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Impact of Wind Turbines on Power Quality: Analysis of Voltage Disturbances and Flicker Coefficient

Olsi Karapici [1]
Department of Electric Power System
Polytechnic University of Tirana
Tirana, Albania
okarapici@gmail.com

Viktor Rrotani [2]
Department of Electric Power System
Polytechnic University of Tirana
Tirana, Albania
viktor.rrotani1999@gmail.com

Rajmonda Bualoti [3]
Department of Electric Power System
Polytechnic University of Tirana
Tirana, Albania
bualoti@gmail.com

Marialis Çelo [4]
Department of Electric Power System
Polytechnic University of Tirana
Tirana, Albania
celomarialis@yahoo.com

***Abstract*— Similar to conventional power plants, wind power plants must deliver the requisite power quality to ensure the stability and reliability of the power system they are connected to, as well as to meet the needs of the customers connected to the same grid. Due to its low consumption of fuel and lack of air pollution, wind energy is a safe, clean, and sustainable renewable energy source that is gaining popularity throughout the world. However, integrating wind power into the existing electrical grid presents challenges such as voltage fluctuations and short-circuit currents, impacting power quality. The power quality issues related to grid-connected wind turbine voltage disturbances are the main topic of this study. A variety of issues are covered in the analysis, such as voltage fluctuations, dips, and flicker, as well as how to test and evaluate them using global standards like IEC 61400-21. MATLAB was used to model a case study that includes a 9 MW wind plant with six 1.5 MW turbines connected to a 25 kV distribution system. The results demonstrate how wind speed affects power and voltage as well as how pitch control operates properly to manage these variations. The study emphasizes the importance of power quality monitoring and the need for appropriate wind turbine models to predict and mitigate power quality issues, ensuring reliable and stable grid integration.**

Keywords*— *Wind turbine; Power Quality; Flicker Coefficient; IEC 61400-21; MatLab

I. INTRODUCTION

Wind energy is a safe, clean, and endless renewable energy source. Due to its lack of fuel consumption and absence of air pollution, wind energy technology has garnered increasing global attention, particularly in light of current climate abnormalities and global warming. Although wind power is a sustainable energy source, its integration with or disconnection from the existing electrical power system can cause voltage fluctuations and short-circuit currents in the grid, thereby affecting power quality. Moreover, the inherently unstable wind speeds can lead to voltage fluctuations produced by the wind turbines, known as voltage flicker. Voltage flicker can lead to unstable lighting of lamps, health issues, and failures in electronic equipment.

The integration of wind generation has become a crucial topic in the evolution of wind power. The substantial experience gained globally in recent years has shaped the challenges associated with incorporating wind into power systems. One such challenge is the impact of wind turbines on the power quality of the grid [1]. Power quality refers to the maintenance of a continuous and sinusoidal voltage with a constant amplitude and frequency. Quality is typically defined by parameters such as frequency, voltage, and interruptions. The voltage quality must meet the requirements specified in national and international standards. According these standards, voltage disturbances are classified into several categories: voltage variations, flicker, transients, and harmonic distortion.

The international standard IEC 61400-21 [2] aims to establish methods for the measurement and assessment of power quality characteristics in grid-connected wind turbines. These characteristics encompass the emissions of flicker and harmonics, voltage dip response, power control, grid protection, and reconnection time.

In this study, we will analyze various aspects of voltage disturbances and methods for assessing energy quality from grid-connected wind turbines. The quality of energy depends on the interaction between the grid and the wind turbines.

This paper is organized into five sections. The second section provides a detailed explanation of the methodologies utilized in the case study. The third section presents the case study itself. The fourth section delves into a discussion of the results. Lastly, the fifth section presents the conclusions derived from the analysis.

II. MATERIAL AND METHODS

Voltage variations can be defined as changes in the effective voltage value occurring over a period of minutes or longer. National standards specify permissible voltage variations from the nominal voltage over a defined period, such as 24 hours. IEC 38 defines the standard voltage as 230/400 V, and the standard frequency as 50 Hz [3]. Consequently, the voltage tolerance should not be more than ± 10% of nominal voltage. Voltage variations in the grid are primarily caused by load fluctuations and generation sources. When considering the energy generated by wind farms, voltage variations are also caused by the energy output from these power plants.

