Electromagnetic Reflectometry with Coaxial Cable Models - Currents in Time Domain

Reflectometers are widely used for non-destructive locating and characterization of discontinuities in metallic cables. **In real-life**, for example, time domain reflectometry is applied for **locating faults in airplane wiring**. For precise locating of cable faults, so called spread spectrum time domain reflectometry is used.

In order to show the capabilities of WIPL-D Pro, a full 3D EM **Method-of-Moments** based solver, and to simulate time domain reflectometry, three models of coaxial cables will be simulated and output results (generator current) will be observed in time domain. **The first model** represents a straight coaxial cable with a fault. The dielectric material between the cable conductors is the air. For this structure, a theoretical result is available and it will be compared with a result of WIPL-D simulations. **The second model** corresponds to a curved cable without any faults. Finally, **the third model** represents a curved cable with a fault. For both curved cables dielectric between the conductors differs from air. All three cables have the same length.

Time Domain Solver

Time Domain Solver (TDS) is add-on tool available for using with **WIPL-D Pro 3D EM Solver**. TDS features a user-friendly interface (Figure 1). It is intended for transient analysis of 3D structures. The time-domain response of a structure is calculated using frequency domain simulation and Fourier transform. The tool is integrated into WIPL-D Pro environment in such way that the frequency domain **simulation and conversion to time-domain are performed automatically**. Visualization of the time domain results includes 2D and 3D graphs. The visualization is also integrated into the WIPL-D environment.
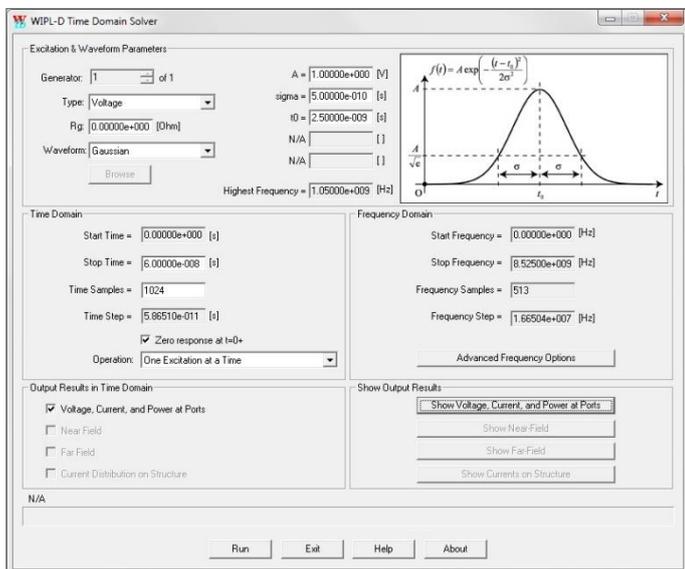

Figure 1. Time Domain Solver user interface

Time-domain excitations can be specified within TDS using variety of **predefined waveforms** (for example: Gaussian pulse, Gaussian monocycle, exponential pulses, etc.), or **user-specified** excitation waveform can be red-in.

Feeding and Termination

Excitation of the modeled coaxial cable is implemented using coaxial feeders (Figure 2). **The dimensions** of the feeder are shown in Figure 2. In order to save simulation time and reduce a number of unknowns, the symmetry of the structure is utilized so that only a half of the structure is simulated (Figure 2).

To complete the simulation settings, a generator must be connected to one end of the cable, while loads will be created at both ends. A generator and concentrated loading are attached to a wire which is a part of the feeder (it is shown in red, in Figure 2). The generator and a concentrated load themselves are not shown in the figure. In this application note, as a symmetry plane has been used, the 50 Ohms coaxial cable is terminated with a 100 Ohms resistor.
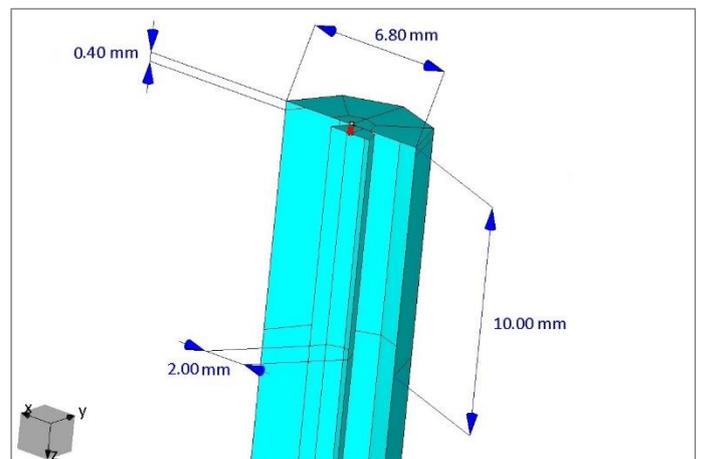

Figure 2. Coaxial feeder

Coaxial Cables

The total length for all the coaxial cables is set to be 7 meters and includes the length of the feeder and a termination of the cable. It means that total length of the simulated cable is measured from the "beginning" of the feeder to the "end" of the cable termination (as shown in Figures 3-4). In the figures, a generator is marked with "g1" while 100 Ohms resistive loadings are marked using "c1" and "c2".

