Impact of Nearby Lightning Strikes on Wireless Power Transfer Ground Assembly

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Direct hits from Lightning Strikes (LS) are commonly recognized as dangerous events for open air installations, but also the much more frequent case of LS hitting nearby can cause overvoltage potentially damaging connected circuits, if not correctly protected. In this paper, adopting a hybrid formulation, we simulate the voltage induced at the terminals of a Wireless Power Transfer (WPT) ground coil by a LS hitting the ground nearby the system. The induced overvoltage has a non-negligible amplitude, depending on the distance of the hit, the tortuosity of the lightning channel, and the inclination of the coil with respect to the ground plane.

***Index Terms*— Wireless Power Transfer, Lightning Strikes, Electromagnetic Compatibility.**

I. Introduction

Wireless power transfer (WPT) is a technology that has already reached a substantial readiness level in consumer electronics applications: devices like rechargeable toothbrushes and mobile phones charging platforms (all developed under the Qi standard [1]) are nowadays part of our lives. These devices operate at low voltages and power and the electronic circuitry is relatively simple ad unexpensive.

On the contrary, WPT systems for electric or hybrid vehicles charging are still object of research and development. even though an official document relative to their regulation (SAE J2954, [2]) has already been released. In [2], the descriptions of the Ground Assembly (GA) and Vehicle Assembly (VA) of a WPT system are included, based on the working principle described in [3].

In the near future it is highly probable that WPT GAs will be present both in residential areas and in dedicated parking lots for electric vehicles fleet. Like photovoltaic (PV) panels, such fixed installations are subject to environmental agents; while pollution and dust, up to a certain extent, would not significantly alter the performance of the system, lightning can be a critical event, as the system is based on electromagnetic induction. Direct lightning will undoubtedly cause the system's disruption, but also indirect lightning could cause induced overvoltage that might be harmful for the electric/electronic circuitry of the excitation system (compensation tank, high frequency converters, etc.). In [4] the authors use a three-dimensional semi-analytical method to simulate the electromagnetic transients caused in PV modules by nearby LS, taking also into account the lightning channel's tortuosity. The differences between a WPT GA and a PV panel are substantial: the WPT GA is composed by spiral windings, ferrite panels and a conductive shield, the latter two are used to reduce leakage flux and to increase mutual coupling with the VA respectively. All these components will be subject to EM field variations, hence to induced currents. In this contribution different parameters that influence the induced overvoltages due to indirect lightning are analyzed, in order to assess the possible relevance of these events for the WPT correct operation. The paper is organized as follows: in Section II a description of the model adopted in this study is presented; in Section III the different parameters possibly impacting on the induced overvoltage level, and analyzed in the study, are introduced; in section III the results relative to the simulations are presented, while in section IV a set of conclusions are drawn.

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II. Modeling the Coupling Between WPT and LS

WPT GAs are realized using different practical layouts; the SAE J2954 describes many of them, providing guidelines for their specific realization. Lately, the so-called *Double-D* (DD) coil solution is one of the most adopted, thanks to its ability to optimize magnetic coupling and to improve the confinement of the magnetic field inside the active area. However, a DD coil is a relatively complex equipment to simulate, especially at the highest frequencies involved in the WPT-LS coupling (in the order of some MHz). Due to this reason, the authors decided to concentrate their attention to a specific set up clearly described in [2] and characterized by a simpler geometry. The adopted model is indeed labelled as Test Station Universal GA, to be used in all the three power classifications WPT1, WPT2 and WPT3. Fig. 1 reports a sketch of the WPT ground coil (left) and the FEM model we used in this study (right).

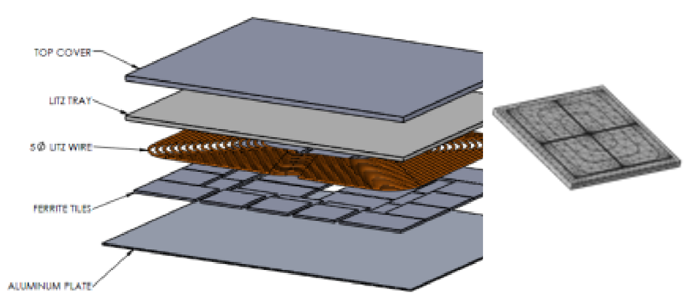

Fig. 1: The WPT ground coil, with the shielding plate and the flux-concentrating ferromagnetic tiles (left) compared with the FEM model of the relevant parts (right).