Fig. 1 shows the calculated voltage of the grid at the PCC at different X/R ratios and at a constant short-circuit ratio. The short-circuit ratio is defined as the ratio between the short-circuit power of the grid at the PCC and the rated power of the wind turbine. As can be seen in Fig. 1, a low X/R ratio will increase the voltage at the PCC while a high X/R ratio will lower the voltage.

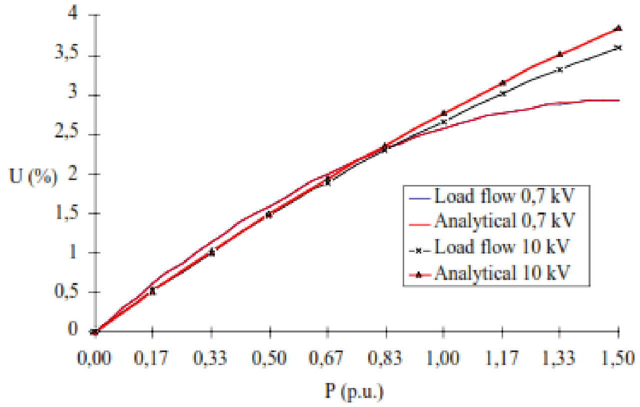

Fig. 1. Voltage variations at different X/R ratios

A. Voltage Dips

Voltage dips are short-duration reductions in RMS voltage, typically caused by faults in the electric supply system or the startup of large loads such as motors. These dips are widely recognized as one of the most critical aspects of power quality [4]. Wind turbines, equipped with starters, do not cause significant voltage sags. A test was conducted on the start-up of a wind turbine with and without a starter. Operating without the starter, the initial voltage drop was 28%. Operating with the starter, the initial voltage drop was 1.5%. According to the Swedish Standard SS 421 18 11, the voltage drop during the start-up of motors should be limited to 5% [5]. When a voltage drop occurs in the grid, wind turbines will shut down. Induction machines are particularly sensitive to a reduction in supply voltage due to increased losses in the rotor winding.

B. Flicker

Flicker is an established method for quantifying voltage fluctuations. This method is based on measuring changes in voltage amplitude, specifically the duration and intensity of the variations. Power fluctuations occurring at a frequency of 1 to 2 Hz are primarily caused by tower shadow effects. According to IEC 868, voltage variations occurring at 1 Hz should be limited to 0.7% [6]. Fig. 2, shows the magnitude of maximum permissible voltage changes with respect to the number of voltage changes per second, according to Standard IEC 60868 [6].

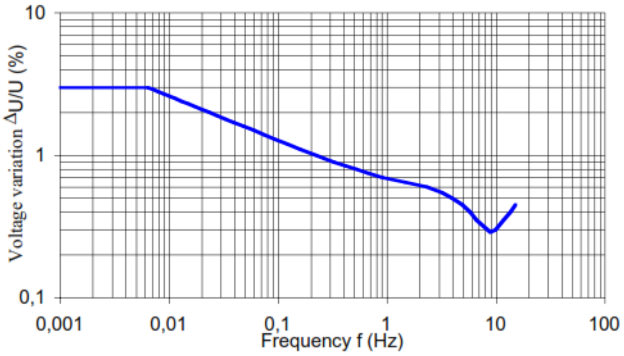

Fig. 2. Flicker curve according to IEC 60868.

C. Flicker Coefficient

According to IEC 61400-21 [2], the flicker coefficient from wind turbines will be determined by applying:

$$c(\Psi_k) = P_{st,fic}\frac{S_{k,fic}}{S_{ref}} \qquad (1)$$

$c(\Psi_k)$ - flicker coefficient

S_{ref} - the rated apparent power of the wind turbine

$P_{st,fic}$ - the short-term flicker severity

$S_{k,fic}$ - the short-circuit apparent power of the fictitious grid.

