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EVALUATING THE IMPACT OF UNDERBUILT WIRES IN TRANSMISSION LINES USING ALTERNATIVE TRANSIENT PROGRAM

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***Abstract* - This work presents a study performed in Alternative Transient Program (ATP) related to its precision to estimate the impact of underbuilt wires installed in transmission lines. This non-conventional technique capable to increase the lightning performance of lines is usually evaluated by electromagnetic models, but not by more widespread time-domain simulation software as ATP. Thus, this paper aims to inquire if coupling effects and the impedance reduction are well estimated by the line models included in ATP. The results obtained show a good precision of ATP to estimate the overvoltage values of lines with underbuilt wires besides the reductions provided by its consideration. In addition, to achieve such results with ATP helps the evaluation of researchers and engineers to preview the lightning performance improvement by the usage of the technique in critical paths of transmission lines through a more widespread software.**

***Keywords* – ATP software, Lightning overvoltage, Time-domain simulation, Transmission lines, Underbuilt wires.**

I. INTRODUCTION

There is a continuous researching for alternative techniques that can improve the performance of transmission lines (TL), notably for lightning strikes. Regions or TL paths with a high rate of lightnings strikes or soils with high resistivity values can demand distinct projects and solutions to achieve the desirable performance and to agree with national standards.

One of the non-conventional techniques reported by works as [1,2] is underbuilt wire (UW). The main idea is to introduce a conductor below the phase cables along two adjacent towers, as illustrated in Figure 1. This conductor does not have the aim of shielding as ground wires (GW), but is capable to decrease the equivalent impedance of towers and cables of a TL path for transients as that derived from lightning strikes. Coupling effects are also correlated to diminish the insulation voltage at the tower besides the draining off part of the transient current through the new path provided by the adoption of a UW [2].

An UW analysis using the hybrid electromagnetic model (HEM) [3,4], an electromagnetic method that is used in many works related to lightning, grounding and transients studies, is performed in [5]. Significative reductions on insulation voltage are observed and highlights a good result of UW, notably for soil with high resistivity values.

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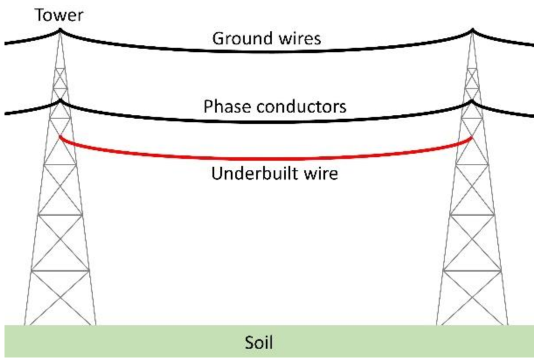
Figure 1: Illustration of a UW in a sag between two adjacent towers



Despite the results, simulations made in [5] are complex to be reproduced due to HEM, which requires its implementation to be used by researchers. Comparisons with more widespread software, as Alternative Transient Program (ATP) or the commercial PSCAD, are not reported and can turn easier the knowledge and estimative of the impacts of UW for researchers and engineers. A recent work compares deep vertical electrodes included in grounding mesh with UW technique using ATP and the validity of the results can be checked by a study aiming this aspect [6].

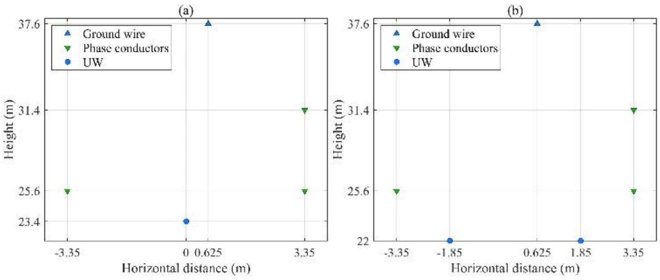
This paper presents an evaluation of simulations performed in [5] using ATP. The main aspects related to the considered TL path, position of conductors and tower modelling are shown, pointing to reproduce the insulation voltage reduction observed in the original paper with HEM.

II. PROBLEM DESCRIPTION

A. TL path considered in [5]

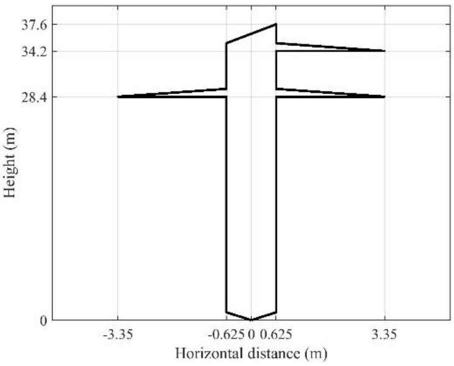
A 230-kV TL is considered based on a cable-stayed tower with a GW and three phase conductors – one conductor per phase. Adjacent towers are assumed with 300 m sag and a grounding mesh modelled as a resistor with the same value of the grounding resistance R_g. A uniform soil is supposed besides the possibility of one or two UW, as illustrated in Figure 2. Following the adjacent towers, a matched impedance is added to nullifies reflective waves that can modify the voltage levels observed on insulator strings.

