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Protection of Cables by Open-Metal Conduits

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Abstract—The performance of metal conduits for protection of cables is investigated. An open U-shaped conduit is chosen as a basic configuration. A number of wires inside represents the actual cables with their shields. This configuration is subjected to a plane-wave excitation to determine the induced currents and voltages, which represent the common-mode signals in the cable shield. The simulated and tested object is 1.5 m long, with a cross section of $9 \times 9$ cm$^2$. Results are presented for frequencies up to 1 GHz, some up to 5 GHz. Measurement and simulation results agree to within 6 dB.

Index Terms—Cabling, conduits, earthing, electromagnetic compatibility (EMC) protection, grounding, installation, wiring.

I. INTRODUCTION

CABLES interconnecting different parts of electronic equipment and systems, are widely regarded as being one of the main sources of electromagnetic compatibility (EMC) issues. For example, inside the office buildings and large industrial installations, the cables extend over large distances, sometimes hundreds of meters, and act as efficient antennas for electromagnetic (EM) fields. The remarkable growth of wireless communications in recent years has resulted in harsh EM environments to which such interconnects are exposed. This may lead to equipment malfunction, and possibly to critical failures. Signal and power cables inside buildings are often routed on metal trays or in conduits. In addition to mechanical support, such structures provide adequate protection against EM interference if properly designed and interconnected. The research on the grounding structures performed in [1] contributed to the development of International Electrotechnical Commissions guidelines [2].

Such grounding structures are introduced in [2] as parallel-earthing conductor (PEC); here we use the word “conduit” as generic name. With a PEC, the induced common-mode (CM) current flows through the conduit rather than the cables, or their shields if present. The smaller interference currents in the cable shields induce lower undesired differential-mode (DM) signals coupled via the cable transfer impedance $Z_t$. The amount of protection of open and closed conduits at the frequencies, where the wavelength is much larger compared to conduit dimensions (below 1 MHz) has been studied in [3] and [4]. A recent study [5] dealt with a U-conduit up to 30 MHz. The measurements and simulation results presented here extend the frequency range up to over 1 GHz, where the resonances on the conduit occur.

A full 3-D EM model of a complete, real-life installation is viable nowadays [6]–[8], although the required computational effort remains high. The complete system is split into several simple typical parts, which are then modeled by a faster 2-D method. This paper focuses on one step in the large system analysis and presents the results for a 1.5-m long U-shaped conduit with wires inside it, illuminated by a plane wave. The conduit length is much larger than the lateral dimensions of 9 cm and end effects do not play a dominant role. The setup also allows a full 3-D analysis of conduit and wires, which can be compared with a simplified model, where the conduit current is calculated in full 3-D, but the wire coupling is derived in a 2-D transmission-line (TL) model. In our model, the wires represent actual cables and the currents in the wires and voltages at the end of the wires can, in principle, be converted into the signals induced in real-life cables via the transfer parameters of the cables. The coupling of incident waves and external fields to TLs has also been extensively studied in the literature—see e.g., [9]–[12]—in both time and frequency domain.

This paper extends earlier work [13]. In Section II, we describe the conduits and the configurations studied. The calculations assume a plane wave incident on the open conduit; the results are presented in Section III with a brief excursion to 5 GHz, where the conduit width becomes comparable to wavelength. The calculations are compared with measurements in a fully anechoic room in Section IV. Some effects of a conducting cover are presented as well. The concluding remarks are given in Section V.

II. CONFIGURATION

Since the U-shaped tray is common in practical installations, it has been chosen as a basic configuration for both numerical and experimental study. However, also construction elements, such as beams with H-, T-, and L-profile may serve for protection, as shown by the quasi-static magnetic field lines in Fig. 1. A crease in a metal plate acts as an extended L-shape. The field lines indicate constant mutual inductance $M$ for a wire or cable shield, with respect to a CM current through the conduit [4]. The $M$ is defined between the CM circuit and the loop formed by wire and the conduit. A far away CM return does not appreciably change the magnetic field in and near the conduit; $M$ is then determined by the conduit shape and the wire position only.

