

PSCAD/EMTDC-Based Modeling and Flicker Estimation for Wind Turbines

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Abstract- The estimation of flicker emission by a wind park is a complex issue because the network is shared with other loads or generators, even with other wind parks, which contribute to the flicker level. This estimation can be done by means of simulation as depicted in international standards, where the wind turbine generator (WTG) is simulated with a fictitious network, and the results of flicker emission can be extrapolated to a real network.

In this paper, modeling and simulation of different WTG technologies are presented. Real measurements from a wind park have been used to validate these models.

An approach based in the methodology that appears in international standards is applied for flicker estimation. In this approach, detailed WTG models are used in the estimation.

Index terms - Wind energy, Wind Turbine Generator, Power Quality, Flicker

I. INTRODUCTION

In recent years, the presence of wind energy in the generation share has been continuously increasing. For example, in 2007, wind energy sharing reached 21% in Denmark's, 12% in Spain and 7% in Germany. Wind energy market is still growing within Europe, meanwhile a major surge of activity is occurring on a global level, especially in U.S., China and India.

Therefore, the impact of WTG's on the power quality has become an important issue nowadays. Flicker is a relevant power quality

parameter related to wind energy. Fluctuation on network voltage is the cause of flicker and it is usually provoked by power flow variations in the network.

Power generated by a WTG has a fluctuating behaviour due to the random nature of wind speed and certain oscillatory phenomena related to wind shear, shadow tower, etc. This provokes load flow changes in the network and they can be responsible of flicker emission, especially in weak grids [1,2,3].

In order to reduce its impact in power quality, some international grid code limits installed wind power in relationship with the short circuit capacity at connection point of wind park. For example, in Spain, wind park nominal power must be lower than a 5% of short circuit capacity, at the connection point in the transmission grid [4].

To avoid simplified rules as these shown above, the provided method by the standard IEC 61400-21 [5] can be used. Following this method, an estimation of the flicker emission of a wind park can be done using current measurements in real working conditions and simulation.

In this article, an estimation of flicker based on the IEC methodology is presented. A PSCAD model of WTG's has been developed and contrasted with real measurements in a wind park [6]. These models are used to estimate the flicker emission, even in working conditions different than those in measurements.

II. FLICKER ESTIMATION

The standard IEC 61400-21 uses a method that combines real measurements with simulation results. Real measurements in a WTG are injected in a fictitious network and the resulting voltage is used in a flicker meter [7].

Fictitious network is represented by a Thevenin Equivalent (see Fig. 1) formed by an ideal voltage source $u_0(t)$ and an impedance Z_{fic} . In this network, measured current is used as a current source, $i_m(t)$. As a result, the voltage at the connection point $u_{fict}(t)$ is calculated. This voltage is used as input in a flickermeter to obtain de flicker severity level P_{st} [5].

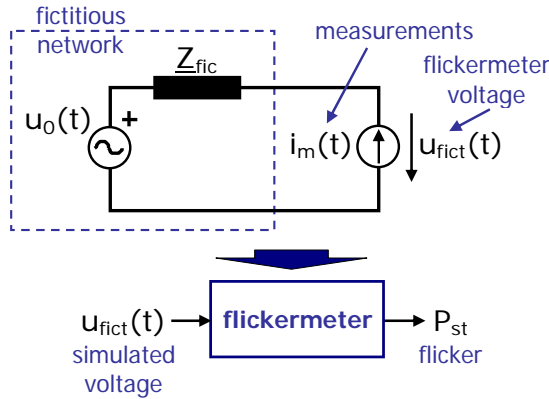


Fig. 1. Network to be simulated to obtain the flicker meter voltage

The level of flicker due to the continuous operation of a WTG can be determined from a flicker coefficient "c". This characteristic ratio of each turbine is calculated for a given angle of the power grid impedance and average annual wind speed by the expression:

$$c(\Psi_k, v_a) = P_{st} \frac{S_{k, fic}}{S_n} \quad (1)$$

where:

