Power Quality Investigation of Grid Connected Wind Turbines

Trinh Trong Chuong

Abstract— *With the continued expansion of the scale of wind power generation, the power quality problems due to grid connected wind farms are concerned widely. The voltage fluctuation and flicker and harmonics are main aspects of power quality problems. The fluctuation of wind farm output and grid voltage due to the random fluctuation of wind speed and inherent characteristics of Wind Turbines (WTs) may cause flicker severity. It is significant to investigate the impact of power quality on load and operation of power system. In this paper, the WTs instantaneously generated power and voltage at the point of common connection (PCC) with grid are simulated by considering all the aerodynamical and mechanical effects, which could affect them. The inherent effect of the wind speed on the entire blade swept area is simulated in the model of the wind speed. The generated power is obtained by the simulation of the wind speed time series into a WTs model. The flickermeter model which expresses voltage fluctuations is simulated according to the IEC standard 61000-4-15. The wind speed, WTs and flickermeter models are simulated in Matlab/Simulink software. Both of grid and site parameters, which affect voltage fluctuation, are investigated. These parameters have a wide influence on voltage fluctuation and flicker emission levels.*

Keywords— **Wind power generation, power network, power quality.**

1. INTRODUCTION

Wind turbine generators are increasingly becoming among the prominent components of power systems. Due to the stochastic nature of wind, electrical power delivered by this type of generation possesses similar features. Furthermore, WTs are usually integrated with the grid at remote terminals, far from central loads or conventional generation. This is raising certain reluctance on the part of utility companies to inject that source of power with unknown behavior and to evaluate the accompanied power quality considerations. Due to the importance of WT power quality considerations, standard IEC 61400-21 [1] provides procedures for determining the power quality characteristics of WTs.

The sources of fluctuations in the generated power are due to stochastic aspects that determine wind speed at different times and heights, and to deterministic or periodic effects. The largest periodic effect known as the tower shadow is at the frequency at which rotor blades pass by the tower. In the common three bladed horizontal axis WTs, this frequency is known as a 3p (p is the rotating frequency of the blade) frequency which is three times the rotational frequency [2]. The reactive power consumption of the WT asynchronous generator depends on the active generated power. The drawn reactive power increases with the increase of the generated active power. Therefore, the reactive power consumption of the generator fluctuates as the wind speed fluctuates. Due to the fluctuations in the active and reactive power, the voltage at PCC fluctuates.

Voltage fluctuation is a serious issue particularly for direct connected WTs because these turbines produce power dependent on the variations of the wind speed and inject it without conditioning into the grid. Voltage fluctuation disturbs the sensitive electric and electronic equipment. This may lead to a great reduction in the life span of most equipment [3]. The lighting flicker level is generally used to measure voltage fluctuation. A case studying the voltage level profile when the power system is integrated with wind generation is given [4]. The influence of WTs on consumer voltage quality is studied [5]. A frequency domain approach to WTs for flicker analysis is presented [6]. The need to accurately simulate the WTs and investigate their interaction with the grid is becoming so important, since the penetration of wind in certain areas reaches significant levels. A suggested nonlinear simulation depending on the collected measured data is presented [7]. This simulation employs the neural network technique to predict the WT output power. The modeling of WTs for power system studies is presented [8]. The aerodynamic loads of the WTs are represented and simulated in frequency domain [9]. A comprehensive model of mechanical part consists of a number of lumped inertias, elastically coupled to each other is presented [10], [11]. The problem in this model that it needs more manufacturer’s design data about turbine elements which is not available in most cases. Soft tools and techniques used for modeling and design simulation of WTs are reviewed [12]. A simple approach to aggregated wind farm equivalent for the analysis of power system operation is presented [11].

This paper presents the comprehensive time-domain modeling of wind speed, WT and flickermeter and investigates the influence different factors on voltage fluctuation caused by WTs. The wind speed, WT and flickermeter models are implemented in Matlab/ Simulink. The wind speed produced from wind speed

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model is applied to the aerodynamic model to extract the aerodynamic torque. This torque is fed to the drive train/generator models to simulate the electrical power from WT.

2. MECHANISM ANALYSIS

The impact of grid-connected wind farm on power quality depends on the following factors: WT type, wind farm layout, short circuit capacity of power network and power line parameters.