Figure 2: Disposal of conductors at the evaluated TL path, assuming (a) one and (b) two UW – adapted from [5]



Phase conductors have 0.5 cm radius, while GW and UW have 0.3 cm radius, with no comments about catenary considerations – cables are supposed to have the same height at the tower and midspan in this work. A triangular 2/50 µs current wave is adopted as the transient source related to a first stroke current at the top of the tower, assuming a peak value of 50 kA. The cable-stayed tower has 37.6 m and a square-shaped structure with sides of 1.25 m, as shown in Figure 3.

Figure 3: Tower profile used for the analysis performed by [5]



B. Implementation of the TL path in ATP

For the implementation performed in ATP, TL tower was modelled as a surge impedance Z_S calculated as [7]:

$$Z_S = 60\left[-1+\ln\left(\frac{4h_t}{r_t}\right)\right] \quad (1)$$

Where:

Z_S - Surge impedance.
h_t - Tower height.
r_t - Equivalent radius of the tower.

Assuming h_t = 37.6 m and r_t = 3.35 m, as suggested in [8], we obtain Z_S = 168 Ω. Its implementation is performed as a transposed line with distributed parameters in ATP, being defined by the Z_S value, propagation velocity $\upsilon = 0.85c$ [8], where c is the light speed, and length of the path l_t. This aspect leads to evaluate the tower with divisions along its extension to obtain the voltage levels with and without UW. Figure 4 presents the tower division and Table I shows the values used for each case. Cross-arms are neglected in this analysis.

All conductors are implemented using JMarti model in ATP [9]. Skin effect and a real transference matrix are

Figure 4: Representation of the tower by its surge impedance – adapted from [6]

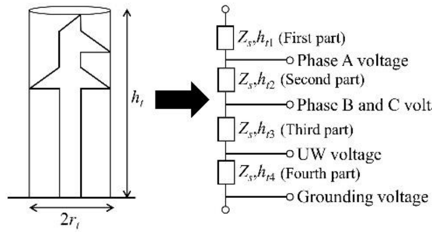


Table I: Surge impedance and height of each part of the tower

Case	Z_S (Ω)	h_{t1} (m)	h_{t2} (m)	h_{t3} (m)	h_{t4} (m)
1 UW	168	3.4	5.8	5.0	23.4
2 UW	168	3.4	5.8	6.4	22.0

assumed, besides the algorithm is run with 8 decades, 20 points per decade, modal matrix estimated at 10 kHz and a steady state frequency of 60 Hz. The center tower and its adjacent structures have 300 m sag with additional paths at the ends of each adjacent tower with 20 km length. The main goal of these is to avoid reflection waves as an alternative procedure compared to matched impedances. We highlight that ground return impedance in ATP is computed by Carson expressions [10], which only considers the soil resistivity, not its permittivity. So, effects related to displacement currents are omitted in simulations and can be source of differences between the results of this work and [5].

Table II shows details on the position and electric properties of the conductors assumed in ATP simulations. Resistance per length is estimated to phase conductors at 65º C and for GW and UW at 40º C. As mentioned before, cables are supposed to have the same height at the tower and midspan.

Table II: Conductors data related to JMarti model

Phase conductors and GW					
Parameters	**Internal radius (cm)**	**External radius (cm)**	**Resistance (Ω/km)**	**Horiz. distance (m)**	**Height (m)**
Phase A	0	0.5	0.544	3.35	31.4
Phase B	0	0.5	0.544	-3.35	25.6
Phase C	0	0.5	0.544	3.35	25.6
GW	0	0.3	4.191	0.625	37.6
Case with 1 UW					
UW	0	0.3	4.191	0	23.4
Case with 2 UW					
UW1	0	0.3	4.191	-1.85	22.0
UW2	0	0.3	4.191	1.85	22.0

Grounding mesh is admitted in ATP simulations as resistors with value equals to R_g, which is proportional to the soil resistivity value ρ_g – the same value considered in JMarti model for soil resistivity. Thus, five cases are tested: R_g = 10 Ω (ρ_g = 800 Ωm), 20 Ω (ρ_g = 1600 Ωm), 30 Ω (ρ_g = 2400 Ωm), 40 Ω (ρ_g = 3200 Ωm) and 80 Ω (ρ_g = 6400 Ωm).

