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# EMC considerations for JLRL direct lightning current measurement

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***Abstract*—In this paper the electromagnetic compatibility (EMC) considerations made to the direct lightning current measuring system that is part of the Johannesburg Lightning Research Laboratory (JLRL) are presented. The output voltages from two series connected shunts and the sending of their analog signals downward a tower to the measuring system, makes this measuring setup particularly critical regarding immunity against the strong effects of the lightning current.**

***Keywords*—*JLRL, lightning, lightning current, lightning current measurement***

## I. INTRODUCTION

The Johannesburg Lightning Research Laboratory (JLRL) is erecting a direct lightning current measurement site on an existing tower on the roof of an 11-storey building of the Witwatersrand University in Johannesburg (Senate House).

The current measuring elements are two series connected shunts, being one a high-level current measurement device, up to 100 kA, and the other a specially constructed device for low-level current measurement, up to 9 A (or 18 A). Despite the low current range of the latter, it has to withstand the full lightning current while limiting the amplitude of the signal sent to the measuring system.

The low-level current measurement together with high-speed video and electric field measurements, is intended to provide experimental data for the study of streamer emission from grounded objects during the phase preceding a lightning connection to the target object or to nearby objects. The study is essential for the understanding of the early stages of lightning attachment to grounded structures and, eventually, other features in the field of discharge physics.

As failure to intercept is as important as lightning interception by the tower, the frequency of direct lightning to the tower is not of utmost importance. Nevertheless, the installation of a higher pole dedicated to this research is under consideration.

The pair of shunts will be installed at tower top due to existing antennae (data-links) already installed at mid-height of the tower, as shown in Fig. 1.

Fig. 1. 10-m tower on top of Senate House, Wits University, before preparations and installation of the measuring system.

The electro/optical (E/O) converters will run on batteries to improve electromagnetic immunity. These devices will be installed at tower base in order to facilitate maintenance work, especially battery replacement. The analog signals will be transmitted downwards by coaxial cables from the shunts to the E/O converters, what requires careful EMC considerations to ensure a clean measuring signal throughout this path. These considerations are discussed in the following sections.

## II. MEASURING SETUP

### A. *Shunts*

The two shunts are physically large, for they are designed to conduct the full lightning current. The Low-Current Shunt (LCS) is shown in Fig. 2 and the High-Current Shunt (HCS) in Fig. 3.

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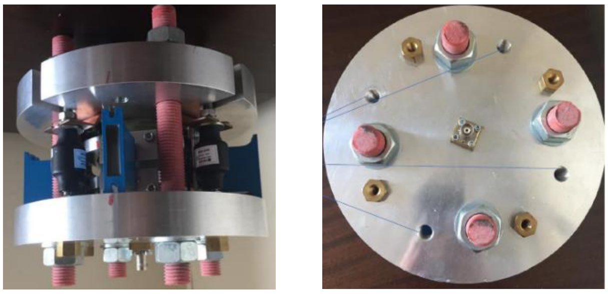
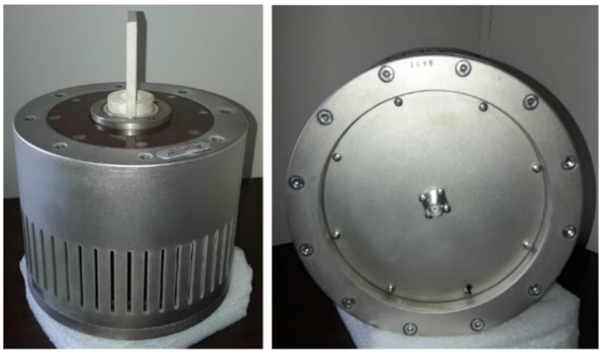


(a) (b)

Fig. 2. Low-Current Shunt (LCS) – 0.5 Ω or 1 Ω; 9 A or 18 A; a) Side-view; b) bottom-view, showing the coaxial output BNC connector.



(a) (b)

Fig. 3. High-Current Shunt (HCS) – 0.25 mΩ; 100 kA; a) Side-view; b) bottom-view, showing the coaxial output BNC connector.