The test conduit was folded from a 1-mm-thick brass plate to form a U-shape with $h = 2w = 90$ mm. The conduit length is $l_z = 1.5$ m. Four wires of $d = 2$ mm diameter are placed
Fig. 1. Different shapes (U, H, T, L) of open conduits used in practical applications. Constant flux lines are indicated for mutual inductances of 20, 50, and 100 nH/m (after [4]). The coordinate system is shown at the center.

at the positions shown in Fig. 2; these will be referred to as “top,” “middle,” “bottom,” and “corner.” Square brass plates are soldered to both ends of the conduit. All wires are directly connected to one end plate, and to BNC connectors at the other plate, where we installed 50 Ω terminations or short-circuits. Six insulating supports maintain the mechanical stability and keep the wires in position over the conduit length. In order to minimize their influence, most of the insulator material has been removed. In the model, we determine either the induced current at midlength in the wire or the induced voltage over 50 Ω at the end of the wire. As current probes 1 mΩ ideal resistors are placed at the center of the wires [see Fig. 3(a)] and all wires are short-circuited to the conduit at both ends. The induced voltages are studied over 50 Ω terminations [see Fig. 3(b)]. In the measurements, the 50 Ω resistors are either the input impedance of the test receiver or actual resistors for wires that are not connected to the receiver. In calculations, the conduit and wires are illuminated by a plane wave with an electric field of 1 V/m strength and linear polarization. The measurement results were normalized to 1 V/m field strength, as explained in Section IV. In most configurations, the electric field vector is parallel to the wires, when the coupling is most effective. Three main possible directions of wave incidence/conduit orientations (“front,” “side,” and “back”) are shown in Fig. 4. The “front” orientation results in the largest coupling, and therefore, it is studied in more detail.

III. SIMULATIONS

In order to calculate the induced currents and voltages in the conduit wires, we employed two different calculation techniques: first, the method of moments (MoM) implemented in CONCEPT software by Technical University of Hamburg-Harburg [14] and FEKO software by EMSS [15], and second, the finite-integration technique (FIT) of Microwave Studio by CST GmbH [16], [17]. The MoM is a frequency-domain approach and discretizes the conductor surfaces only. FIT meshes the full 3-D computational space; it is a time-domain approach, eventually followed by discrete Fourier transform (DFT) to generate frequency-domain results. In all calculations, we model the conduit and the wires as perfect electric conductors. The actual dimensions have been taken into account in FIT, including the brass thickness. In the MoM calculations, we neglect the thickness of the conduit walls and regard them as surfaces. Symmetry planes (magnetic and electric conducting walls) reduce the calculation domain by 50% or 75%, depending on the configuration. Special attention has to be paid to the meshing of the conduit surfaces. The mesh has to be refined near the “bottom” and “corner” wires because the standard λ/10 rule is not sufficient for accurate determination of the small currents in...
these wires. Still, the large currents of the upper two wires are quite accurately predicted even with a coarse mesh.

In the FIT method, we use as excitation a Gaussian-shape pulse of the width corresponding to the frequency range of simulations (0.8 ns for 1 GHz and 0.16 ns for 5 GHz). The resulting currents and voltages in the lumped elements (1 mΩ and 50 Ω resistors, respectively) are calculated in the time domain as well. The total energy in the calculation domain is used as a stop criterion; it has been set at −60 dB with respect to initial value.

A. Induced Currents

First, we determine the induced currents when wires are short-circuited to the conduit at both ends. Such a configuration resembles the typical middle section of the real-world conduit with the cable shields connected to it. The induced currents are monitored in 1 mΩ resistors shown in Fig. 3(a). The “front” excitation indicated in Fig. 4(a) is used. Fig. 5 shows the results calculated by FIT with all four wires present. As could be expected, the largest values are observed for the “top” wire, and the lowest for the wire in the corner. The resonant features around 0.2 and 0.4 GHz relate to multiple wavelength effects in the 1.5-m-long TL.