- c is the flicker coefficient
- v_a : is the mean wind speed
- Ψ_k : is the angle of network Z_{fic}
- P_{st} : is the flicker level emitted by one WTG
- $S_{k, fic}$: is the network short circuit power of fictitious network
- S_n : is the nominal apparent power of the WTG

From flicker coefficients, the total flicker $P_{st, \Sigma}$ emitted for a wind park can be estimated using

the expression:

$$P_{st, \Sigma} = \frac{1}{S_k} \sqrt{\sum_{i=1}^N (c_i(\Psi_k, v_a) \cdot S_{n,i})^2} \quad (2)$$

- c_i , $S_{n,i}$ are the flicker coefficient and nominal apparent power of WTG "i"
- S_k : is the short circuit capacity at the connection point
- N is the number of WTG's to be considered

III. MEASUREMENTS IN A WIND PARK

For this study, a set of measurements have been done in the Sotavento Experimental Wind Park [8]. This wind park has installed 24 WTG's (see Table 1) with a total power of 17.56 MW and an estimated annual energy production of 38.5 GWh.

Table 1. WTG's installed in the Sotavento Experimental Wind Park

WTG code	Number of WTG	Power (kW)	Speed	Pitch
FF1	4	660	Fixed	Fixed
FF2	4	750	Fixed	Fixed
FF3	4	640	Fixed	Fixed
FF4	4	600	Fixed	Fixed
-	1	900	Fixed	Fixed
-	1	1320	Fixed	Fixed
FV1	1	1300	Fixed	Variable
VV1	1	800	Variable	Variable
VV2	4	660	Variable	Variable

A long-term recorder has been installed in those WTG's considered representatives (see Fig. 2). Measured variables were (see Fig. 3):

- Voltage (instantaneous and RMS)
- Current (instantaneous and RMS)
- Power (instantaneous, active and reactive)
- Wind Speed (instantaneous)

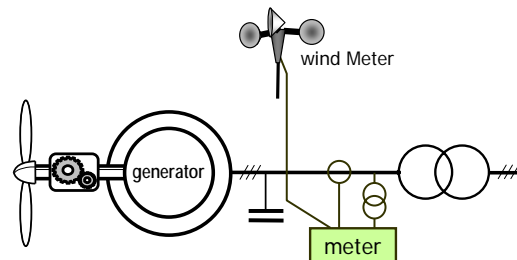


Fig. 2. Meter connection in a fixed speed WTG

An example of measurement results in a fixed speed WTG is shown in Fig. 3 where RMS voltage, power and wind speed are represented.