TABLE I. SHUNTS MAIN ELECTRICAL CHARACTERISTICS

| **Shunt type** | **Characteristics** | | |
|---|---|---|---|
| | ***Current range*** | ***Nominal resistance*** | ***Bandwidth*** |
| HCS[a] | 100 kA | 0.25 mΩ | DC – 50 MHz |
| LCS[b] | 9 or 18 A | 1 or 0.5 Ω | DC – 10 MHz |

[a] HILO-TEST GmbH, type ISM 500.

[b] Designed and constructed by Marley Becerra.

The LCS comprises a series of large ceramic disc resistors combined with properly coordinated surge protection devices and lightning current arresters. When current exceeds the desired range for this shunt, the network of protectors divert the current away from the resistor elements. The HCS is a commercial 100 kA shunt with cylindrical body where the current is injected on a center terminal and flows radially to the edges.

Both shunts have volumes in the order of 20 x 20 x 20 cm and weight of approximately 9 kg.

### B. *E/O converters*

The electrical signals from the shunts are converted to optical signals by transmitter units installed at tower base, and then to the receiver units at some safe distance from the lightning path, to be connected to a datalogger. The E/O converter type is under consideration regarding the required bandwidth (BW) for proper transmission of the signal.

### C. *Measuring setup*

The shunts will be positioned at the tower top, being electrically interconnected by aluminum bars and supports designed to fix the shunts in position without forcing their terminals, to conduct the lightning current and to reduce, by their geometry, the strong electric and magnetic near fields in the region where the coaxial cables are highly exposed to these fields. The shunts shall also be protected against the environment, rain and dust mainly.

There is one special reason for the LCS to be installed at tower top. As it is intended to measure low currents associated with streamers, it has to be near the tip of the tower, where the streamers are emitted, otherwise capacitive currents flowing radially along the tower due to changing electric field in the surroundings, would mingle with the streamer current in the measured current, making it difficult to analyze.

The signals from the shunts are transmitted in coaxial cables (RG-214) to a metallic enclosure at the tower base housing the E/O converters, as shown in Fig. 4. Each converter has its own 12 V battery (not shown in Fig. 4). The cables are routed inside a metallic tube (or two tubes, as discussed in Section III-C). The tower height is about 10 m. Signals are transmitted and received on 50 Ω systems (shunts outputs, cables, attenuators, coaxial surge protectors and E/O converters inputs). The only communication with external world is by optical fibers.

## III. EMC CONSIDERATIONS

### A. *General*

The classical solution for taking the voltage from a coaxial shunt conducting high, fast varying currents, is to provide a current path that is a continuation of the shunt body, which entirely surrounds the signal cable, down to the interconnected circuits, with an uniform distribution so that the field inside is very low, ideally null. Unfortunately, this solution is not achievable in this project, because there are two series connected shunts and the lower one (HCS) is not prepared to provide an internal path for the signal cable from the upper one (LCS) to pass through. It means that the signal cable from the LCS has to go around the HCS.

### B. *First approach*

The coaxial cables (Fig. 4) are to be enclosed in a metal tube. A thick and good metal tube (low transfer impedance) is needed to ensure a relatively low voltage between the outer conductors of the coaxial cables and metallic parts near the cable ends (shunts, tower, and metallic enclosure). For this, the tube must be well bonded to the tower top and bottom, and to the enclosure at bottom as well. For good shielding performance, the tube must be welded to the enclosures at both ends.

Note: “Outer conductor” (of a coaxial cable) and “cable shield” are herein used with the same meaning.

Fig. 5 shows in more detail a view of the cables and tube at the shunts end, where the HCS will be enclosed in a metal drum through which the lightning current is expected to flow symmetrically distributed around the HCS axis, resulting in a space with low magnetic field for the cables. This space adjoins the interior of the tube through which the cables ingress.

The outer conductor of the coaxial cable connected to LCS BNC connector cannot be bonded to any other point near the shunts, otherwise it would short-circuit the HCS. For this

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reason, this cable runs exposed to the intense magnetic field of the lightning current in the effective induction area bounded by this cable and the lightning current path, see "induction area" in Fig. 5. The voltage induced in that area is inevitably injected into the tube, propagating inside it. In this case, the cable shield and the tube form a transmission line where the induced voltage propagates, subject to reflections depending on how it is terminated at the bottom end. Note that such transmission line is short terminated at the upper end.