The transient source is a slope-ramp current wave, with a peak value of 1 kA and a 2/50 µs characteristic. While 50 kA are assumed in [5], all results are normalized by this peak value and justifies the option for a 1 kA amplitude current wave. Time step considered in all ATP simulations is 1 ns and a period time of 10 µs.

It is important to repeat that the aim of the simulations is to know if ATP can estimate similar voltage insulation reductions by the consideration of UW in TL as HEM, not the absolute overvoltage obtained in each case. With these results, it is able to conclude if ATP can be a tooling to preview the percentage performance gains related to the adoption of UW.

III. RESULTS

Figure 5 shows the implemented circuit in ATP for the original problem, while Figure 6 presents the circuits that uses a single or two UW.

Figure 5: Circuit implemented in ATP without UW

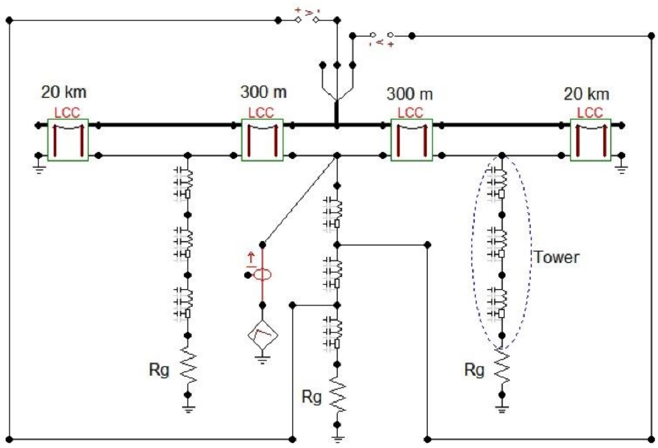
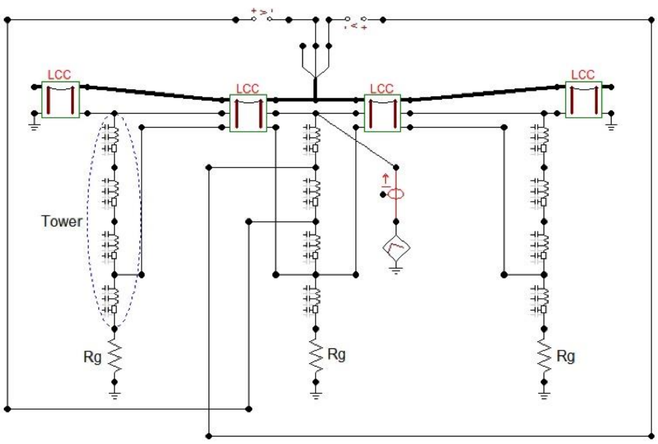


Figure 6: Circuit implemented in ATP with a single or two UW



The first comparison aims to comprehend the percentage reduction on voltage insulation due to the decrease of R_g and ρ_g values along the line. All cases evaluated in [5] and by ATP in this work are shown in Table III.

Table III shows a very similar voltage insulation reduction obtained by ATP and HEM assuming different values of R_g and ρ_g. Simulations using ATP seems to provide greater voltage peak values compared to HEM, up to 15% for R_g = 80 Ω and 22% for R_g = 40 Ω. For lower resistivities, the difference diminishes and reaches 7% for R_g = 10 Ω.

Table III: Estimated peak values of overvoltage for distinct R_g and ρ_g values through the upper and lower insulation strings

HEM [5]					
Condition		**Upper insulation string**		**Lower insulation string**	
R_g (Ω)	**ρ_g (Ωm)**	**Voltage peak value (kV/kA)**	**Red.**	**Voltage peak value (kV/kA)**	**Red.**
80	6400	43.95	---	48.56	---
40	3200	26.98	38.6%	27.53	43.3%
30	2400	23.45	46.6%	23.59	51.4%
20	1600	19.40	55.9%	19.08	60.7%
10	800	14.80	66.3%	13.95	71.3%
ATP					
Condition		**Upper insulation string**		**Lower insulation string**	
R_g (Ω)	**ρ_g (Ωm)**	**Voltage peak value (kV/kA)**	**Red.**	**Voltage peak value (kV/kA)**	**Red.**
80	6400	50.82	---	54.16	---
40	3200	32.26	36.5%	33.63	37.9%
30	2400	26.87	47.1%	27.68	48.9%
20	1600	21.11	58.5%	21.32	60.6%
10	800	14.58	71.3%	14.97	72.4%

Furthermore, upper insulation string has a lower voltage peak value compared to lower insulation string in all cases using ATP, behavior that is reported by HEM for $R_g \geq 30$ Ω. Despite this, considering the idea to obtain the reduction percentage due to the addiction of UW, results obtained by ATP are equivalent to that from HEM [5].