2.1 Schematic diagram of WT integrating into power network

In order to explain the mechanism of voltage fluctuation and flicker due to WT, fig 1 shows the schematic diagram of WT integrating into power network, where $\dot{E}$ represents the voltage phasor of WT terminal, $\dot{U}$ represents grid voltage phasor, R and X represent resistance and reactance of power line, respectively, and $\dot{I}$ represents the current.

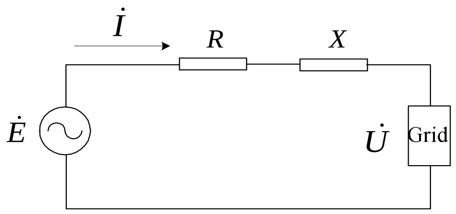

Fig. 1. Schematic diagram of WT integrating into power network.

It is assumed that the active and reactive output power are P and Q, respectively. So the following equation can be concluded.

$$\dot{U} = E - \frac{PR + QX}{E} - j\frac{PX - QR}{E} \qquad (1)$$

Therefore, it can be seen that the grid voltage will fluctuate when the output power of WT is fluctuating, resulting in flicker. The mechanical power of WT can be represented by equation (2).

$$P = \frac{1}{2}\rho C_p(\lambda, \beta) A v^3 \qquad (2)$$

here, P is power (W), ρ is air density(kg/m^3), A is swept area(m^2), v is wind speed(m/s), C_P is power coefficient, and λ is tip speed ratio:

$$\lambda = \frac{\omega R}{v} \qquad (3)$$

here, ω is angular velocity of blade rotor (rad/s), and R is radius of blade rotor (m).

It can be seen from equation (2) that there are some factors causing output power of WT, such as air density, angular velocity of blade, pitch angle and wind speed and so on. The wind speed variation is stochastic, depending on meteorological condition. In general, it is not the main reason causing flicker because the frequency of wind speed variation is quite low. The variations of angular velocity of blade and pitch angle depend on WT type and control system. The variation of output power of WT can be decreased by the advanced control system.

2.2 Voltage fluctuation and flicker

During the WT continuous operation, the mechanical torque of WT is unstable due to wind shear, tower shadow effect and yawing uncertainty. The mechanical torque fluctuation will cause output power fluctuation. Generally, the frequency of output power fluctuation is same as frequency of blade rotor passing the tower. For WTs with three-blades, the frequencies of voltage fluctuations are 3p and times of 3p. As the frequency band of 3p is often in the range of 1~3Hz, the flicker severity produced by the periodic voltage fluctuations at these frequencies may be large part of the flicker severity.

The grid-connected WT not only cause voltage fluctuation and flicker during the continuous operation but also switching operation. The typical switching operation includes start-up and shutdown of WT and switching between generators (applicable only to WTs with more than one generator or a generator with multiple windings). These output power fluctuation due to switching operation will cause voltage fluctuation and flicker at the load node.

In this section we analyse the voltage variations produced when a source of variable power is connected to a weak network. We assume a simplified model representing the source of power (WT) and the grid impedance. The aim is to find an expression which gives the voltage at the generator terminal as a function of the power generated and the impedance of the grid (Fig. 2).

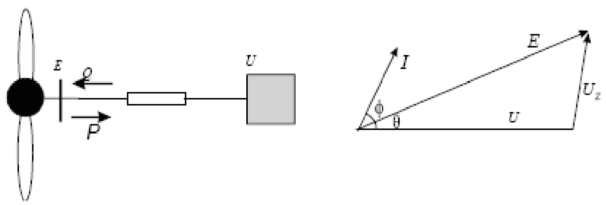

Fig. 2. Generator-grid model and phasor diagram.

From phasor diagram:

$$U_z^2 = U^2 + E^2 - 2EU\cos\theta = I^2(R^2 + X^2) \qquad (4)$$

If $I^2E^2 = P^2 + Q^2$ we have:

$$\frac{P^2 + Q^2}{E^2}(R^2 + X^2) = U^2 + E^2 - 2.U.E.\cos\theta \qquad (5)$$

From the phasor diagram:

$$E = U\cos\theta + RI\cos\phi - XI\sin\phi \qquad (6)$$

After some manipulation:

$$E^4 - \left[2(PR - QX) + U^2\right]E^2 + \\ + (P^2 + Q^2)(R^2 + X^2) = 0 \qquad (7)$$

Solving Equation above, the voltage E can be expressed as:

$$E = \sqrt{c_1 + \sqrt{c_1^2 - c_2}} \qquad (8)$$

with:

$$c_1 = \frac{U^2}{2} + (PR - QX);\; c_2 = (P^2 + Q^2)(R^2 + X^2)$$

If we set Z equal to 0.05 p.u., and a constant voltage U= 1 p.u., the short circuit ratio is 1/Z = 20 for P=1 p.u. The power factor has been chosen equal to 0.97. Fig 3 shows the relation between E and the output power with the ratio X/R as a parameter for two different short circuit ratio SCR=20. The figures below show how the voltage varies with respect to the active power flow and the network characteristics [1].