To estimate the level of protection offered by the conduit, the induced currents are recalculated in the similar configuration with the “front” excitation and all four 1.5 m long wires short-circuited at both ends to a pair of square plates, but with the conduit removed from the model. In the absence of conduit and at the frequency of 150 MHz, the currents in all wires are about the same value of −60 dB (see Table I). Without conduit, the “top” wire apparently “shields” the other wires slightly. The U-shaped conduit strongly reduces the coupling, even for the most exposed “top” wire. The “corner” wire is best protected, by more than 60 dB.

The same configuration for the induced currents was also modeled in the frequency domain by a different approach. The CONCEPT II MoM software was used for the benchmarking purpose. Fig. 5 includes the results for the “top” and “middle” wires. Good agreement along the whole frequency range is apparent. Deviations occur near the resonance frequencies, where the current amplitudes are more sensitive to the environment, which is free space in MoM or absorbing boundaries in FIT. Both methods are limited by the finite discretization of space (FIT) or conduit (MoM). Minor ripples in the FIT current near the resonances are caused by the −60 dB stop criterion.

B. Induced Voltages

The voltages can be calculated about 20 times faster than the currents in FIT. The four 50 Ω wire terminations absorb the excitation energy faster than the 1 mΩ resistors, and the −60 dB energy criterium is met earlier. Nevertheless, the terminations should not be regarded as an approximate open circuit because the characteristic impedance of the wires in the conduit is larger than 100 Ω (see Section III-C). Again, we consider the “front” excitation. The results are presented in Fig. 6. The differences with respect to the top wire voltage are the same as in the current configuration: −19, −42, and −54 dB at off-resonance frequencies. Thus, the protection by the conduit is also well demonstrated by the voltages. The resonant dips at the multiples of 0.1 GHz correspond to the half-wavelength resonances in 1.5 m long TL. Apart from the dips, the voltages are remarkably independent of frequency; the variation as function of frequency is certainly less than for the current, in particular, near the resonances.

In most practical applications, as well as in the conduit, we used for measurements, there will be more than one cable (wire) present. To investigate how these additional conductors influ-
ence the coupling, the calculations were repeated four times with only one wire present, for comparison with the setup with four wires. The results are summarized in Table II. While the voltage at the “top” wire remains the same, the voltages at the lower wires are significantly smaller when all wires are present. Due to the coupling between the wires or cable shields in practical situations, the wires located at the top of the conduit act as an additional protection for the wires placed deeply inside the conduit.

### C. TL Approach

We also used the TL approach to calculate the induced signals in the conduit wires. This method has several advantages. If the position of a wire changes, both FIT and MoM require the whole configuration to be recalculated, which takes a few hours of computer time. In the TL approach, the field distribution inside the empty conduit has to be calculated only once per conduit geometry and excitation. The field inside the conduit is regarded as excitation source for the TL formed by the wires and conduit. The TL parameters for the bare wires considered here can be accurately and quickly calculated by a 2-D method, for example, by MoM [18], [19] or Schwarz–Christoffel (SC) transformation (see Appendix). In case of 2-D MoM [20], the round wires were approximated by 16-sided polygons. In the numerical SC [21], the conduit is mapped onto a unit disk and the wire positions are mapped to the inside of the disk (see Appendix). The full L-matrix is calculated under the assumption that the field generated by each wire is negligibly perturbed by the others because of their small diameter compared to the distances:

\[
L = \begin{pmatrix}
849.84 & 108.05 & 8.10 & 1.39 \\
108.05 & 795.42 & 30.79 & 4.49 \\
8.10 & 30.79 & 458.52 & 2.08 \\
1.39 & 4.49 & 2.08 & 391.19
\end{pmatrix}
\]

with values in nanohenry per meter. For the bare wires, the corresponding capacitance matrix follows from the inversion of L:

\[
C = L^{-1}/c_0^2,
\]