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Lightning is a transient, high-current electric discharge between the ground and the clouds whose path length can consequently reach up to kilometres. A commonly adopted model for the lightning current consists in considering a current propagation velocity along the strike equal to one-third of the light speed in vacuum, while the current waveform at the channel base is modelled according to the International Electrotechnical Commission (IEC) standard [6]:

$$I_0(t) = I_{max} \frac{\left({}^{t}/_{\tau_1}\right)^n}{1 + \left({}^{t}/_{\tau_1}\right)^n} e^{-\frac{t}{\tau_2}} \tag{1}$$

where I_{max} is the peak value of the lightning current (in this case considered $I_{max} = 50kA$), t is the time, τ_1 is the rise time constant (0.45 µs), τ_2 is the delay time constant (143 µs), and n is the power factor of current rise speed (n=10). Values for subsequent negative impulse, as suggested by IEC, have been used in this study. The waveform and the spectrum of the current are reported in Fig. 2. The spectral content of EM fields from lightning strikes mostly lies below 5 MHz.

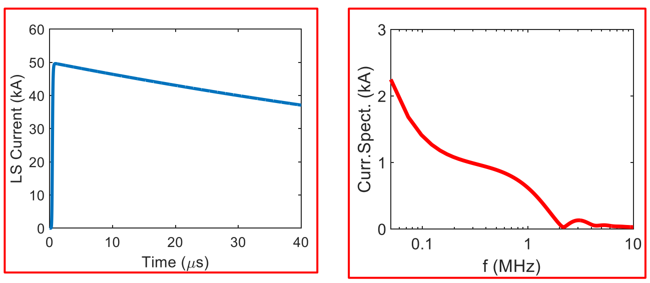

Fig. 2. IEC-62305-2 LS Current: waveform (left) and spectrum (right).

The modelling of the lightning channel is usually carried out as a straight path, but the actual shape is tortuous. This difference is relevant for the coupling phenomenon at hand, since the presence of non-vertical sections can increase the coupling of the LS channel with the WPT coils, which are basically laid parallel to the horizontal ground. Consequently, in this study tortuous channels [4] will be considered by generating several random paths.

The voltage induced at the terminals by nearby LS is calculated in the frequency domain using a FEM model able to consider tortuous channels. A full wave, E-field formulation, with tetrahedral discretization, is used for the WPT system. The LS current along the channel is modelled using multiple edge current elements for tortuous channels, while a single edge is used in case of a straight vertical lightning channel. The induced voltage on the WPT-GA coil is calculated by integrating the resulting electric field (produced by the lightning current) along the coil path: this is the dominant component, but there are additional contributions due to the presence of the conductive shield and the ferrite plates.

The WPT-GA backplate is assumed to be aluminum, while the magnetic plates are composed of MnZn, as specified in SAE J2954 Standard. This ferrite has a non-linear magnetization curve, but the amplitude of the magnetic fields induced by LS in the magnetic tiles' region is typically well below the saturation level. In order to allow a frequency analysis and to speed up computation, in this study the magnetic permeability of ferrite cores is assumed constant. Key parameters of the model are the following: the aluminium plate conductivity $\sigma_{Plate} = 10^5 S/m$, and the magnetic tiles have a relative permeability $\mu_{rTiles} = 10^3$ and a conductivity of $\sigma_{Tiles} = 10^2 S/m$. The ground is considered as a homogenous conductor, with conductivity equal to $\sigma_{ground} = 10^3 S/m$.

In section II the importance of the tilt angle of the WPT GA with respect to the ground was mentioned. In Fig. 3 the meaning of the angle α is explained graphically: when $\alpha = 0$, the lightning channel is perpendicular to the coils, as they are laid horizontally. Depending on the relative position of the LS hit point on the ground, non-vanishing tilt angles imply a LS channel facing the coils or facing the aluminium back plate.