Phase angle is determined as:

$$\Psi_k = arctan\left(\frac{X_k}{R_k}\right) \qquad (2)$$

The short-term flicker severity produced by a grid-connected wind turbine with a short-circuit apparent power S_k can be calculated as follows:

$$P_{st} = c(\Psi_k) * \frac{S_{ref}}{S_k} \qquad (3)$$

According to IEC 61400-21 [2], the following equation is valid for determining the flicker contribution from grid-connected wind turbines at a common point:

$$P_{st\Sigma} = \sqrt{\sum_i P_{st,i}^2} \qquad (4)$$

$P_{st,i}$ - the short-term flicker severity produced each wind turbine.

IEC 61000-3-3 describes a method for evaluating flicker based on a limited number of independent voltage fluctuations [7]. The interval between the end of one voltage variation and the start of another must exceed 1 second. In these circumstances, long-term flicker can be expressed as:

$$P_{lt} = \sqrt[3.2]{\frac{\sum_i 2.3(F_i * d_i)^{3.2}}{T}} \qquad (5)$$

d_i - The maximum relative change in voltage, expressed as a percentage,

F_i – the factor of the voltage change,

T – the period expressed in seconds.

The maximum relative change in voltage, can be expressed as below:

$$d = \frac{I_{start} * I_n * U}{I_k * I_n * U} * 100 = k_i * \frac{S_{ref}}{S_k} * 100 \qquad (6)$$

k_i – the ratio between starting currents I_{start} and short circuit currents I_k,

S_{ref} - the rated power of wind turbines,

S_k – the short circuit current at Point of Common Coupling (PCC).

D. Flicker Coefficient

As expected, the impact on power quality from the operation of wind turbines depend on their power output. Regarding switching operations, the impact of wind turbines on power quality, we have:

$$S_N \le \frac{S_{SC}}{50} \qquad (7)$$

S_N – the power of wind turbines installed,

S_{SC} – the network's fault level.

The formula (7) indicates that if the installed power of the wind plant exceeds 2% of the network's fault level, it must be taken measures to minimize the impact on the power quality in the grid due to the connection and disconnection of the wind power plant.

III. CASE STUDY

A wind plant composed of six 1.5 MW wind turbines is connected to a 25 kV distribution system, which is then connected to a 120 kV grid via a 25 kV line with a length of 25 km. The 9 MW wind farm is simulated by six pairs of 1.5 MW wind turbines. The wind turbines use induction generators (IG) with squirrel-cage rotors. The stator winding is directly connected to the 60 Hz grid, and the rotor is driven by a variable-pitch wind turbine. The pitch angle is controlled to limit the generator's output power to its nominal value for wind speeds exceeding the nominal speed (11 m/s). In order to generate electricity, the speed of the induction generator (IG) must be slightly above synchronous speed. Reactive power is absorbed by the induction generators (IGs), partially compensated by capacitor banks connected to the terminals of each low-voltage wind turbine (400 kVAr per each set of 1.5 MW turbines). The remaining reactive power needed to maintain the voltage at 25 kV on the B25 busbars close to unity is provided by a 3 MVAr STATCOM with a ±3% regulation capability. In Fig. 3 is illustrated the connection of wind plant with the grid in MATLAB [8].

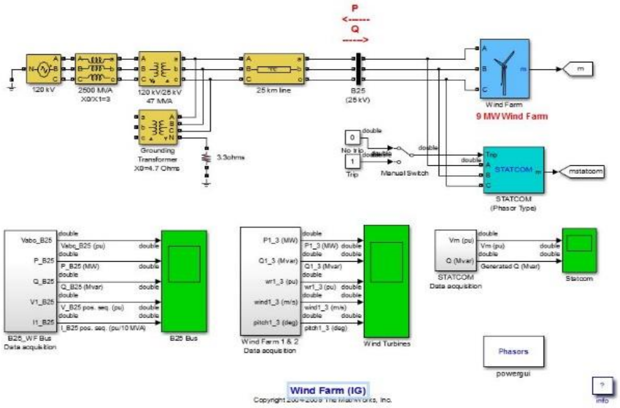

Fig. 3. Wind plant (IG) model from MATLAB

In Fig. 4 is shown the wind plant model with six wind turbines which are grouped two by two. The change I made from the MATLAB's example model is that I have replaced the constant wind with a variable one.

