AN ENGINEERING APPROACH IN MODELING OVERVOLTAGE EFFECTS ON WIND PARKS CAUSED BY TRAVELLING WAVES

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Abstract: Recently, norms and safety standards recommend, that the wind turbine's earthing (grounding) systems in the wind park shall be galvanically connected by means of earthing cables; this practice is followed in order to achieve a common earth-potential in the wind park. The objective of this publication is to provide tools for predicting potential risk of damage due to overvoltages caused by lightning strikes in wind parks from an engineering approach. Finally the effects of the installation of overvoltage protection (MOVs) are discussed. The simulation program EMTP-ATP, pre-processing program ATPDraw and post-processing program PLOTXY were chosen for this study

1 INTRODUCTION

Considering the general trending of increasing the dimensions of modern multi-megawatt wind turbines, unexpected effects in form of overvoltages and overcurrents, which may be the result of electromagnetic traveling waves caused by lightning strikes, are the essential motivation of this publication.

Moderns standards and certification organization recommend that the earthing (grounding) systems of the wind turbines (WTs) have to be galvanic connected in order to ensure a common earth potential in the wind park; however these techniques may lead to other effects such as overvoltages caused by direct lightning strikes.

2 APPROACH AND MODELING

The components of the wind park were modeled in form of surge impedances with a propagation velocity of the travelling wave.

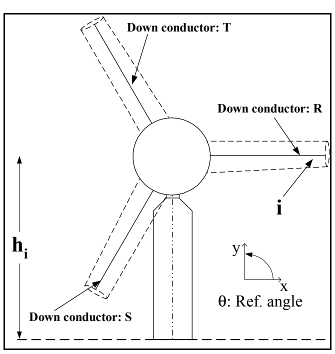

Fig. 1. References for the calculations.

Fig. 1 depicts the assumptions and references for the simulations, where, i corresponds to the index of the down conductor of the corresponding rotor blade i; h_i the height of the conductor above ground and r_i the radius of the conductor i.

2.1 Rotor Blades

The rotor blade lightning protection system (LPS) chosen for the model was the receptor-based lightning protection system widely explained in [1] and [2]. Table 1 shows the parameters of a decoupled surge impedance model for the blades as an attempt to represent their electromagnetic response to fast transients.

Table 1: Parameters: Rotor Blades (two segments with a length of 18.75m).

L_{Blade} [mH]	C_{Blade} [μF]	Z_w [Ω]	v [m/μs]	Length [m]
4.15E-2	9.43E-5	21.00	280.00	18.75

Each rotor blade segment is modeled with its own characteristic surge impedance Z_w and a propagation velocity v, using the theory of explained in [4].

2.2 Rotor Blades and Azimuth Bearings

The bearing's metal parts (flanges and metal balls) were modeled as a resistance R_{bear} in series with an inductance L_{bear} calculated at an electric frequency of 500 kHz in order to consider the skin effect and afterwards connected in parallel along the complete circumference of the bearing.

The non-conductive parts such as the thin layer of lubricants between the bearing balls were modeled as a thin capacitor C_{layer} and the surrounding lubrication layers with a shunt capacitor C_{lub}, which are short-circuited with a voltage-controlled switch after a certain flashover voltage threshold has been reached; in this simulation the threshold voltage was set to 1000 V. Table 2 depicts the parameters used for the bearings, which are connected in series.

Table 2: Parameters: Rotor Blades and Azimuth Bearings.

Part	L_{bear} [mH]	C_{layer} [μF]	R_{bear} [Ω]	C_{lub} [μF]
Blade	7.67E-8	4.72E-2	3.17E-6	1.06E-4
Azimuth	6.07E-8	1.17E-4	1.65E-5	2.63E-4

2.3 Tower

The tower is usually manufactured in steel or reinforced concrete. Table 3 shows the parameters for the three segments of the steel tower assumed for this study.

Table 3: Parameters: Tower (three segments with a length of 29.00m each).

