power only depends on wind speed. Curve describing this dependence is shown in Fig. 4.
Labels on the diagram (Fig. 4.) have the following meaning:

- $P_r$ - reference power of the wind turbine, or the maximum available power that can reach.
- $v_r$ - reference wind speed, or rate at which reaches maximum power.
- $v_u$ - input wind speed, or wind speed at the wind turbine starts power delivery.
- $v_i$ - more top wind speed at which the turbine operates.

Curve shown in Fig. 4. most often is described by a polynomial of the n-order (5) with constant coefficients. Order polynomial is determined by conditions in the accuracy of interpolation, and standard deviations. The authors of this work are the opinions of proportion to the amount of standard deviation compared to the nominal power of the wind turbines.

In the event that this is a pitch angle regulated WT, power is not expressed only in terms of wind speed, but also of the coefficients $C_p(\beta, \lambda)$. Coefficient $C_p(\beta, \lambda)$ depends on the rotor blade pitch angle $\beta$ (°) and the relation $\lambda$ between the top speed of the blades and medium wind speed $v$.

The diagram shown on the Fig. 5. represents the dependence $C_p(\beta, \lambda)$ only in the function of $\beta$ and $\lambda$. We can see that for every pitch angle we have a new diagram; the increase of the pitch angle reduces the power of turbines. Draw conclusions from this one of the basic advantages of pitch angle regulated WT: that is the regulation of WT power.

Asynchronous generator power

Asynchronous machine can work in three regimes:
1. Motor regime
2. Generator regime
3. Electromagnetic breaker

The basic characteristics of the generator regime is that the machine brings power to the axle $P_2$ or $PT$, as a result of the connectors on the generator have an active power $P_1$ or $Pg$ and consuming reactive power $Qg$.

![Fig. 5: Power coefficient $C_p(\beta, \lambda)$ in function of $\beta$ and $\lambda$](image)

Procedure in deciding the WT power is to the next. For known wind speed $v$ (m / s), angle pitch speed $\omega$ (rad / s) and pitch angle $\beta$ (°), determine the $\lambda$ (4), and $C_p(\beta, \lambda)$ from diagram we can calculate WT power (3).

C. Asynchronous generator power

Asynchronous machine can work in three regimes:
1. Motor regime
2. Generator regime
3. Electromagnetic breaker

The basic characteristics of the generator regime is that the machine brings power to the axle $P_2$ or $PT$, as a result of the connectors on the generator have an active power $P_1$ or $Pg$ and consuming reactive power $Qg$.

![Fig. 6: Balance equation of active power generators](image)

On the basis of the Fig. 6. we can define asynchronous generator efficiency (6).

\[
\text{Asynchronous generator efficiency } = \frac{\text{Mechanical power at the entrance to the generator}}{\text{Electro-magnetic power}}
\]
Asynchronous generator efficiency is range within the limits of 0.95 to 0.99.

From the above mentioned, we can conclude that mechanical power have asynchronous generator is transferred to the generator output power, reduced for generator efficiency factor (7)

\[ P_g = \eta \cdot P_T \]  

Reactive power consumed by the asynchronous generator \( Q_g \) spent on flux and dissipative flux generation. This reactive power is supplied from the PS or the capacitor bank, as shown in Fig. 7.

![Equivalent circuit of asynchronous generator with capacitor bank connected to the generator.](image)

Equation (11), also gives very good results when determining the WT reactive power consumed with the capacitor bank [3].

\[ Q_g(P_T) = b_0 P_T^2 + b_1 P_T + b_2 \]  

Where are:
- \( U_1 \) - input voltage (V)
- \( X_C \) - capacitor bank reactance (Ω)
- \( X_\mu \) - asynchronous generator reactance (Ω)
- \( R \) - serial equivalent circuit resistance (Ω)
- \( X \) - serial equivalent circuit reactance (Ω)