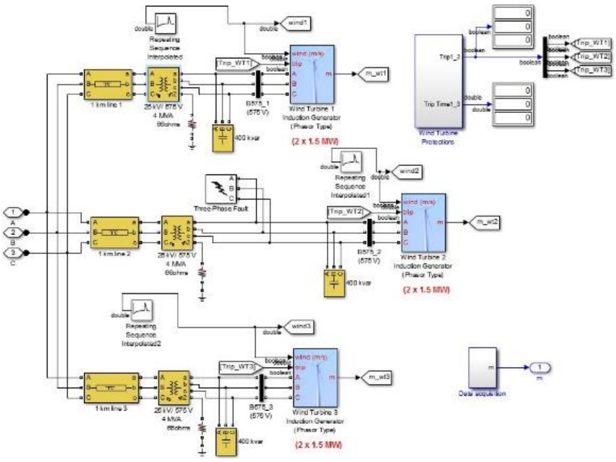

Fig. 4. Block diagram inside Wind Plant block

IV. RESULTS AND ANALYSIS

In Fig. 5, is observed the wind characteristics and the pitch angle. It seems we have two peaks in wind speed, one at the beginning and one at the end of the observed time period. here, we notice that the wind has exceeded its nominal speed by more than 1.005. Also, the pitch angle has changed as a result of the wind speed exceeding its nominal value, which has caused the blade angle to adjust in order to limit generator output.

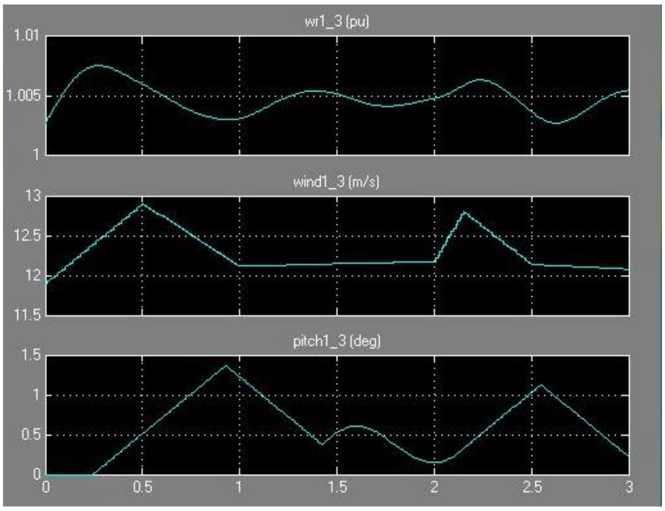

Fig. 5. Wind speed and pitch angle

In Fig. 6, we distinguish the active and reactive power for the entire farm, as well as the voltage in relative nominal units. It is clear, as mentioned earlier, that power increases with wind speed, but conversely, we observe a decrease in voltage expressed in relative units. The deepest drop is noticed precisely when the wind speed peaks.

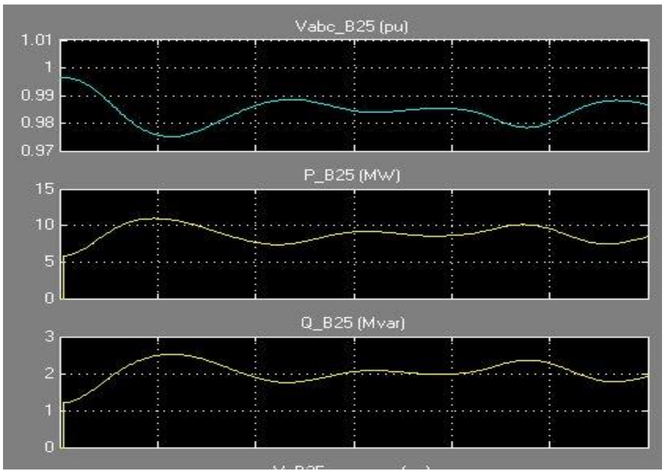

Fig. 6. Power and voltage in p.u of the plant

In Fig. 7, we clearly distinguish the active and reactive power of a pair of turbines, which vary as expected due to changes in wind speed at the turbine. The greatest increase is observed at the moment when there was also the highest increase in wind speed, and after the Pitch control acted by changing the blade angle, we see a decrease in the generated power.