Z_{wTower} [Ω]	*Length* [m]	*v* [m/μs]
198.00	29.00	250.00

The tower height and base radius of the equivalent cone of the tower are used as input parameters to obtain the equivalent surge impedance Z_{tower} [5].

2.4 Earthing System

The earthing type B described in [1] was chosen for this study; the footing resistance R_T can be modeled from the guidelines proposed in [6].

Table 4 shows the parameters used for the calculation of the footing resistance with a variation of the soil resistivity from 100 Ωm (Boggy soil, humus, etc.) up to 500 Ωm (Gravel type, etc.) base on the theory explained in [7].

Table 4: Parameters: Earthing System.

ρ_{soil} [Ωm]	*Electrode x-side* [m]	*Inner Radius a* [m]	*Buried Depth d* [m]	R_T [Ω]
100.00	9.00	0.50	3.50	1.28
200.00	9.00	0.50	3.50	2.56
300.00	9.00	0.50	3.50	3.83
400.00	9.00	0.50	3.50	5.11
500.00	9.00	0.50	3.50	6.39

The earthing rods, used for the earthing of the connection point of the LV-side the transformer (Star) and the wind turbine LV and the MV cables (Delta) were modeled as a resistance in parallel with a capacitor as proposed in [8].

2.5 Low and Medium Voltage Cables

The non-shielded low voltage (LV) cables connecting the WT panelboard to the low voltage side of the WT distribution transformer were modeled with a PI-equivalent model:, three conductors/phase (equivalent to a 1000 Kcmil in AWG-notation) and one additional copper conductor for earthing (Equivalent to a 4/0 in AWG-notation).

The medium voltage (MV) cables with a sheath, connecting the primary side of the WT transformers to the MV grid were simulated and calculated with the JMARTI model of EMTP-ATP at 500 kHz (10 decades, 9 Points/Dec).

Table 5 describes the dimensions and the physical properties of the materials for the calculation of the cable parameters [4].

Table 5: Parameters: LV and MV Cables.

Part	*Radius* [m]	*Length* [m]	ε_r	ρ [Ωm]
LV	1.40E-2	30.00	2.00	2.30E-2
LV_{Earth}	0.70E-2	30.00	1.00	2.30E-2
MV	2.63E-2	300.00	2.70	2.30E-2
MV_{Earth}	2.63E-2	300.00	2.70	2.30E-2

2.6 Wind Turbine Distribution Transformer

Each WT was assumed to be galvanically connected to a distribution transformer, which was modeled in order to address the overvoltage effects on the LV and MV sides.

Table 6 depicts the input parameters. The surge capacitances were modeled using the guidelines proposed in [8].

Table 6: Parameters: WTs Transformers.

R_{Prim} [Ω]	L_{Prim} [mH]	R_{Shunt} [Ω]	R_{Sec} [Ω]	L_{Sec} [mH]
1.00E-4	1.00E-3	1.00E+6	2.00E-3	5.20E-2

2.7 LV and MV MOVs

The representation chosen for the low (LV) and medium voltage (MV) MOVs was in form of a non-linear resistance (type 92).

It was assumed that these devices did not observe degradation in their dynamic response considering aging, environmental conditions, duty cycle, switching frequencies of electronic converters, etc.

Fig. 2 depicts the characteristic curve assumed for the LV MOV.

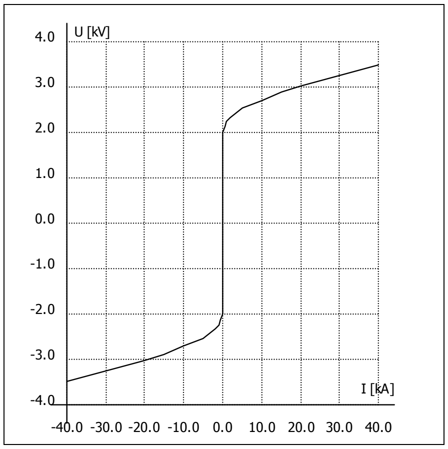

Fig. 2. Characteristic Curve: Low Voltage MOV

Fig. 3 depicts the characteristic curve assumed for the MV MOV.