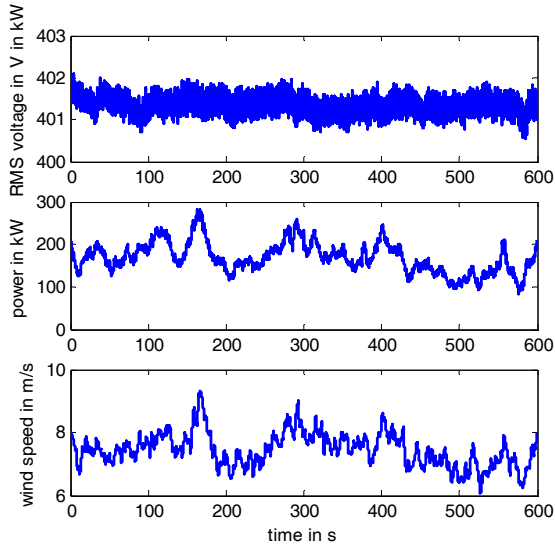


Fig. 3. RMS voltage, power and wind speed measured in a fixed speed WTG

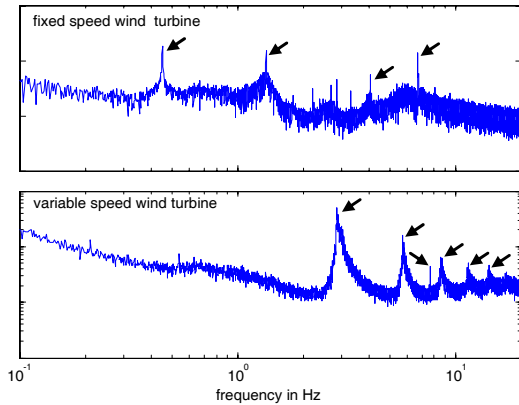


Fig. 4. Mean power spectrum in a fixed speed WTG and in variable speed WTG

In order to detect the oscillating components in the power injected by WTG's, a spectrum analysis is done. In the resulting spectrum, the presence of power peaks reveals the presence of the oscillating power components (Fig. 4). The frequencies that dominate the spectrum are those related to turbine rotation (1p) and its multiples (2p, 3p, etc) [1,2,3,9]. Frequencies, except p-multiples, in the low part of the spectrum (very low hertz) are related to mechanical modes in WTG's.

As an example, results from the power spectrum analysis in a fixed speed WTG, whose main data is shown in Table 2, are summarized in Table 3. As can be seen in the spectrum, oscillatory components 1p, 3p... have been

found. For this WTG with two speeds, the index "-l" is used for frequencies related with the low speed of turbine, and the index "-h" is related with the high one.

Relationships between mean wind speed and the amplitude of the mentioned components is calculated.

Table 2. Main data of a fixed speed WTG (FF1)

Nominal Power (kW)	660
Rotor diameter (m)	46
Tower Heigh (m)	45.25
Rotor Speed (rpm)	17 - 25.5
Gearbox ratio	59.5
Pitch Control	Fixed
Tensión (V)	690
Generator	Asynch.; two speeds

Table 3. Main oscillatory frequencies in a fixed speed WTG (FF1)

Mean Wind Speed (m/s)	2,7	5,2	8,3	10,8	15,2
Mean Power (kW)	2,7	46,4	261,7	475,8	644,4
Oscillation Frequency (Hz)	Oscillation Power in kW				
0,28 1p-l	0,37	0,21	0,42	0,91	1,65
0,42 1p-h	0,07	0,40	0,75	1,12	1,82
0,85 3p-l	0,33	0,70	0,65	1,02	1,80
1,27 3p-h	0,01	0,57	1,93	3,41	7,23
1,70 6p-l	0,06	0,09	0,09	0,19	0,51
2,54 6p-h	0,03	0,06	0,23	0,35	0,81
2,55 9p-l	0,03	0,06	0,23	0,35	0,81
3,82 9p-h	0,01	0,03	0,14	0,25	0,61
4,25 15p-l	0,01	0,03	0,09	0,11	0,21
6,36 15p-h	0,00	0,01	0,05	0,06	0,10
0,66 Other	0,07	0,13	0,67	1,17	3,38

In Table 4, results of analysis of the main WTG topologies in the Sotavento Wind Park are presented. These topologies are:

- FS/FP. A fixed speed and fixed pitch WTG with an asynchronous generator.
- FS/VP: A fixed speed and variable pitch WTG with an asynchronous generator.
- VS/VP (DFIG): Variable Speed and Variable Pitch WTG with a DFIG.
- VS/VP (Synch + AC/AC): Variable Speed and Variable Pitch WTG with a synchronous generator and full size back to back converter.

The presence oscillating power components with 1p and 3p frequencies in the power spectrum is demonstrated through this study. As a first conclusion, it can be seen that the power delivered by variable speed WTG tends to show the lower levels of oscillating components.