In Table 1, are shown the results from the calculation of Flicker coefficient. The flicker coefficient of 8.558, calculated based on the short-term flicker severity and the system parameters, suggests that the contribution of the wind turbines to flicker is substantial. This flicker coefficient indicates that under certain conditions, flicker may become an issue, especially with rapidly changing wind conditions.

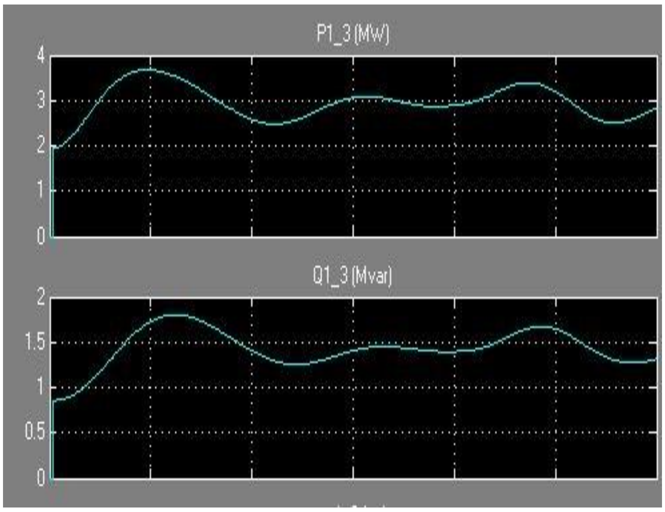

Fig. 7. Active and Reactive power of a pair of turbines

TABLE I. THE CALCULATION OF FLICKER COEFFICIENT

Parameter	Description	Value
I_k	short circuit currents	8.673
d	The max. relative change in voltage	10.4
P_{lt}	long-term flicker	0.055
Ψ_k	Phase angle	1°
P_{st}	short-term flicker severity	0.57
$c(\Psi_k)$	Flicker Coefficient	8.558

V. CONCLUSIONS

Power quality monitoring, dynamic disturbance recording, and digital fault recording are examples of wind plant monitoring that assist manufacturers, wind plant operators, and network operators in making the best choices and taking the necessary measures. This can enhance turbine reliability, power quality, and system stability.

There are various categories into which wind turbines can be divided. Fixed-speed and variable-speed wind turbines are the two primary categories into which they can be separated from an electrical perspective. In terms of how they interact with the grid and the quality of the power they produce, both types of wind turbines have advantages as well as disadvantages.

The unequal power production of wind turbines is caused by the wind's natural changes. For every type of wind turbine, the unequal power production is the same. A turbine blade enters the tower shadow each time it goes by. A varying power will be produced by the tower shadow if the turbine is running at a set speed. Voltage differences are caused by both uneven power production and power fluctuation. One benefit of using load flow equations is that they can be used to determine gradual voltage fluctuations brought on by the inconsistent power output from wind turbines.

Flicker disruptions could be brought on by the tower shadow's power fluctuations. The size of the power dips or the flicker emission from the source must be determined in order to determine the flicker impact. The variable nature of the wind is reflected in the variability of the generated power as well as other parameters such as voltage, frequency, etc.

Our analysis focused on voltage variations, and among the quality indicators, we concentrated on assessing the flicker coefficient. The calculation method is based on the IEC 61400-21 standard, and to determine this indicator, simulations were performed using MATLAB software. The analysis considered a scheme with nine 1.5 MW turbines. The same assessment method can be applied to real schemes based on the above model. Additionally, we applied an analytical method to determine the flicker value and found its coefficient for the case and parameters obtained from the MATLAB models.

In order to predict the interaction between wind turbines and the grid, additional wind turbine models are necessary. These models can be valuable tools for forecasting the power quality from wind turbines. An improper combination of a specific type of turbine with a particular grid can cause power quality issues, which can be identified at an early planning stage and addressed by replacing them with a more suitable type of turbine.

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