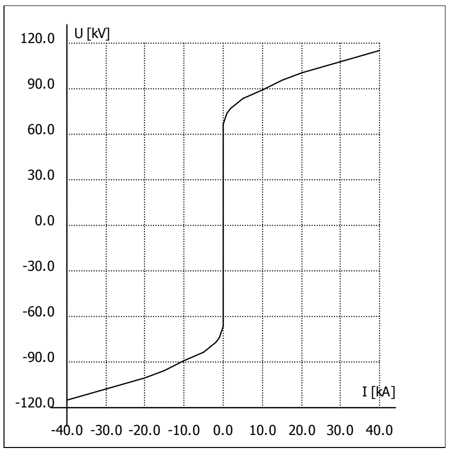

Fig. 3. Characteristic Curve: Medium Voltage MOV

2.8 Thevenin Equivalent of the Wind Park Substation (S/E)

A total of five wind turbines (WTs) to from a small wind park (WP) were modeled, were each WT is connected to a medium voltage Thevenin-equivalent network with a short circuit three-phase impedance for 75.00 MVA, 33.00 kV or Z_{base}; this in order to simulate the medium voltage connection of the WTs distribution transformers to a main substation (S/E).

The earthing systems of the WTs described in the section 2.4 were galvanic connected to each other on the distribution transformer's LV-Side (star connection) and firmly earthed on each end connection point with earthing rods as explained in section 2.4.

Each MV cable sheath and earthing conductor was connected to the earthing system of the WT. The separation distance between the WTs is 300.00 meters.

3 SIMULATION RESULTS

For the simulations a time step of 0.50 ns for a total simulation time of 120.00 µs was chosen.

The lightning stroke was simulated by means of a Heidler source [3]; the factor influencing the rate of rise of the function (Steepness) was set to the value of 2.00.

3.1 Case Study: 30 kA (10/350 µs) First Short Lightning Stroke <u>without</u> MOVs

A positive downward lightning stroke (30 kA, 10/350 µs) on the en section (tip region) of the 37.50 meters long rotor blade R of the WT1 was simulated, in order to explore the effects of the traveling waves effects across the WP.

Table 7 and table 8 depicts the overvoltage effects on the LV and MV sides of the WT distribution transformers respectively, when the soil resistivity is varied from 100 Ωm up to 500 Ωm.

The installation of MOVs in this simulation cases was not considered in order to estimate the worst case scenario.

Table 7: Induced overvoltages on the LV side of the WT-transformers

WT	ρ_{soil} [Ωm] 100	200	300	400	500
WT1	45.98	68.80	80.42	88.44	94.12
WT2	14.59	24.38	31.07	35.92	39.48
WT3	3.88	6.07	8.77	10.39	11.63
WT4	1.21	2.18	2.97	3.63	4.19
WT5	0.89	1.70	2.38	2.92	3.34

Fig. 1 and fig. 2 depict the plots of the induced overvoltages on the LV and MV sides of the WT1 with the variation of the soil resistivity.

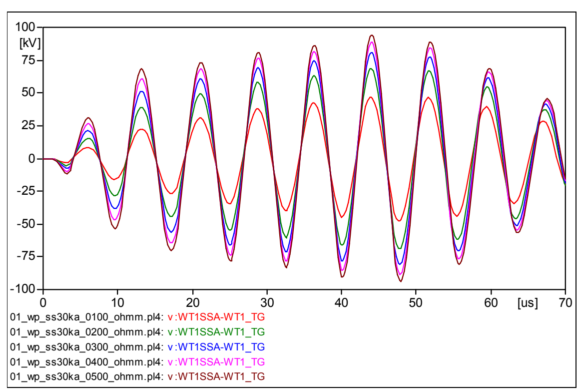

Fig. 1. Overvoltages induced on the LV side with variation of the soil resistivity: WT1