Common case is the lack of data with models asynchronous generators, and some authors of articles [3], [4], [5] prove and suggested that the reactive power can be present only in dependence on the active power to the second degree polynomial with constant coefficients (10). This assumption leads to the conclusion that you do not take into account the dependence of consumed reactive power of the generator voltage

\[ Q_g = \frac{X_\mu - X_C}{X_C} \frac{U_1^2 - 2P_T}{2R^2 + X^2} - \frac{\sqrt{(U_1^2 - 2P_T)^2 - 4P_T^2 (R^2 + X^2)}}{2 (R^2 + X^2)} \]  

Where are:
- \( U_1 \) - input voltage (V)
- \( X_{Cm} \) - capacitor bank reactance (Ω)
- \( U_{Cm} \) - asynchronous generator reactance (Ω)

If the WT in the LF analysis is modeled over the PQ bus is
already pre-define capacitor bank power, and power consumed by the WT, depending on the generator active. As a result of LF calculation is bus voltage, which can disturb capacitor bank operation (reduce or increase capacitor bank reactive power efficiency), and that is disabled in the delivery of the necessary reactive power asynchronous generator, and the lack of reactive power must be compensated from the PS. This may occur if the calculation does not take reactance particular terms (12). Because we know how shunt compensatory device when you cut voltage reduces the reactive force provided in the PS (13).

Inputs in the LF calculation are WT active power \( P_g \), requiring WT reactive power \( Q_g \) (with sign -) and the shunt reactance \( X_C \).

\[
X_C = \frac{|U_n|^2}{Q_{nc}} \tag{12}
\]

Where are:
- \( U_n \) - capacitor bank rated voltage (V)
- \( Q_{nc} \) - capacitor bank rated reactive power (VAR).

Calculated reactance it is necessary to include in the LF calculation as a concentrated shunt parameter to bus which is connected WT. (Fig. 9.) Concentrated parameter has capacitive value (-j\( X_C \)). By analyzing injected capacitor bank reactive power, with LF calculation it has been proved, that capacitor bank satisfies demand for reactive power in WT.

If the WT to the LF analysis modeled through \( P|U| \) then the bus is already pre-set an active power \( P_g \) and voltage module \( |U_S| \). The results of calculation are reactive power \( Q_S \) and voltage angle \( \theta_S \). Compute angle \( \theta_S \) may affect the power transmission stability in the rest of the network. \( Q_S \) is a needed reactive power from the bus that enabled specify voltage module.

Inputs in LF calculation are WT active power \( P_g \) and requested module voltage \( |U_s| \). Necessary reactive power for desired voltage modulus and asynchronous are ensured from capacitor bank.

\[
Q_c = Q_d + Q_g \tag{14}
\]

Presentations WT using \( P|U| \), is only possible when the compensation device has continual regulation.

### III. EXAMPLE

Analyzes the connection of two WT installed capacity 2x850 kW on PS. Calculation is carried out when the system in the Quasi-steady state (LF). On Fig. 10. shows the scheme encountered examples of the PS parameters and load. PS is considered with maximum designed power, without the WT. The requirement is that the system is symmetrical, and that the system of loads symmetric. Draw conclusions from this LF calculation can be implemented by direct scheme.

![Fig. 9. Graphical interpretation of WT (a) PQ bus (b) P|U| bus](image_url)

Fig. 9. Graphical interpretation of WT (a) PQ bus (b) P|U| bus

Reactive power of capacitor bank which gives the system is not equal to rated power (13). The reason for this is lower than rated voltage at the place connecting the capacitor bank.

\[
Q' = Q_n \left( \frac{U}{U_n} \right)^2 \tag{13}
\]

Where are:
- \( Q' \) - reactive power that capacitor bank injects in the system when voltages are not rated (kVAR)
- \( Q_n \) - rated capacitor bank reactive power (kVAR)
- \( U \) - un-rated capacitor bank voltage (V)
- \( U' \) - voltage at which defines capacitor bank reactive power injects in the system (V)

Case with two installed WT between buses 2 and 4 with real and reactive power in PS, lines reactive load flow and power production at bus 0 (reference bus), before and after WT installation for different capacitor banks, is analyzed.