Table 4: Main oscillatory frequencies in the Sotavento Wind Park

WTG Code	Wind Turbine Topology	Peak Value of Power oscillations			Main Power Oscillation Components
		Low Wind Speed	Medium Wind Speed	High Wind Speed	
FF1	FS/FP	1,50%	0,74%	1,12%	3P
FF2	FS/FP	4,23%	1,32%	-	1P and 3P
FF3	FS/FP	2,96%	1,65%	-	1P
FF4	FS/FP	28,36%	2,17%	-	1P and 3P
FV1	FS/VP	5,11%	1,11%	-	3P
VV1	VS/VP SYNC+AC/A	0,77%	0,07%	-	1P
VV2	VS/VP (DFIG)	3,12%	0,21%	-	1P and 20Hz

FS or VS: fixed or variable speed; FP or VP: Fixed or variable pitch

IV. MODELING

In this work, the WTG's have been modeled to estimate flicker in different situations that can be different from those during measurements. Models for all mentioned above topologies (see Fig. 5) have been implemented in PSCAD/EMTDC [11].

In order to take into account oscillating power components, mechanical torque in the generator shaft is calculated adding these two components [1,2] (see Fig. 6):

- Rotor aerodynamic behaviour; torque is calculated from aerodynamic turbine behaviour.
- Oscillating power components calculated from measurements are added to the aerodynamic torque.

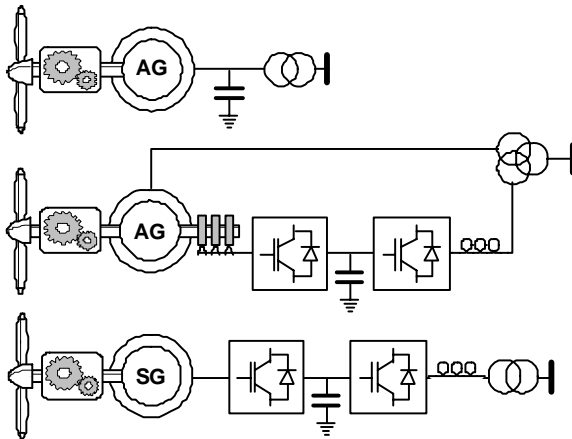


Fig. 5. Topologies modeled in PSCAD: Fixed Speed, Variable Speed (DIFG) and Variable Speed (Synch+AC/AC).

Results of simulation are compared with measurements data in order to validate the models. From Fig. 7 to Fig. 9 a comparison between simulation results and measurements is presented. As shown in figures, there is a reasonable agreement between them.

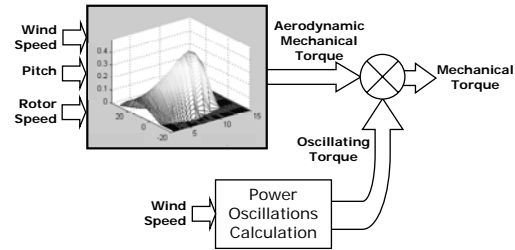


Fig. 6. Calculation method for mechanical torque.

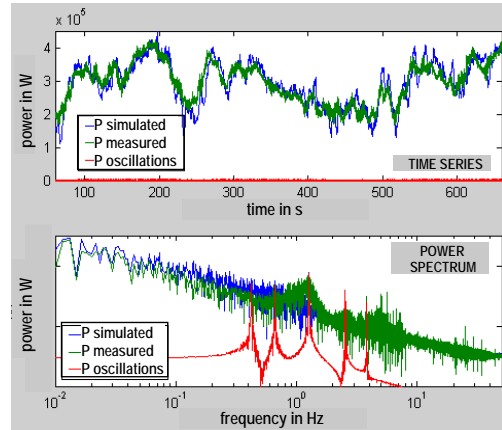


Fig. 7. Simulation results for FS/FP WTG (FF1).

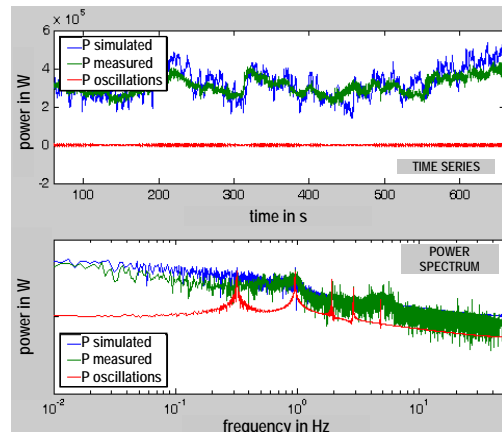


Fig. 8. Simulation results for FS/VP WTG (FV1).