Table 8: Induced overvoltages on the MV side of the WT-transformers

WT	ρ_{soil} [Ωm] 100	200	300	400	500
WT1	98.06	101.70	102.61	102.87	102.96
WT2	86.56	87.90	88.79	89.49	90.08
WT3	83.74	84.00	84.49	85.24	85.63
WT4	83.88	84.08	84.13	84.29	84.32
WT5	83.47	83.69	83.88	84.01	84.10

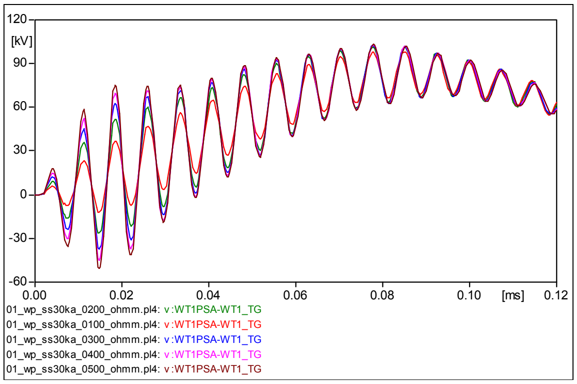

Fig. 2. Overvoltages induced on the MV side with variation of the soil resistivity: WT1

The WT struck by lightning observes the highest overvoltage values. It can be noticed that the induced overvoltages vary in a non-linear basis with respect to variation of the soil resistivity. Furthermore these elevated values can lead to failures in the electric installation in form of flashovers, electric arcs and the like.

An oscillation of approx. 128 kHz is observed; this effect may be caused by the effects of transmission and reflection of travelling waves along the WP's earthing system. Fig. 3 depicts the time delay of approx. 22μs between WT1 and WT5 with soil resistivity of 500 Ωm.

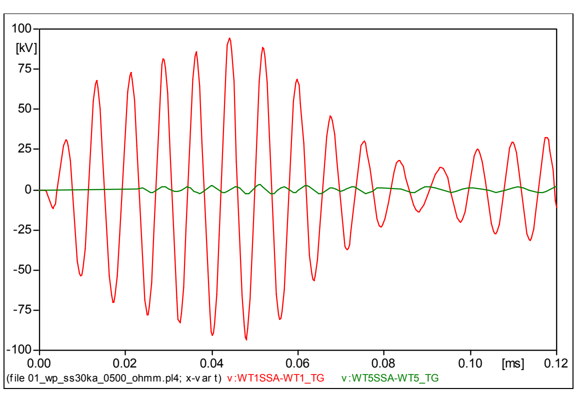

Fig. 3. Delay in the induced overvoltages (LV side) caused by travelling waves between the WT1 and WT5 (Soil resistivity 500 Ωm)

3.2 Case Study: 30 kA (10/350 μs) First Short Lightning Stroke with MOVs

A positive downward lightning stroke (30 kA, 10/350 μs) on the tip of the rotor blade R of the WT1 in order to explore the effects of the traveling waves effects across the WP. In this case the MOVs connected on the LV and MV side of the transformer side were included.

Table 7 and table 8 depicts the overvoltage effects on the LV and MV sides of the WT distribution transformers, when the soil resistivity is varied from 100 Ωm up to 500 Ωm. It can be noticed that the induced overvoltages are maintained within a range, which is regulated by the MOVs. Fig. 4 and fig. 5 depict the plots of the induced overvoltages on the LV and MV sides of the WT1 with the variation of the soil resistivity.

Table 9: Induced overvoltages on the LV side of the WT-transformers with MOVs

WT	ρ_{soil} [Ωm] 100	200	300	400	500
WT1	4.29	5.60	6.63	7.27	7.74
WT2	2.49	2.90	3.18	3.40	3.59
WT3	1.04	1.23	1.44	1.55	1.71
WT4	0.56	0.67	0.73	0.86	0.95
WT5	0.43	0.48	0.57	0.66	0.72