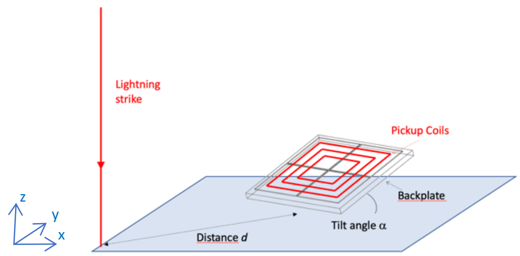

Fig. 3: a sketch of the relative positions between the LS and the WPT-GA coil for different tilt angles.

When a tortuous LC is considered, its geometric model is generated by randomly defining number and position along the channel of a set of breaking points. For each breaking point P_b, three random numbers are generated: the length of the connecting segment L_s to the previous point and the two angles β_1 and β_2, as it is shown in figure 4 [6]. The number of generated points is different for each sample, whereas the overall length is kept constant over the database of random channels. All LC are supposed to hit the ground in the origin of the reference frame, while WPT-GA is located at ground level (or below ground level for buried cases) at a distance $d = \|d_x\hat{\boldsymbol{x}} + d_y\hat{\boldsymbol{y}}\|$, in the order of a few meters.

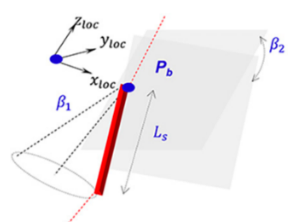

Fig. 4: definition of random parameters in tortuous LC creation

III. Key Coupling Parameters

The reference case considered in this study is a vertical LC, hitting at $d_x = 5$ m, $d_y = 5$ m from the WPT-GA, which is buried about 30 cm below the ground level. The ground, the plate and the ferrite tiles have the conductivities and permeabilities reported above. Spectral content of the voltage induced on the coils at 0.2, 0.5, 1, 2 and 5 MHz is considered in the following, as below lower limit the inductive coupling mechanism is not very effective.

The choice of the specific design shown in Fig. 1 allows the authors to concentrate in the different aspects influencing the magnitude of the overvoltages, that are the following:

A. Distance between the LC and the WPT GA

It is obvious that lower distances lead to higher overvoltages, however, without some specific simulations, it is not possible to know a-priori how sensitive the system towards this parameter is.

B. Tortuosity of the lightning channel

A set of simulations relative to 28 randomly generated tortuous LC have been run. The average induced voltage and its standard variation are reported.

C. Presence of the ferrite bars and aluminum shield

While ferrite bars and aluminum shield are always adopted in case of WPT for automotive applications, it is anyway of noteworthy importance, in the authors' opinion, to understand their role in the overvoltages creation.

D. WPT GA tilt angle with respect to the LS

It is understandable that orientation of WPT GA with respect to the LC plays a key role in the EM coupling between the lightning and the coils. In addition, the system is not symmetrical with respect to tilting, since the shield and the ferrite cores lay on one side of the GA only. Simulations run at different tilt angles and different relative positions between LC hit point and WPT-GA show the relevance of these parameters.

E. Burial depth of the GA

According to [2] the GA can be mounted in different ways considering its position with respect to the ground surface. In particular the three possibilities are above ground, flush ground and buried mounting. While [2] currently only specifies above ground mounting, proposed specifications for flush and buried mounting will be considered in the future. This of course affects the behavior with respect to LS because the ground does not have the same electrical characteristics of air; in addition, burial depth and tilt angle together give a combined effect on the LS overvoltages.

IV. Numerical Results

In this section the results obtained by the use of the model described below are shown. They are organized in different subsections, with the goal of highlighting the different parameters affecting the system's behavior.