An analysis is made to determine the best termination for the transmission lines formed by the cable shields and tube at bottom end. Fig. 6 shows the terminations $Z_L$ at cable ends, between cable shields and tube/structure.

The abovementioned inductive coupling to the LCS coaxial cable can be represented by a transfer inductance $L_T$. Due to complex circuit geometry, this inductance will be opportunely determined by measurement in JLRL laboratories. The value was however estimated by approximate formulas, being its maximum determined as:

$$L_{T\,max} = 0.1\ \mu\text{H}$$

In this analysis, the lightning event can be separated in two moments: the one preceding the lightning attachment, when the information of interest come from the LCS (up to 9 A), and the one when current exceeds 9 A, i.e. when the information of interest come from the HCS related to lightning stroke or upward leader currents.

In the case of streamers, the expected maximum current derivative ($di/dt$) is 1 kA/µs. Therefore, the maximum induced voltage injected on the transmission line formed by cable and tube is:

$$L_{T\,max} \times di/dt \;\cong 100\ \text{V}$$

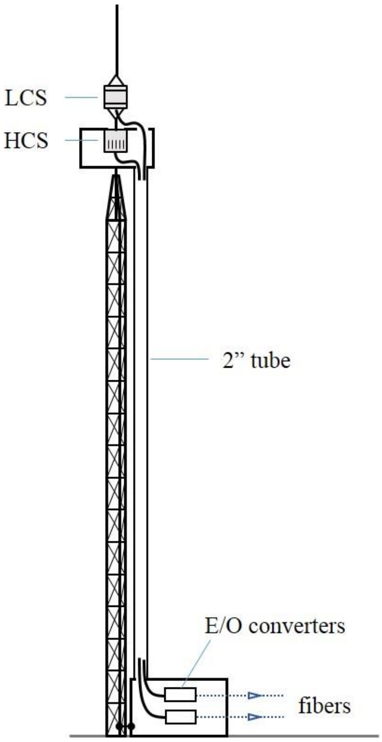

Fig. 4. Direct lightning current measurement setup overview.

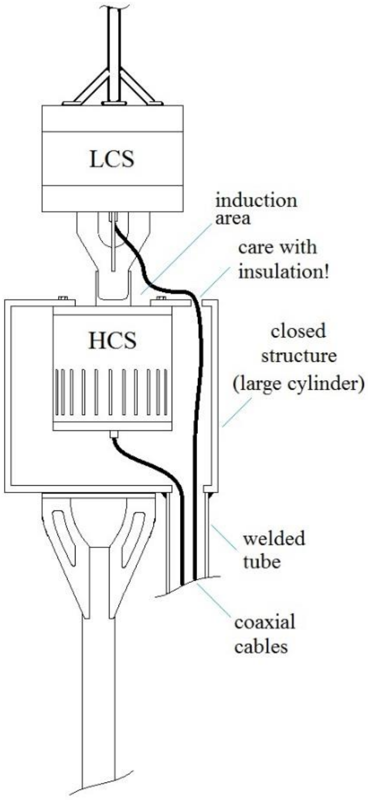

Fig. 5. Direct lightning current measurement setup; detailed view of the shunt connections, considering one shielding tube for the two coaxial cables.

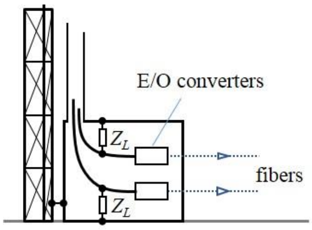

Fig. 6. Terminations ($Z_L$) between cable shields and enclosure (or tube), for the transmission lines formed by cables and tube. Each E/O converter shall be related to the grounded enclosure through the respective $Z_L$.

The initial current injected on cable shield is given by the induced voltage divided by the characteristic impedance $Z_C$ of the transmission line formed by the coaxial cable and the tube. Fig. 7 presents the characteristic impedances for several tube sizes and an RG-214 in any position inside the tube, according to fig. 8. The curves in fig. 7 assume that the current concentrates on the outer surface of the cable shield and in the inner surface of the tube (high frequency).