The second analysis goals to promote simulations in ATP that able a comparison of voltage insulation reduction based on the consideration of UW in TL. For cases with one and two UW, Table IV and Table V present the results from [5] and this work.

Table IV: Overvoltage peak value for the cases evaluated with R_g = 10 and 20 Ω

R_g = 10 Ω and ρ_g = 800 Ωm					
Configuration		**Upper insulation string**		**Lower insulation string**	
		Voltage peak value (kV/kA)	**Reduction**	**Voltage peak value (kV/kA)**	**Reduction**
HEM	Original	14.8	---	13.95	---
	+ 1 UW	12.4	16.2%	10.38	25.6%
	+ 2 UW	11.25	24.0%	8.87	36.4%
ATP	Original	14.58	---	14.97	---
	+ 1 UW	10.95	24.9%	12.37	17.4%
	+ 2 UW	9.46	35.1%	11.28	24.6%
R_g = 20 Ω and ρ_g = 1600 Ωm					
Configuration		**Upper insulation string**		**Lower insulation string**	
		Voltage peak value (kV/kA)	**Reduction**	**Voltage peak value (kV/kA)**	**Reduction**
HEM	Original	19.4	---	19.08	---
	+ 1 UW	15.71	19.0%	13.72	28.1%
	+ 2 UW	14.37	26.0%	11.83	38.0%
ATP	Original	21.11	---	21.32	---
	+ 1 UW	15.41	27.0%	16.79	21.2%
	+ 2 UW	12.97	38.6%	14.94	29.9%

Again, very similar percentage reduction in voltage peak values are noted comparing HEM and ATP. In Table IV, related with lower ρ_g values, ATP results for upper insulation string are equivalent to that from HEM for lower insulation string and vice versa. This does not happen only for the

Table V: Overvoltage peak value for the cases evaluated with R_g = 40 and 80 Ω

Configuration		Upper insulation string: Voltage peak value (kV/kA)	Upper insulation string: Reduction	Lower insulation string: Voltage peak value (kV/kA)	Lower insulation string: Reduction
R_g = 40 Ω and ρ_g = 3200 Ωm					
HEM	Original	26.98	---	27.53	---
	+ 1 UW	20.93	22.4%	18.99	31.0%
	+ 2 UW	18.69	30.7%	15.95	42.1%
ATP	Original	32.26	---	33.63	---
	+ 1 UW	23.11	28.4%	24.38	27.5%
	+ 2 UW	18.80	41.7%	21.03	37.5%
R_g = 80 Ω and ρ_g = 6400 Ωm					
HEM	Original	43.95	---	48.56	---
	+ 1 UW	29.95	31.9%	29.82	38.6%
	+ 2 UW	24.8	43.6%	23.19	52.3%
ATP	Original	50.82	---	54.16	---
	+ 1 UW	34.85	31.4%	35.94	33.6%
	+ 2 UW	27.30	46.3%	29.92	44.8%

original TL path without UW in Table V. The differences between the techniques, including the lack of displacement current effects by JMarti model and a possible underestimation of coupling effects, justify the distinct results.

If the maximum reduction percentage is observed for each case, the equivalence of ATP and HEM to evaluate the performance of UW is remarkable – this is the main procedure evaluated in real-world conditions. Thus, results suggest that ATP can be used to infer the performance of UW aiming the percentage reduction of voltage insulation in TL. Furthermore, conclusions from [6] related to deep vertical electrodes compared to UW are also supported. If the values of voltage insulation in structures are desired, ATP tends to provide greater values than HEM and the required precision for the analysis needs to be studied to allows the usage of this software.

IV. CONCLUSIONS

This work investigated the results of ATP as a tooling to evaluate the performance of UW in TL. Comparisons were made with HEM results and leads to conclude that ATP can provide precise percentage reduction values of voltage insulation when UW is added to simulations. Thus, ATP can be applied to preview the UW performance for TL with problems related to lightning strikes.

The lack of displacement current effects by JMarti model in ATP can depreciate results for overvoltage, but the maximum percentage reduction of voltage insulation maintains equivalent values compared to HEM. To assume other line models, as Universal Line Model, by external numerical routines can be an alternative to reach even better results shown in this work with ATP.

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