A. Reference case: buried GA for different tilt angles

As reference case, the authors refer to a buried GA, equipped with ferrite bars and shield with location $d_x = 5$ m, $d_y = 5$ m. he numerical results relative to the reference case are reported in Table I, in which three different tilt angles are considered. By analyzing its entries, we can understand that in the case of a perfectly aligned GA (α=0°) a LS hitting at low distance has little effect in terms of overvoltages. At the same time, low tilting angles of different sign ("face" or "back" directed towards the LC), show differences in the overvoltages in the range of 1%. This is because of the conducting ground all around the system. The same reference case has been evaluated imposing a constant value of the tilt angle (α=2°) and different impact point of the LS $d_x = d_y = [2, 4, 6, 8]$ m. These results are shown in Fig. 5, and demonstrate how sensitive is the system towards the impact point of a LS; it is obvious that closer impact points have a larger effect, and that 10 meters far from the WPT GA, the overvoltages are below the value of 1V

As additional partial result, it is interesting to note that, despite the decrease of the spectral content of the current, the overvoltages show a peak around 1 MHz: considering the dimensions of the system and the distances involved, at $f = 5MHz$ propagation effect is still not prevalent, and this behavior is due to the combined effect of current spectrum and high-pass filtering effect due to inductive coupling.

Table I
Induced Voltages for different parameters combinations.

Case	Induced Voltage (V) at indicated frequency				
	0.2 MHz	0.5 MHz	1 MHz	2 MHz	5 MHz
α=0°	0.69E-03	1.87E-03	2.86E-03	0.66E-03	4.49E-03
α=2°	0.42	0.85	1.19	0.30	0.79
α=-2°	0.42	0.86	1.20	0.30	0.80

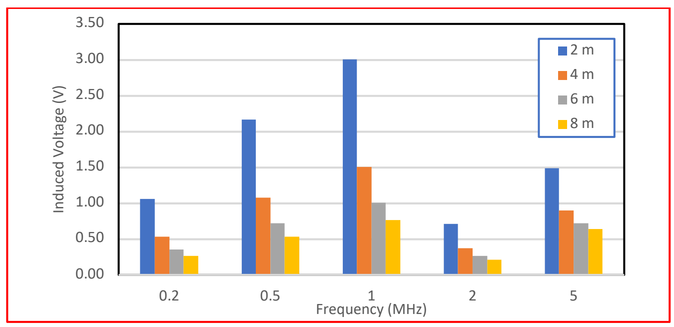

Fig. 5: Induced voltage relative to the reference case for different distances from the LC and tilt angle α=2°.

B. Effect of the tilt angle with shield and ferrite bars

In order to highlight the non-symmetric effect of the shield and ferrite tiles, a set of simulations with the surface mounted GA for different tilt angles ranging from α=-8° and α=8°, with $d_x = 0.1$ m and $d_y = 5$ m is shown in Fig. 6. This particular configuration has been chosen as it shows the highest effect in terms of induced overvoltage. At all frequencies, it is evident that positive tilt angles (face directed to the LC, as depicted in Fig. 3) lead to higher overvoltages; the explanation of this behaviour lies in the fact that the ferromagnetic material and the shield act as partial shield with respect to the LS, when they are located in between the coils and the LC itself. In case of a design process that takes into account also robustness towards indirect lightning, such non symmetric behaviour should be taken into account.

C. Effect of the burial depth without shield and ferrite bars

The conductivity of the ground has a non-negligible effect on the induced voltages; this is shown in Fig. 7, showing the behaviour of the GA for different tilt angles both with buried mounting and surface mounting. Analysing Fig. 7 we can conclude that buried mounting of GA offers the possibility of obtaining a more robust system towards lightning effect due to the conductivity of the ground. The ground reaction to the LS that reduces the induced voltage is stronger when the GA is buried.

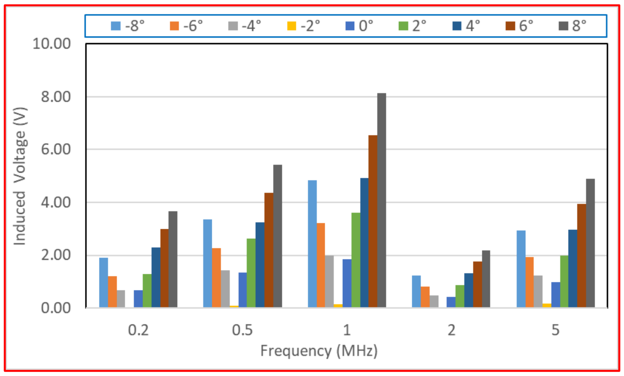

Fig. 6: Induced voltage for different tilt angles with GA mounted above ground.