Selecting a 2" tube and coaxial cable near the center, the peak current on cable shield is around 100 V / 100 Ω = 1 A. Note that this current is an induced impulse resulting from de current derivative, so it is of short duration (maximum a few tens of ns). In a very conservative estimate, this current multiplied by the DC transfer impedance of 10 m of RG-214 (fig. 9), will cause a voltage coupling to the measuring system of 43 mV. This is rather low as compared with the full-scale, 9 V of the measuring system (0.5 %), or 4.3 % relative to 1 A. In reality, for short impulses, even if repetitive due to multiple reflections, the coupled voltage through the shield is expectedly lower due to lower $Z_T$ values at higher frequencies.

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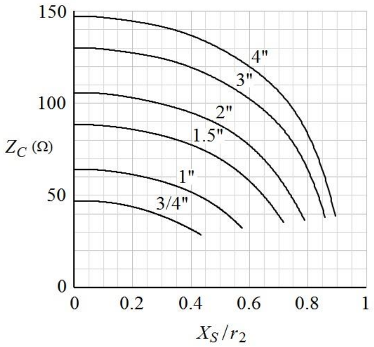

Fig. 7. Characteristic impedance $Z_C$ of transmission line formed by tubes of several sizes (diameters in inches) and the outer conductor (shield) of an RG-214 inside. For $r_2$ and $X_S$ see fig. 7.

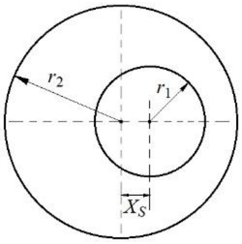

Fig. 8. Radius of RG-214 cable shield ($r_1$), internal radius of the tube ($r_2$) and distance between cable axis and tube axis ($X_S$).

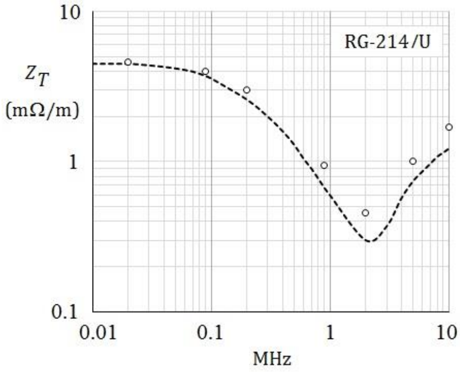

Fig. 9. Transfer impedance $Z_T$ of RG-214; Circles: measured data by Andrew Corporation [3]; Dashed line: measured data provided to the author on a private basis.

For long duration (continuing) currents, the current is practically DC and it is shared by tower, tube and coaxial cables (assuming the cables are grounded at both ends), according to their DC resistance. If a low current (< 9 A) with long duration is measured by the LCS, the DC coupling from the current going through the shield to the measuring system is negligible with respect to the measured signal, since the shunt resistance is relatively high (1 Ω).

Note: tower DC resistance has been estimated from the size of steel elements, and tube DC resistance has been calculated considering a 2" copper tube. These values shall be properly measured by JLRL before the implementation of the measuring site.

For the measurement of long duration (continuing) currents on the HCS however, assuming again that the cables are grounded at both ends, the situation is bad because the HCS resistance is too low (0.25 mΩ). Estimations of the current sharing among all conductors indicate that the DC voltage drop along the HCS coaxial cable is in the same order of magnitude of the measured signal. The error in the amplitude of continuing current would be unacceptable. Therefore, the coaxial cable of the HCS cannot be directly grounded at the bottom end. Therefore, $Z_L$ shall not be short terminated.

The major problem occurs at high impulse currents, especially during the fast rise of subsequent strokes. Suppose a maximum $di/dt$ of 160 kA/μs, which corresponds to 5 % probability of occurrence for subsequent strokes [1]. This current rate of rise will induce a voltage between the LCS cable shield and the metallic structure at the tower top (see fig. 5), including the tube edge, of $L_{T\,max} \times di/dt \cong 16$ kV.