where \(c_0\) is the free-space velocity of light. Such a TL
configuration is then placed in an otherwise homogeneous magnetic field $H_{0,x}$ corresponding to the 1 V/m “front” excitation. The induced wire currents are obtained from the requirement of zero flux between the images of each wire and the unit disk. The current amplitudes are given in Table IV. The close-to-exact SC approach demonstrates the accuracy of the FIT and MoM results at low frequency. The SC markers on the left scale of Fig. 5 agree within 2 dB with the extrapolated FIT and MoM values. The ratio of the wire currents does not depend strongly on the type of excitation. For instance, one may assume a $I_{CM} = 1$ A CM current through the conduit as an alternative excitation. The calculated results for the various excitations are summarized in the Table IV. As can be seen, the simple, and therefore, fast 2-D approaches quite accurately predict the ratios of the induced currents. The full 3-D calculations again deviate less than 2 dB.

For other incident field directions, the variation in the $E_z$ along the conduit length should be incorporated into the TL model. The analysis of systems containing multiple cables, including those with dielectrics, has been reported earlier in the literature, e.g., [22]–[24].

### D. Different Shapes

To investigate the influence of the conduit shape on the provided protection, we repeated the “voltage” calculations for two additional configurations with one or both sidewalls removed to form an L-shape or flat plate, respectively. T- and H-shapes shown in Fig. 1 were not analyzed. The results for the “middle” wire calculated in presence of all four wires are shown in Fig. 9.

### E. Different Orientations and Polarization

It is expected that the “front” orientation, as in Fig. 4(a) with the electric field polarization parallel to the wires and the conduit results in the largest coupling. For the U-shaped conduit, other possible situations were also modeled by FIT in the frequency range up to 1 GHz. If we rotate the “front” orientation polarization over 90°, now with the H-field of the incident wave parallel to the wires and E-field normal to them, the magnetic flux between the conduit and wires is strongly reduced. The voltages in all wires lay below the $-100$ dBV (10 $\mu$V) level; for the “middle” wire, the reduction is of the order of 60 dB.

Another brief comparison was made for all three orientations shown in Fig. 4. The results for the “middle” wire are shown in Fig. 10. The largest difference between the “front” and the “side” orientations for this wire is about 10 dB. The same holds for the other three wires. For the “side” orientation, the magnetic field component of the incident field is oriented in the $y$-direction (see Fig. 1), perpendicular to the bottom and parallel to the plane of the wires. Again, the magnetic flux between the wires and the conduit is strongly reduced.

### F. Higher Frequencies

The results of the previous sections for induced currents and voltages as a position of the wire are valid up to 1 GHz. At higher frequencies, the wavelength approaches the cross-sectional dimensions of the conduit (9 cm), and other modes than TEM will also be excited inside the conduit. The simulation results are indicated in Fig. 11 for the frequencies up to 5 GHz. The most notable feature is the reduced protection for the “bottom” and “corner” wires above 2 GHz, the frequency, where the half wavelength and lateral dimension of the conduit become comparable.
IV. MEASUREMENTS

In order to validate the simulation results, measurements have been carried out in the 3-m fully anechoic room (FAR) at Philips EMC Center [25]. The FAR floor was covered by the same absorbing ferrite tiles as the wall and the ceiling. This provides a reflection-free environment up to 1 GHz. The conduit is placed at 1 m above the floor. A significant length of the measuring cable from the conduit wires to the test receiver is exposed to the field generated by the antenna. This may lead to a large induced CM current in the cable shield. To minimize the effect, the cable was loaded with ferrite rings over the whole length inside the FAR. In order to determine the cable influence, two different orientation of conduit were considered. They are referred to as “vertical” and “horizontal” and schematically shown in Fig. 12. Under otherwise equal circumstances, the horizontal orientation is preferable, since in this case, the incident electric field is perpendicular to the cable and the coupling is up to $-6\,\text{dB}$ less. The conduit was placed at 3 m distance from the antenna. A minor wavefront curvature at the conduit could have been expected, but was not taken into account. The signals were measured with HP 8546A EMI Receiver. The 0 dBm output of the tracking generator was connected to the CBL 6112B antenna, which was used as excitation source. The frequency range of 30 MHz–1 GHz is split in several subranges to obtain a higher resolution. A second log-periodic antenna with known antenna factor replaced the conduit in introductory measurements to determine the incident electric field at the conduit. Fig. 13 shows the results for the “top” and the “middle” wires and their comparison with FIT calculations in case of the 50 Ω load. The measured voltages are scaled to the 1 V/m electric field in the calculations. Good agreement over the whole frequency range is observed. The ripples in the measured results were caused by minor reflections in the signal cable. Similar measurements with an FCC F-2000 current probe on the wire currents compare less well with the calculations, mostly because the coupled inductance of the probe loads the wire and the probe metal shield introduces additional local capacitance. Because of the protection, is equally well demonstrated in the voltage measurements, we limit the presentation to these.