On the basis of data on wind speed, at the place of installation WT, selected with the WT data from Table I. Mostly wind speed range within the limits of 8 m / s to 18 m / s. For this wind speed will be displayed voltage profile for all the bus, when the selected capacitor bank, which satisfies the conditions that the voltage at the place of connection WT (bus 4) is within the limits of ± 10% nominal voltage. In this WT is installed asynchronous generator. During the calculation it is
that the turbine rotation speed is constant. From this it follows that can be taken that the level of asynchronous generator efficiency factor is constant.

### TABLE I

**ANALYZED WT DATA**

<table>
<thead>
<tr>
<th>2 x WT (GAMESA G58-850 kW)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Rated voltage</strong></td>
</tr>
<tr>
<td><strong>Rated frequency</strong></td>
</tr>
<tr>
<td><strong>Turbine Power</strong></td>
</tr>
<tr>
<td><strong>Rated generator Power</strong></td>
</tr>
<tr>
<td><strong>Generator efficiency factor</strong></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Generator power factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>Full load</td>
</tr>
<tr>
<td>¼ load</td>
</tr>
<tr>
<td>½ load</td>
</tr>
<tr>
<td>¼ load</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>2 x Capacitor banks</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>C1</strong></td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td><strong>C2</strong></td>
</tr>
<tr>
<td></td>
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</tbody>
</table>

Active power participation of these two WT in total active power is 18.69% when WT are in full capacity.

This example is a combination of several examples and aims to set the basic principles in the analysis of connecting to the WT PS.

On the basis of known information about the wind turbine power $P_T$ in function secondary wind speed $v$ (data taken from the catalog of WT), a given curve interpolation polynomial ninth row. Chosen polynomial satisfies the criteria that the authors of this work set in the power turbine cases ($\sigma = 0.65\%$).

Fig. 11. shows the obtained polynomial interpolation and the polynomial is given (14)

$P_T(v) = -0.0000086752v^9 + 0.000965638v^8 - 0.04595v^7 + 1.219375v^6 - 19.7463v^5 + 200.88v^4 - 1276.4v^3 + 4879.8v^2 - 10154.5v + 8571.6$  \[(14)\]

Obtained polynomial (14) is used for determining the WT active power in the function of speed, at constant speed turbine. This polynomial can be used in analyzing the stability of wind farms. It should be noted that it is valid only for the WT without pitch angle regulation.

Reactive power consumed by the WT is approximated polynomial second degree, based on the generator power factor (Fig. 12.).

On Fig. 12. Shown is obtained polynomial interpolation and the polynomial is given (15)

$Q_g(P_g) = -0.00032522P_g^2 + 0.039521958P_g - 234.842$  \[(15)\]

This polynomial (15) shows input consumed reactive power in function of output real power. This curve does not show influence of capacitor bank.

One of the basic diagrams that give input to the LF calculation is a diagram that shows the dependence of WT active and reactive power in function of wind speed. This diagram is shown in Fig. 13. Diagram is obtained on the basis of (14), (15) and generator efficiency factor
With the diagrams Fig. 13. can perform one of the conclusions. During low wind speeds (from 3 m/s to 6 m/s) output real power is twice than WT or capacitor bank input reactive power. Conclusion is that this WT is not profitable in this area wind speed

Please note that the average wind speeds that occur are the 8 m / s to 18 m / s, and from these reasons, the WT is taken into consideration.

LF calculation is made in EDTS software package [7]. Input data file for LF calculation is shown in Fig. 10. In case of wind speed 8 m/s WT power is 365,03 kW and -263,75 kVAr, and in case of wind speed 13 m/s WT power is 841,00 kW and -431,63 kVAr. From these values, values of capacitor bank reactive power on bus 5 could be concluded.