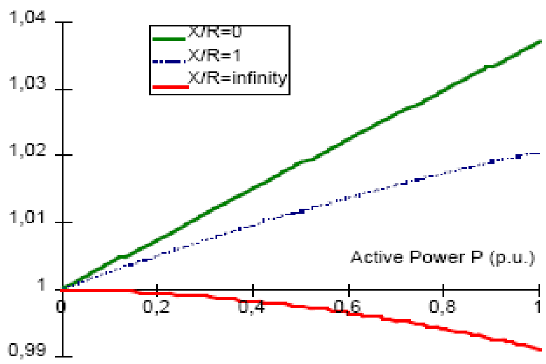

Fig 3. Voltage E as a function of active power, X/R.

The WT induction generator injects fluctuated active power into the grid and correspondingly it draws fluctuated reactive power from the grid. If the variation of the active power injected to the grid is ΔP and the corresponding variation of the reactive power absorbed from the grid is ΔQ, then voltage fluctuation, at PCC, ΔE/E, is given in (9). The nominal voltage is 1 pu. This can be rewritten as follows:

$$\frac{\Delta E}{E} = \Delta P.R - \Delta Q.X \approx \Delta S.Z\cos(\theta + \phi) \qquad (9)$$

where:

R resistance of the grid impedance (pu);
X reactance of the grid impedance (pu);
ΔS apparent power variation,

$$\Delta S = (\Delta P^2 + \Delta Q^2)^{1/2} \text{ (pu)};$$

Z grid impedance amplitude (pu);
θ grid impeadance angle; and φ is $\tan^{-1}(\Delta Q/\Delta P)$.

2.3 Harmonics

Harmonic distortion is another power quality problem due to wind power generation. For any type of WTs, harmonic current caused by generator can be ignored. The power electronic converter is real source of harmonic current. The constant speed WT will not produce harmonic current during the continuous operation, because there is not power electronic converter involved in WT. It will produce a little harmonic current when starting up, because soft-starter is in operation. But the start-up time is very short, the harmonic current due to start-up can be ignored.

However, a WT with power electronic converter will produce harmonic current, because the converter is always working during the continuous operation. In the normal operation, harmonics caused by WT depends on structure design of converter and filters installed in the WT, and also network short circuit capacity. Because the switching frequency of converter is not fixed, WT with force commutated converter will produce harmonic current as well as inter-harmonic current. The PWM switching converter and appropriate filters can minimize the harmonic distortion.

3. SIMULATION RESULTS

The studied model represents an equivalent of a distribution segment in LySon, VietNam. The model represents a 540kW wind power station consisting 3 turbines with Fixed Speed Induction Generator connected to the grid. Extend one of the 22kV lines to the WTs. The turbines are stall regulated types, with a rating of 180 kW each. The diesel generator power station has, at present, a very limited capacity of 850kW connected WTs.

The applicability of results from the simulation modelling depends how accurate and comprehensive the input data are that are used to build the model. Data collection was mostly carried out by the Institute of Energy, Vietnam.The main data groups for the model are:

- Power system circuit diagram
- Diesel generator specifications
- System controllers / operation procedures
- Power system transformers; Cables / overhead lines
- Loads and load profiles
- Other equipment e.g. storage, dump loads, etc.
- Wind resource

The data can be found in [11].

3.1 Samples of Results of Wind Speed and WT Modeling

Using the parameters of the WT generator which are given in the appendix, the wind speed and WT models have been implemented under Matlab/Simulink. The WT ratings are taken as base quantities. The grid fault level and X/R ratio are assumed 50 pu and 10 respectively. The no-load reactive power demand of the induction generator under study is compensated by capacitor banks installed at PCC. Figure 4 presents a sample of selected model outputs; equivalent wind speed, active/reactive power and voltage at PCC.