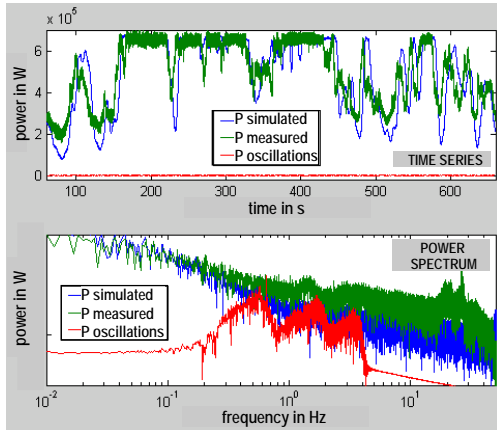


Fig. 9. Simulation results for VS/VP WTG (VV1)

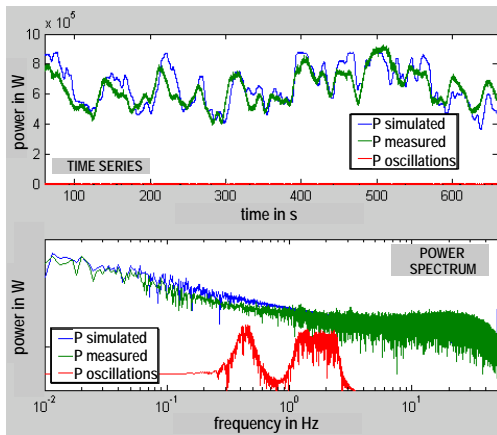


Fig. 10. Simulation results for VS/VP WTG (VV2).

V. FLICKER ESTIMATION

Once models of wind turbines have been implemented and validated, estimation of flicker emission can be done. In this paper a variation of the method in IEC 61400-21 [5] (see paragraph II) is presented. In this case, the current source shown in Fig. 1 is substituted by the completed WTG model (see Fig. 11). In this way, simulations at different conditions than those during measurements can be done.



Fig. 11. Fictitious network with complete WTG model

In this case, flicker emission estimations for different short circuit capacity values in the point of common coupling (PCC) of WTG are presented.

Two situations are considered to estimate flicker emission (Pst). The first one consists in a simulation of single WTG. In the second one, a wind park formed by equal turbines to those that have been simulated is supposed. In these cases different short circuit capacities are considered (see Table 5):

- Scc Min. The minimum value of short circuit power at the Sotavento PCC in the 132 kV level is considered.
- Scc Max. The maximum value of short circuit power at the Sotavento PCC in the 132 kV level is considered.
- Scc 20x. The short circuit power in PCC is supposed to be about 20 times higher than WTG nominal power.

For each WTG, four Pst values are obtained:

- Pst WT, is the flicker level emission for a single WTG with a determined short circuit capacity.
- Using Pst WT the flicker levels in Scc Min, Scc Max and Scc 20x scenarios are calculated. In this case, a wind park, with a nominal power about 17,5 MW, formed by equal wind turbines is supposed.

Table 5. Short circuit power capacity in the different scenarios

Shortcircuit Power at 132 kV (MVA)	
Scc Min	4.755
Scc Max	5.023
Scc 20x	20 x Pnom. WTG x n

Results for all different types of WTG's in Sotavento Wind Park are shown from Table 6 to Table 12. The severity of flicker is calculated from PSCAD simulations with a determined short circuit capacity (Scc WT in tables). The flicker in the different scenarios is calculated by means of Flicker coefficient using equations (1) and (2).