Five cases have been considered. The results of the LF calculation are given in Fig. 14 Analyze the losses of active, reactive power in the PS, the flow of reactive power to the transformer 5-6, and the power capacitor banks.

Fig. 14. Real P and reactive Q losses in PS, COM power (capacitor bank) Qc and load flow on transformer 5-6 Ql in dependence of several typical cases in the system.

A. Without WT

Analyzed the case without WT and lines that connect it with buses 2 and 3 in this case there is maximum need for reactive power of all the considered examples. Active power losses are also highest in this case.

B. WT without COM

Analyzed the case of connecting WT without compensating devices (this approach is not applicable in practice). Compared with previous events received slightly better results. The need for lower reactive power in the PS is a result of the load lines (3-4 and 2-4), which provide reactive power in the PS.

C. WT with C1

Compensating device C1 setting (WT for each one) losses and reactive power flows in the PS are reduced. The capacitor bank does not ensure enough reactive power WT, so WT still takes the reactive power from the system. Reactive power that C1 gives the system is lower than the nominal voltage reduction due to the C1 voltage decreasing (13).

D. WT with C1 || C2

Parallel connections C1 and C2 gives enough reactive power necessary for the WT operation. This case is most favorable for the PS, for power losses in the PS and voltage profiles. For wind speed greater than 8 m / s, which have been subject to analysis, we conclude that should be included C2 to its fullest capacity. Profile voltages considered buses depending on the wind speed is shown in Fig. 15.

Fig. 15. Voltage profile in dependence of wind speed. Wind speed is from 8,0 m/s to 18 m/s

According to the shown voltage profile there is no reactive load flow to the WT from which follows the well-derived reactive power compensation. At lower wind speeds (8 m/s to 12 m/s) injected reactive power in PS is larger, which has positive effect on voltages in PS.

E. WT with fix U

This example considers the case of over compensation of WT installation places. Here shows that in PS there is an excess of reactive power, which affects the increase in voltage module PS. Taking into account that the system nominally loaded, this compensation could adversely affect the stress conditions in the system at a lower load. Forward from the above mentioned reasons for over compensation WT is not desirable.
IV. CONCLUSIONS

This paper, like all the others that analyze these or similar problems, WT integration in PS, shows how complex this problem is.

Input data in LF calculation of WT are real and reactive power in dependence of wind speed. This diagram is the most important for LF analyzes in PS. Diagram directly depends of WT components (wind power, type and power of wind turbine and asynchronous and synchronous generator).

WT with asynchronous generators, that are today widely spread (doubly fed machines), have need for reactive power. This reactive power is ensured from compensating devices. During compensating device installation, it should be designed in the way that WT for every wind speed does not take from the PS or input in the PS large amount of reactive power.

Analyses of specifically cases, give answers to questions of WT installation pay off, technical possibility of WT connection to PS, maintenance and controlling of WT in combination with other sources of electrical energy. These cases have to be carefully chosen and analyzed.

Further analyses for example in this paper are:

- Reactive load flow in PS in dependence of wind speed, capacitor bank continuously controlled.
- Reactive power load flow in PS in dependence from reactive load flow on 35/0,69 kV transformer (4-5), capacitor bank continuously controlled.
- Stability analyses of real power transmission on lines without WT and in certain operating points of PS.
- Economic questions of WT installation.

One of the main problems in PS with distributed generation is controlling and coordination of generated energy from distributed and conventional sources.

V. REFERENCES


VI. BIOGRAPHIES

Selma Hanjaljić was born in Herceg Novi in Montenegro, on January 4, 1968. She received her Dipl.-Ing. and MSc degrees in electrical engineering from the University of Sarajevo/Bosnia and Herzegovina in 1991 and 2004, respectively. From 1991 she is a research assistant, a teaching assistant and a senior teaching assistant at the Faculty of electrical engineering Sarajevo. Her special field of interests includes electric power network and systems, computer methods in electrical power engineering, power generation, dispersed energy resources and economics in engineering.

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