The wind speed variation, assuming turbulence intensity of 10%, and v = 12 m/sec., is shown in Fig. 4(a). The corresponding aerodynamic power and electrical output power are shown in Fig. 4(b). Not all variations in the aerodynamic power are transmitted to the electrical power. It means that the soft shaft coupling and the inertia of WT rotor and generator rotor masses damp and smooth the variations of the aerodynamic power. Figure 4(c) shows the variation of the absorbed reactive power from grid. It is clear that the voltage fluctuation, in Fig. 4(d), is very small due the high fault level of the grid.

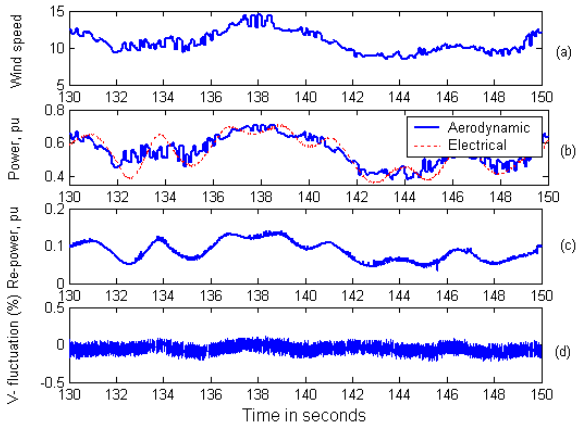

Fig. 4. Samples of the discussed modeling outputs (a) wind speed in m/sec. (b)- aerodynamic and electrical output power in pu (c)-absorbed reactive power in pu. (d)- voltage fluctuation at PCC (ΔE/E, %).

Figure 5 traces the variation of the absorbed reactive power with the injected active power for the integrated wind energy system and the induction generator under study. The drawn reactive power increases with the increase of the generated active power. This relation is known as P-Q characteristic of the induction generator.

The grid parameters affecting the WT flicker emission are the fault level, and X/R ratio of the gird impedance.

Fault Level

Figure 6 shows the variation of the short-term flicker index with different grid fault levels. This simulation test is carried out with two cases of grid impedance angles; 45^0 and 70^0. The mean wind speed at hub level is manitained at 12m/s and site turbulence is 10%.

X/R Ratio of grid impedance

The X/R ratio of the gird impedance is studied in terms of the impedance angle, $\theta = \tan^{-1}(X/R)$. Figure 7 shows the variation of the short-term flicker index with the impedance angle. The fault level is maintained at 10 pu. The mean wind speed at hub level is 12 m/sec. and site turbulence is 10%.

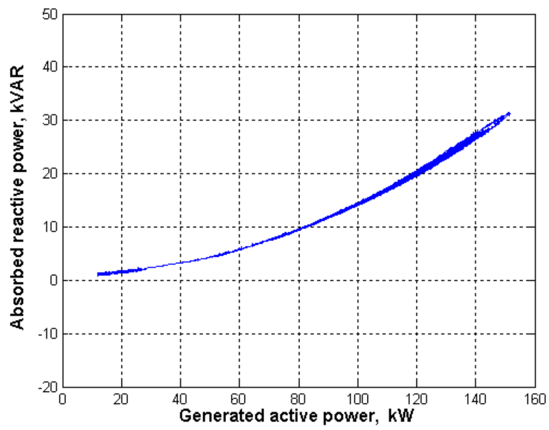

Fig. 5. The absorbed reactive power versus the injected active power for the induction generator under study.

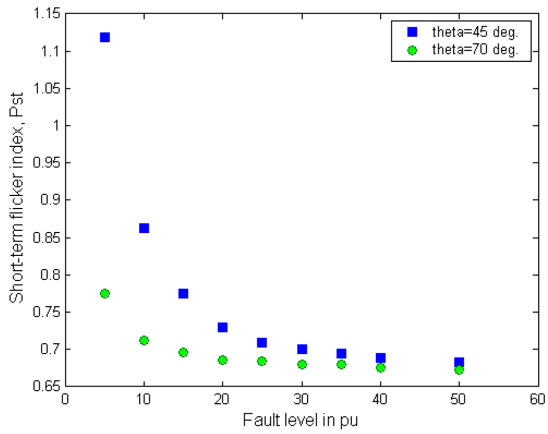

Fig. 6. Variation of P_{st} with the grid fault level.