Table 6. Results for a FS/FP WTG (FF1)

Scs WT (MVA) (MVA)	13
Scs WT (°)	71,56
Mean Wind Speed (m/s)	8,38
Pst WT Sim.	0,012706
Flicker Coefficient	0,25027
Pst Scs Max	0,00018
Pst Scs Min	0,00017
Pst Scs 20x	0,00248

Table 7. Results for a FS/FP WTG (FF2)

Scs WT (MVA) (MVA)	13
Scs WT (°)	71,56
Mean Wind Speed (m/s)	10,76
Pst WT Sim.	0,022567
Flicker Coefficient	0,39116
Pst Scs Max	0,00030
Pst Scs Min	0,00028
Pst Scs 20x	0,00414

Table 8. Results for a FS/FP WTG (FF3)

Scs WT (MVA)	6
Scs WT (°)	71,56
Mean Wind Speed (m/s)	9,2344
Pst WT Sim.	0,027209
Flicker Coefficient	0,25508
Pst Scs Max	0,00018
Pst Scs Min	0,00017
Pst Scs 20x	0,00249

Table 9. Results for a FS/FP WTG (FF4)

Scs WT (MVA)	6
Scs WT (°)	71,56
Mean Wind Speed (m/s)	8,1795
Pst WT Sim.	0,026456
Flicker Coefficient	0,26456
Pst Scs Max	0,00018
Pst Scs Min	0,00017
Pst Scs 20x	0,00247

Table 10. Results for a FS/VP WTG (FV1)

Scs WT (MVA) (MVA)	13
Scs WT (°)	71,56
Mean Wind Speed (m/s)	7
Pst WT Sim.	0,022304
Flicker Coefficient	0,22304
Pst Scs Max	0,00022
Pst Scs Min	0,00021
Pst Scs 20x	0,00307

Table 11: Results for a VS/VP WTG (VV1)

Scs WT (MVA) (MVA)	13
Scs WT (°)	71,56
Mean Wind Speed (m/s)	10,3616
Pst WT Sim.	0,044174
Flicker Coefficient	0,71783
Pst Scs Max	0,00055
Pst Scs Min	0,00052
Pst Scs 20x	0,00774

Table 12: Results for a VS/VP WTG (VV2)

Scs WT (MVA) (MVA)	13
Scs WT (°)	71,56
Mean Wind Speed (m/s)	10,3526
Pst WT Sim.	0,09
Flicker Coefficient	1,77273
Pst Scs Max	0,00125
Pst Scs Min	0,00119
Pst Scs 20x	0,01755

The effect of including the power oscillation components in the model can be observed in the examples shown in Table 13 and 15. The Pst values calculated with and without the oscillating components are shown in those tables.

The main consequence of neglecting oscillating components in the model is that the flicker could be significantly underestimated.

Table 13. Pst in a FS/FP WTG (FF4), with and without oscillating power components.

WTG nominal power (MW)	0,60
Scs WT (MVA) (MVA)	6,00
Scs WT (°)	71,56
Mean Wind Speed (m/s)	8,1795
Pst WT	0,0265
Pst WT without oscill.	0,0119
Pst error	55,1%

Table 14. Pst in a FS/VP WTG (FV1), with and without oscillating power components.

WTG nominal power (MW)	1,30
Scs WT (MVA) (MVA)	13,00
Scs WT (°)	71,56
Mean Wind Speed (m/s)	7,0000
Pst WT	0,0223
Pst WT without oscill.	0,0119
Pst error	46,8%

VI. CONCLUSIONS

In this paper, a method to evaluate flicker based in IEC 61400-21 is presented. Current measurement data used in this standard have been replaced for a complete wind turbine model. In this model, oscillating power components (shadow tower, wind shear, etc) have been included with the intention of getting more realistic results.

WTG models have been validated by comparing the simulation results with the measured data.

The proposed method allows calculating flicker emission of single WTG or wind parks at different working conditions.

VII. ACKNOWLEDGMENT

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