At such high impulse voltage, care with the insulation of the cable is very important. Even though the LCS is out of operation at such high currents, the high voltage induced on its cable shield may cause damage to the external insulation (cable jacket) and the high current surge on this cable in the tube may interfere with the measurement on the HCS system.

Some simulations were made in ATP/EMTP [2]. The model is very simple and considers a 164 kA/μs current surge on a 0.1 μH inductance as the source that injects the voltage impulse on a line inside a tube, simulating the LCS coaxial cable, with the presence of a second line simulating the HCS coaxial cable in the same tube.

Fig. 10 shows the impulse voltages and currents on the two coaxial cables with respect to the tube, at both ends, for a 164 kA/μs risetime current in the shunts, for open terminated lines. Note that the LCS coaxial cable excites the line with the induced voltage in the induction area (Fig. 5), while HCS cable suffers induction from the LCS cable. Note also that the peak voltage at the bottom (open) end doubles (32 kV) with respect to the injected impulse (16 kV), what makes the situation more complicated at the E/O converters end, regarding insulation. Voltage and current on both cables oscillate at about 7.5 MHz, which is due to multiple reflections in a 10 m tube (cable insulation was neglected in the line model). The current amplitudes are high on both cables.

### *C. Matched lines*

Fig. 11 shows the impulse voltages and currents on the two coaxial cables with respect to the tube at both ends, for a 164 kA/μs risetime current flowing along the shunts, for matched lines, $Z_L = 100$ Ω, which is a value close to the characteristic impedance of the lines. The oscillations disappeared, but the first current impulse on HCS cable associated with the first transit of the signal on the line is still present (Fig. 11 (b), blue curve). The 100 A peak on this cable will transfer some 1 V inside the cable that will superimpose to the measured signal. Taking the HCS resistance of 0.25 mΩ, it will result in a false current information of 4 kA. If compared to the 22 kA amplitude subsequent stroke that was used to generate the desired d*i*/d*t*, it means about 18 % error.

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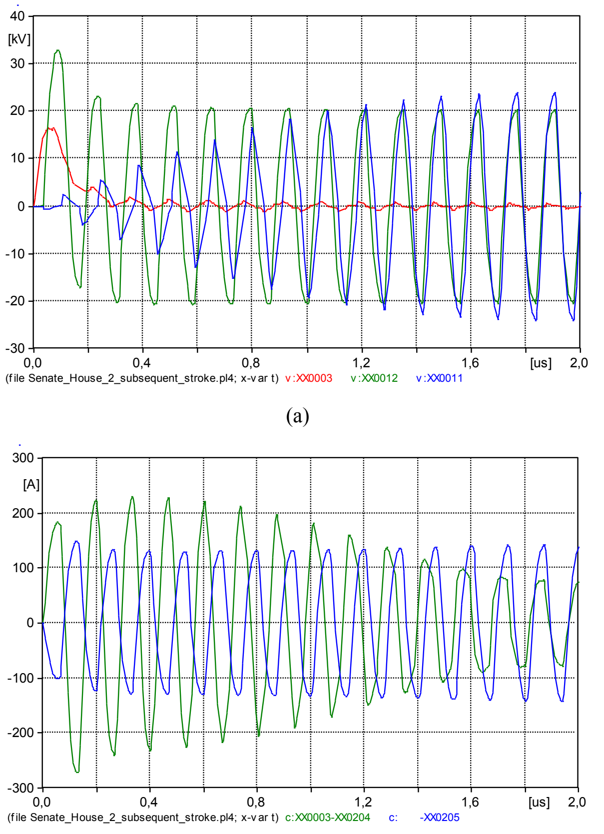
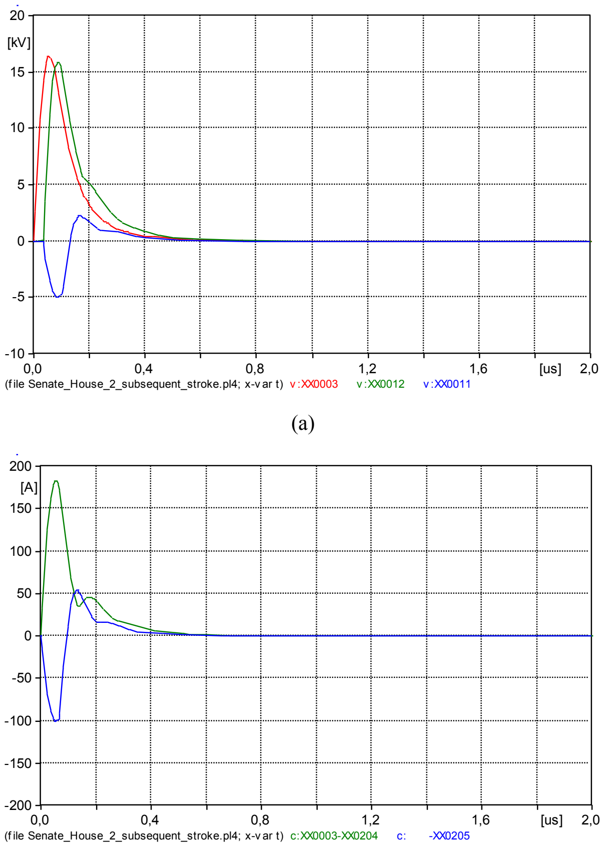