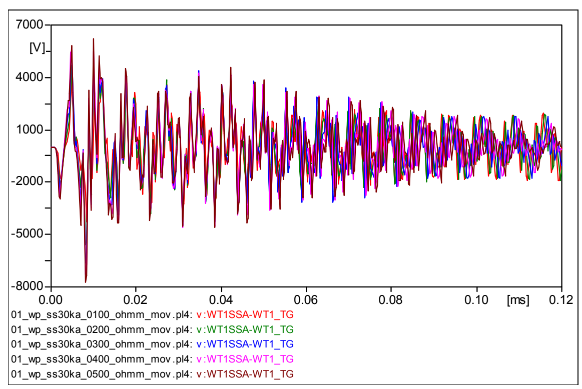

Fig. 4. Overvoltages induced on the LV side with variation of the soil resistivity: WT1

Table 10: Induced overvoltages on the MV side of the WT-transformers with MOVs

WT	ρ_{soil} [Ωm] 100	200	300	400	500
WT1	67.93	68.09	68.05	68.05	68.01
WT2	65.95	65.87	66.38	66.40	66.53
WT3	65.92	65.92	65.91	65.94	65.98
WT4	65.91	65.92	65.94	65.97	66.00
WT5	65.89	65.93	65.94	65.97	65.98

Fig. 6 shows a time delay of approx. 22 μs in the simulated induced overvoltages between the WT1 and WT5 with a soil resistivity of 500 Ωm. In this case and due to the effect of the MOVs, it was not possible to estimate a fixed oscillation; however this effect is observed along the WP's earthing system.

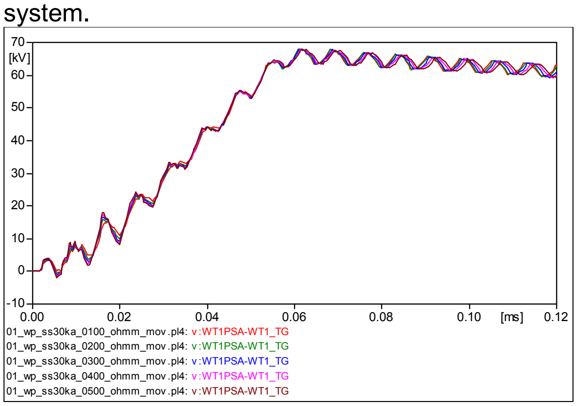

Fig. 5. Overvoltages induced on the MV side with variation of the soil resistivity: WT1

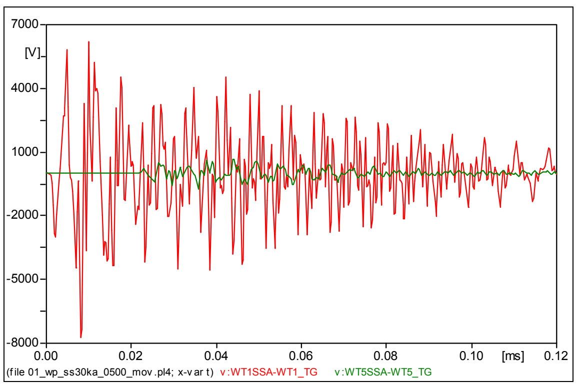

Fig. 6. Delay in the induced overvoltages (LV side) caused by travelling waves between the WT1 and WT5 with the MOVs connected (Soil resistivity 500 Ωm)

4 CONCLUSION

Overvoltage effects of traveling waves caused by direct lightning strikes on WPs were addressed using models from the fast transient modeling theory.

The proposed WT rotor blade models in form of decoupled surge impedances are an attempt to suggest a model for these complex structures manufactured in composite materials; however these models are subject to further improvement and discussion in the scientific councils.

During a direct lightning strike to a wind turbine, the electromagnetic effects on the earthing system in form of overvoltages amplitudes were modeled in the wind turbine struck by lightning and in the nearby-located wind turbines.

The installation of MOVs on the LV and MV side of the transformer is an acceptable practice, provided that their effectiveness, duty cycle and aging offer a similar level of response and energy dissipation against overvoltages over their duty cycle. Monitoring of strategic MOVs may be a good practice in the safe operation of WTs.

The presented methodology followed the worst case approach and an acceptable level of simplification for common engineering practices.

5 ACKNOWLEDGMENTS

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6 REFERENCES

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