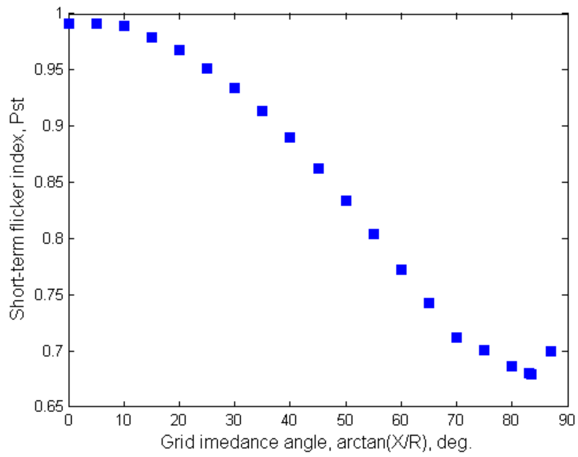

Fig. 7. Variation of P_{st} with the grid impedance angle.

3.2 Influences of Grid Parameters on Flicker Caused by WTs

From Fig. 7 it can be seen that the flicker decreases with the increase of until the minimum point, then the slope is reversed and flicker increases with increase of θ. The minimum point of voltage fluctuation is occurred when $\theta + \phi = 90^0$. The angle ϕ can be obtained according to the incremental variation, $\Delta Q/\Delta P$, of P-Q characteristic of the induction generator (Fig. 5). The P-Q characteristic of the generator determines the ϕ-P relation.

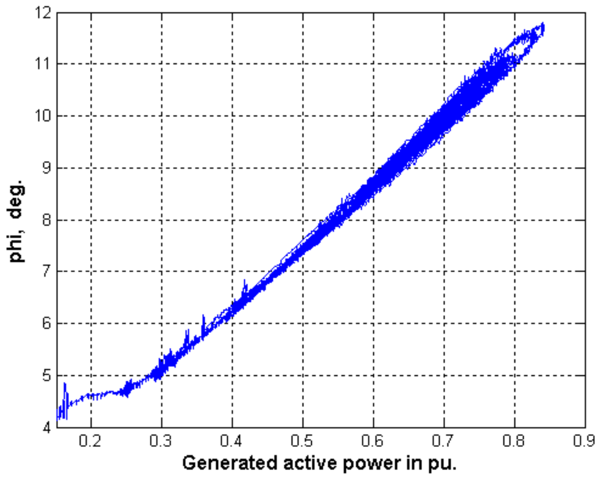

Fig. 8. Variation of the angle ϕ with generated active power for the induction generator under study.

Then the mean generated power (operating point) determines the value of φ and consequently $\theta = 90^0 - \phi$ at the point of minimum flicker emission. Figure 8 shows the variation of angle ϕ with the active generated power. The mean active generated power is estimated accordance to the WT power curve at mean wind speed. In this case, it is approximately 0.6 pu. as shown in Fig. 4(b). Then $\phi = 8.6^0$ which gives $\theta = 81.6^0$ at minimum flicker emission. The minimum point of flicker emission cannot be zero because the power swings up and down the mean value.

3.3 Effects of Site Parameters on WT Flicker Emission

Mean Wind Speed

The flicker severity is calculated for the same site turbulence (I_u=10%) and different mean wind speed. The fault level of the grid is 10 pu. The P_{st} values versus the mean wind speed are estimated for two grid impedance angles, 45^0 and 70^0.

The P_{st} variation with the mean wind speed is illustrated in Fig. 9. It can be explained by the WT power curve, shown in Fig.10. From Fig. 9, it can concluded that the output power and its fluctuations in the low wind region are low and therefore the induced voltage fluctuation is small. As the wind speed increases from cut in speed to 13 m/sec., the output power fluctuations and P_{st} increase, approximately in linear relation with the mean wind speed. However, in the stall region (greater than 13 m/sec.), the rate of change of the aerodynamic power curve is reduced, resulting in a corresponding reduction in the output electrical power variability. Then P_{st} values vary in small range with the increase of the wind speed as shown in Fig. 9.