It has been shown in [3] for frequencies below 1 MHz that even a nonconnected brass cover reduces the coupling from the outside world by factor of six, as compared with an open U-shaped conduit. The slit between cover and conduit was 1 mm wide and the overlap was 20 mm. Four bolts at the corners connect the cover and conduit, and reduce the coupling further by an order of magnitude. Here, we extend these results. As is well known, at higher frequencies, where conduit becomes electrically large, a floating cover is not effective. As a rule of thumb, the bolts should be placed not further than $\lambda_s/10$ apart, where $\lambda_s$ is the smallest wavelength of interest. The 1.5-m long conduit becomes electrically large ($l_z = \lambda/10$) at 20 MHz, which is below the 30 MHz lower limit of the antenna in the FAR. To increase the critical frequency up to 100 MHz, additional bolts were placed along the whole length at distances of 24.5 cm apart. Measurements show that a configuration with a floating (not galvanically connected to the conduit) cover does not provide the desired positive effect. On the average, the voltage is slightly reduced, but more importantly, additional large resonance peaks appear over the whole frequency range. Fig. 14 compares the induced voltage at the end of the “top” wire for the open U-shaped conduit (thick solid line), the conduit with all screws are put in place (dashed line) and the conduit connected to the cover by copper tape (diamond pattern type) over the full length (thin solid line). The bolted cover indeed reduces the coupling by up to 30 dB, but only below 300 MHz. The copper tape
reduces the signal level by 30 dB over the full-frequency range, most likely limited by the random contact between cover, tape, and conduit.

V. CONCLUDING REMARKS

The protection offered by an open U-shaped cable conduit has been analyzed. Previous studies of similar configurations concerned mainly low frequencies (below 1 or 30 MHz); this study extends the frequency range up to a few gigahertz. The induced currents and voltages over a 50 Ω load on wires inside the conduit have been exposed to plane-wave excitation. A good agreement between measurements and simulations was observed. Both showed a significant protection for the inside wires, especially when the wires are located near the conduit walls. This is valid for frequencies until a half wavelength becomes comparable to the lateral dimensions. Some practical aspects of the measurement setups have been discussed as well.

Ideally, the variations in electric field along the conduit length should be incorporated into the TL model of Section III-C to account for the effects near the end plates. When several wires are present, the mutual coupling between them must be also included in the model. The off-diagonal elements (mutual inductances) of the L-matrix can be calculated by a SC approach. The corresponding capacitance matrix is then obtained by the inversion of this inductance matrix. The analysis of systems containing multiple cables has been earlier reported in the literature [22]–[24].

The conduit considered in this paper contains only four sparsely placed parallel wires. The real-world conduits are normally more densely filled with cables in randomly interweaved bundles. The sharp resonances in the currents of Fig. 5 may cause an increased coupling to the cables in the conduit. For calculations, the actual wave velocities outside and inside the cable, as well as the amplitude and the phase of the transfer parameters Zt and Yt, have to be known. The theory has been already formulated by Vance [10, p. 147].