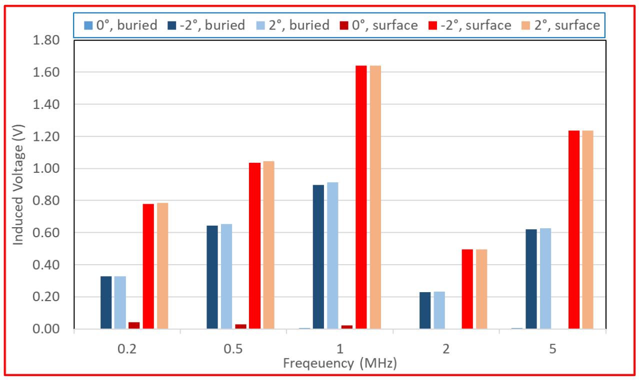

Fig. 7: Comparison between buried and surface mounting of GA without shield and ferrite bars.

D. Different cases with random tortuous lightning channel

For this set of results, the GA is considered as buried mounted, equipped with shield and ferrite bars, placed at $d_x = 5$ m, $d_y = 5$ m and α=2°. The tortuous LC has been modeled according to the description of Section II, and 28 different random LC have been obtained. Standard deviation of the angles is 0.15 rad., while it is 1 cm for the section length. Table II shows the results in terms of average value and standard deviation calculated for a reduced set of frequencies, due to the computational burden implied, while Fig. 8 shows an example of induced voltage in the case of a single tortuous channel, compared to LS current waveform (taking >120 minutes on a Intel i9 workstation to simulate) . Comparing the mean value relative to the tortuous LC cases to the values reported in the second row of Table II (same tilt angle) it is easy to verify that a tortuous channel leads to much higher overvoltage, due to the direction of magnetic field created by the lightning current and the way it concatenates with the WPT GA.

In the literature, the use of straight LC is prevalent because of the objective uncertainty of this natural event and the consequent need to deal with it from a statistical point of view. In addition, the mathematical and modelling complication of the implementation of a tortuous LC, lead many authors to simplify the approach. However, the results presented in this section show that considering only straight LC might lead to a strong under-estimation of the phenomenon under analysis and possible wrong results in terms system's robustness evaluation.

V. Conclusion

The present study shows that the effects of indirect LS strikes hitting nearby WPT GA charge systems may be relevant, especially when considering the tortuous nature of the channel. Suitable counter measures should be investigated in the design phase to mitigate the risk of damage to the system circuitry. Furthermore, the exhaustive set of simulations show what are the constructive parameters the designed should take into account when designing a WPT GA system not prone to malfunctioning due to LS. The most interesting results are summarized as follow: a buried GA mounting offers more robustness towards LS; higher tilting angle leads to higher overvoltages, even though the system itself is symmetrical with the tilting angle; tortuous LC should be considered in order to correctly evaluate its effect. Further work would be to analyse more complex WPT GA systems and study the effect of the induced overvoltages on the electronic circuitry connected to it.

Table II
Effects of Lightning Channel Tortuosity

	Induced Voltage (V) at Indicated Frequency		
	1 MHz	2 MHz	5 MHz
Mean	8.25	1.91	4.9
STD	0.24	0.08	0.3
	Figures for a vertical channel		
	2.86E-3	0.6E-3	4.4E-3

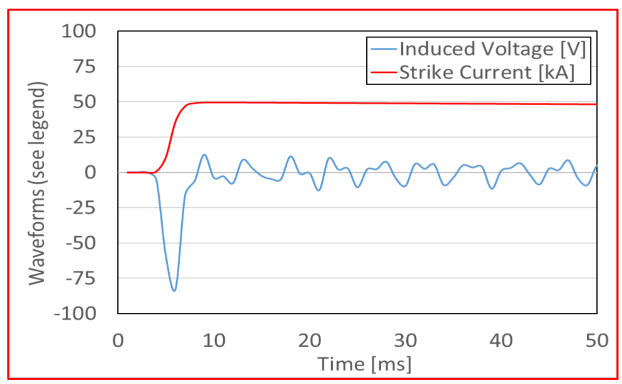

Fig. 8: An example of induced voltage for a tortuous channel.

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