(a)

(b)

Fig. 10. Open-terminated lines ($Z_L = \infty$); a) Red: Voltage between LCS coaxial cable and tube at entrance to the tube; Green: Voltage across LCS cable and tube at bottom end; Blue: Voltage across HCS cable and tube at bottom end; b) Green: Current on LCS cable; Blue: Current on HCS cable.



(a)

(b)

Fig. 11. Matched lines ($Z_L = 100\ \Omega$); a) Red: Voltage between LCS coaxial cable and tube at entrance to the tube; Green: Voltage across LCS cable termination ($Z_L$); Blue: Voltage across HCS cable termination ($Z_L$); b) Green: Current on LCS cable; Blue: Current on HCS cable.

### *D. Separate tubes*

In order to eliminate the coupling between the two cables in the tube, due to the injection of induced impulses on the exposed part of the LCS cable, the cables shall run in separate tubes, as shown in Fig. 12.

Recalling: the $Z_L$ terminations in Fig. 12 are there to eliminate oscillations and to reduce the errors associated with the measurement of long duration currents, especially continuing currents. No tube of reasonable, practical thickness can help to reduce satisfactorily the current of short continuing currents (10 – 40 ms) [4], or longer, from coaxial cables.

The characteristic impedance of the lines formed by the coaxial cable and the tube shall be determined and possibly verified in the lab. It is recommended to have as large as possible a tube in order to get higher values of $Z_C$ (Fig. 7), in order to reduce the injected current and to make the insulation between cable and tube easier. For this, the cable shall be fixed in the center (axis) of the tube.

Regarding the high lightning current through the tubes, it is important to note that line terminations $Z_L$ help with the reduction (limitation) of the current flowing on cable shields. In fact, as the tubes are exposed (outside the tower) and therefore share a significant amount of lightning current with the tower, the line terminations $Z_L$ are essential to keep errors under satisfactory levels.

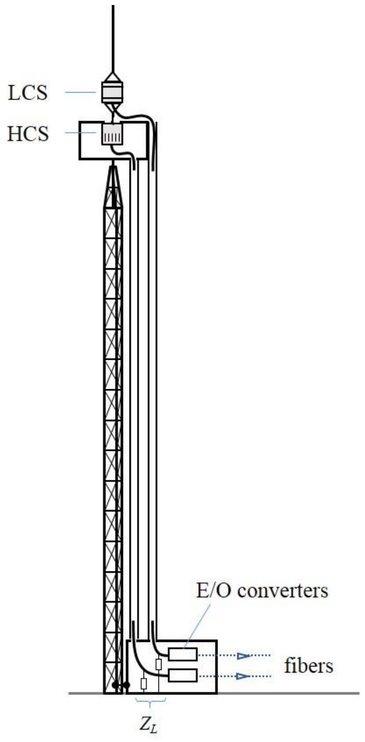


Fig. 12. Shunt cables in separate tubes.