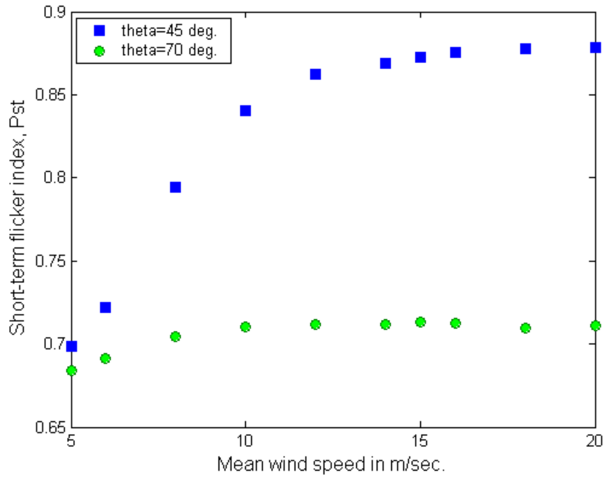

Fig. 9. Variation of P_{st} with mean wind speed for 45^0 and 70^0.

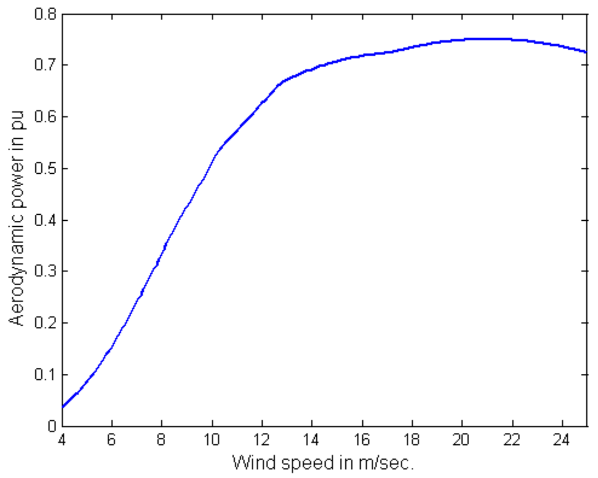

Fig. 10. WT power curve.

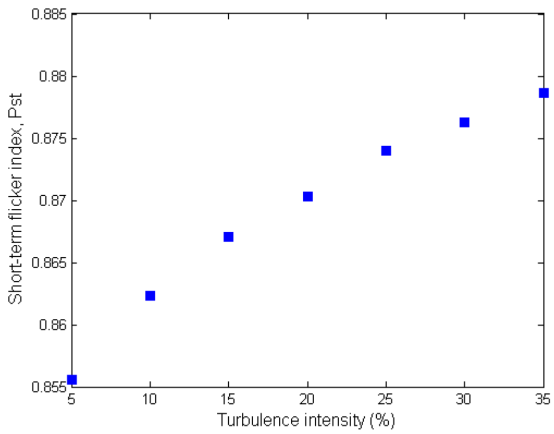

Fig. 11. Variation of P_{st} with wind speed turbulence.

Turbulence Intensity

In this case, the mean wind speed at hub level is maintained at 12 m/sec., the fault level is 10 pu., and the grid impedance angle is 45^0. Figure 11 shows the variation of P_{st} with the turbulence intensity. The increase in the wind speed turbulence increases the power variability then the flicker emission increases with the increase of the turbulence intensity.

4. CONCLUSION

The comprehensive wind speed and WT models can be applied for voltage fluctuation and power quality studies. The flicker level caused by voltage fluctuation is evaluated by the flickermeter, described in IEC 61000-4-15. From simulation results, voltage fluctuations are widely affected by the grid strength and X/R ratio of grid internal impedance. The flicker emission is decreased with higher fault levels. The risk of voltage fluctuation increases in the resistive grids. The WT operating point and the Q-P characteristic of the generator determine the point of minimum flicker emission. The trend of flicker variation with the mean wind speed depends mainly on the WT power curve. The power variability and consequently flicker emission increases with turbulence increase. A wide look on the results indicates that grid parameters have more effect on flicker emission than site parameters.

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APPENDIX

The WT Data, Drive Train Data and Generator Data are stated as follows:

- Rated power 180 kW;
- Hub height 30 m;
- Rotor diameter 23.2 m;
- Number of blades three;
- Rotor speed 42 r/min;
- Blade profile NACA-63 200;
- Gearbox ratio 23.75.
- Turbine inertia 102.8 kg.m^2 ;
- Generator inertia 4.5 kg.m^2 ;
- Stiffness of the shaft 2700 N.m/rad;
- Nominal voltage 400 V;
- Number of pole-pairs three;
- Stator resistance 0.0092 Ohm;
- Rotor resistance (referred to the stator) 0.0061 Ohm;
- Stator leakage inductance 0.186 mH;
- Rotor leakage inductance (referred to the stator) 0.427 mH;
- Magnetizing inductance 6.7 mH.