| TABLE V
<p>| CONDUIT CORNERS (IN CM), αk AND PREVERTICES wk ON THE UNIT CIRCLE FOR T1 |</p>
<table>
<thead>
<tr>
<th>k</th>
<th>zk</th>
<th>αk</th>
<th>wk</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>−4.5 + 0.0i</td>
<td>1.5</td>
<td>1.00000 + 0.00000i</td>
</tr>
<tr>
<td>2</td>
<td>−4.5 + 9.0i</td>
<td>0.5</td>
<td>0.89027 − 0.45543i</td>
</tr>
<tr>
<td>3</td>
<td>−4.6 + 0.0i</td>
<td>0.5</td>
<td>0.82871 − 0.53590i</td>
</tr>
<tr>
<td>4</td>
<td>−4.6 − 0.1i</td>
<td>0.5</td>
<td>−0.69087 − 0.74247i</td>
</tr>
<tr>
<td>5</td>
<td>4.6 − 0.1i</td>
<td>0.5</td>
<td>−0.71028 + 0.70392i</td>
</tr>
<tr>
<td>6</td>
<td>4.6 + 9.0i</td>
<td>0.5</td>
<td>0.79616 + 0.60508i</td>
</tr>
<tr>
<td>7</td>
<td>4.5 + 9.0i</td>
<td>0.5</td>
<td>0.86346 + 0.50442i</td>
</tr>
<tr>
<td>8</td>
<td>4.5 + 0.0i</td>
<td>1.5</td>
<td>0.99844 + 0.05583i</td>
</tr>
</tbody>
</table>

Fig. 14. Effect of the conduit cover and the type of connection. Measured voltage (in dB μV) of the “top” wire.

Fig. 15. Three SC transformations for the conduit, with corresponding field lines for a horizontal external magnetic field. In the lower left part, the position t = 1 is indicated. In both w-planes, the unit circle is drawn, with markers on the upper right indicating the prevertices wk. The wk = 1 marker corresponds to the left corner inside the conduit. The upper left part of the figure shows the conduit, scaled by a factor of 1/5.

APPENDIX

SCHWARZ-CHRISTOFFEL APPROACH

The conduit shape (h = 9 cm, 2w = 9 cm, and d = 1 mm) is obtained by transformation T1 from the unit disk (see Fig. 15). For the determination of the TL parameters T1 [21, eq. (4.6)] suffices.

\[
T_1 : f_1(w) = A + C \int_{w}^{1} \left( 1 - \zeta/w_k \right)^{1-\alpha_k} d\zeta
\]

(2)

\[
T_2 : f_2(w) = e^{i\varphi} / w
\]

(3)

\[
T_3 : f_3(t) = t + \sqrt{t - 1} \cdot \sqrt{t + 1}
\]

(4)

In (2), A and C are constants, wk are the prevertices on the unit circle, and the αk are given by the turning angles. Values for the conduit are given in Table V. As shown, the wk are truncated to five digits. Far more accurate values have been used in the calculations; the lengths of the conduit edges were accurate to within 10⁻¹² cm. The procedure toward the L-matrix using the unit circle image has been described in Section III-C and [4, Appendix] and is not repeated here.

The transformation T2 maps the complex plane outside the unit circle onto the disk and rotates the w-plane over \( \varphi = \pi/2 + (\arg w_1 + \arg w_8)/2 \) to have the correct orientation for magnetic field in t. The transformation T3 maps the full complex t-plane onto the w-plane. A homogeneous magnetic
field $H_0$ oriented along the real axis in $t$ is described by the complex potential $H_0 \cdot t$. The complex conjugate of the magnetic field in the $z$-plane [26, p. 58] is $H^* (z) = H_0 \times \frac{\partial T}{\partial t}$ with $T(t) = T_1(T_2(T_3(t)))$. At large distances $z$ from the conduit, or $w$ near the origin, $T_1$ behaves as $C/\omega$ and $T_3$ as $2t$. The homogeneous field at large distance in $z$ is then $H_0 \cdot |2C|$. The flux between the wire images in the $t$-plane and the conduit has been corrected with this factor. Note [21, p. 53] that $|C|$ is logarithmic capacity of transformation $T_1$; here we have $C = 0.14366555 - 5.1424224i$.

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