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Estimates indicate that a 2” tube with 4 mm wall thickness, either copper or steel, is sufficient to keep errors in the HCS measurements, due to currents flowing down the tube and the cable inside, within 0.01 %. Assumptions: a) 100 kA stroke; b) 200 µs duration, i.e. time to half value on the tail (only 5 % of first negative strokes will exceed it, according to [1]); and c) lightning current equally divided among the tower and the two tubes. (Note: The current sharing among tower and tubes have not been properly calculated yet, neither measured).

For long waves, such as positive strokes with 2 ms duration or for continuing currents, which exceeds the diffusion time of the tube (see transfer impedance concept, e.g. in [5]), the error increase for copper is negligible and for steel the increase is about 5 times. If a 0.1 % error can be considered acceptable, the tube walls can be thinner, like 1 mm for copper and 2 mm for steel, disregarding mechanical requirements.

The terminations $Z_L$ as suggested here are not trivial, since they have to be placed right at the tube end, radially disposed from the outer conductors of coaxial cables to the tube, like coaxial loads. It may be implemented by a proper disk resistor or by a network of resistors. The value is around 100 Ω, which may be better determined experimentally. The energy is relatively low on such resistance, as the high voltage impulses are associated with short duration front times of lightning current, but the peak voltage can be as high as 16 kV, as previously mentioned.

Contact resistances were not considered in the calculations. They shall be thoroughly evaluated during the installation of the measuring site.

Special considerations shall be made on the parts above the HCS, to avoid uncontrolled emission of streamers from shunt body and connections. The emission is desired to occur at the tip of a known lightning rod, for proper theoretical studies and mathematical modelling. That is one reason why the LCS is placed on top of the HCS and at the tower top.

### *E. Other solutions*

Other conditions could make EMC easier in this test setup, namely:

- Having a dedicated metallic pole instead of the existing tower, where the LCS would be installed at the top, with cable coming inside the pole to its E/O converter and battery near the base for easy access, inside the pole. The HCS would be installed right below, with respective accessories in the pole. Of course, the pole shall be split for insertion of the HCS.
- PoF (power over fiber). The E/O converters could be installed right below their respective shunts, at the tower top, in enclosures that would work as current path and shielding, if power supply was sent up through optical fibers. There would be optical fibers sending power upward and fibers sending signal downward. This solution is under consideration.

## IV. CONCLUSIONS

A JLRL direct lightning current measurement system has been analyzed in terms of electromagnetic immunity against measurement errors and damage caused by the lightning current. The main issues are reported in this paper. Various electrical tests are being planned for the whole system to evaluate the lightning current distribution, dangerous voltage levels, noise-free signals, surge protection, attenuators, power supply etc.

The fact that there are two series connected shunts at the tower top impose a great difficulty, because the coaxial cable connected to the upper shunt is exposed to strong voltage induction as it goes around the lower shunt. The induced voltage on the cable shield is injected into the tube, inside which propagation effects and coupling between the two cables are expected to cause problems to the measurements.

Depending on how the cable shields are terminated at the bottom end, the problems are different. If short terminated, the current through cable shields is high enough to cause large errors in the measured current, especially for long (continuing) currents. No tube with reasonable wall thickness could help with this problem related to DC resistance. If open-terminated, the high voltage induced on one of the cables propagates inside the tube and its amplitude doubles at the bottom end, being more difficult to control, especially because the electronics receiving this cable will be subject to such high voltage with respect to the enclosure. If matched, however, the voltage does not double, the multiple reflections are eliminated and, very importantly, the currents coupled to cable shields are limited. However, the impulse injected in the tube by one of the cables still interfere with the signal in the other cable.

To solve these anticipated problems, the recommendations are that:

- The cables go down the tower in separate tubes, and fixed at tube axis for characteristic impedance control;
- The cables are properly terminated at the bottom end with the characteristic impedance of the transmission line formed by the cable shield and tube;
- Careful measures are taken to protect the insulation of one of the coaxial cables to the tube and to other metallic parts.
- The electro-optical converters installed at the tower base, which are connected to the coaxial cables, including attenuators, surge protection devices and terminations, shall be carefully isolated from the enclosure. Their connections to the enclosure shall be through the mentioned line terminations only.

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