The coaxial cables are modeled using *Body-of-Revolution* (a WIPL-D Pro built in object; Figure 2 and Figure 5). Dimensions of inner and outer coaxial conductors are shown in Figure 2.

For straight coaxial cable, a dielectric between the conductors is air. Lengths of the cable sections are shown in Figure 3. The generator is "followed" with straight section of the cable, a discontinuity and again, a straight section of the cable (Figure 3).
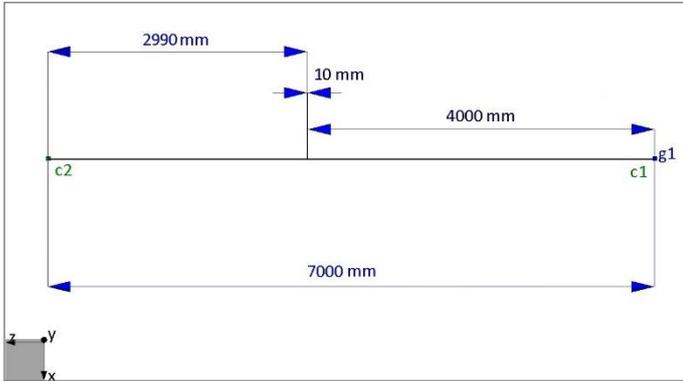

Figure 3. Dimensions of the straight coaxial cable filled with air

For curved cables appropriate dimensions are shown in Figure 4. The generator is "followed" with straight section of the cable and curved section (Figure 4). Radius of the curved section is 1000 mm. The curvature is modeled using 40 segments, each about 39.267 mm long. The "next" section is straight one, "followed" with a discontinuity. The "last" section is also a straight section.
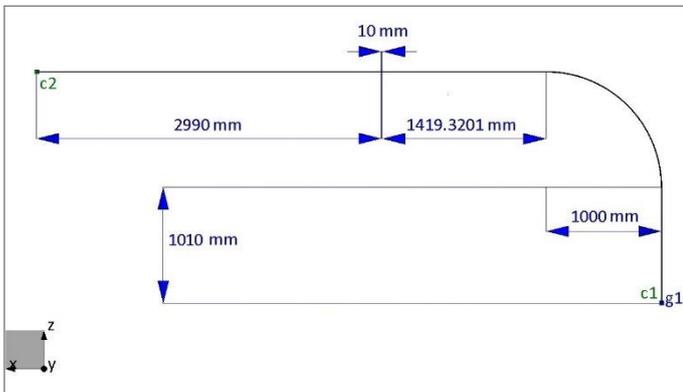

Figure 4. Dimensions of the curved coaxial cable filled with dielectric

A discontinuity is located just before the last section of the cable (Figures 3-4). Details regarding modeling of the cable fault are shown in Figure 5.
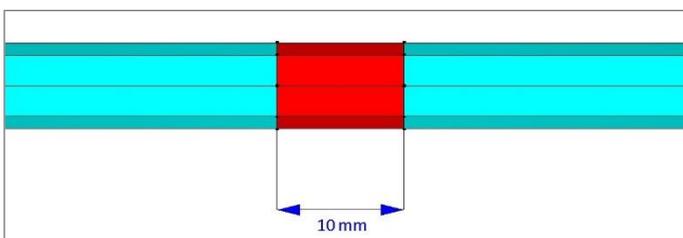

Figure 5. Length of the fault in coaxial cable filled with dielectric

The fault itself represents a discontinuity in outer conductor. The length where the conductor has been removed from the cable is 10 mm.

The parameters of the dielectric used in the models of curved coaxial cables have been selected to be **frequency dependent**. The functional dependency of relative dielectric permittivity (Er), and loss tangent (TgD) is presented in Table 1.

Table 1. Dependence of Er and TgD on frequency

Frequency [GHz]	Dielectric	
	Er	TgD
0.0	2.28	0.0009
0.1	2.26	0.0009
0.2	2.24	0.0009
0.3	2.20	0.0010
0.4	2.19	0.0011
0.5	2.18	0.0011
0.6	2.17	0.0013
0.7	2.17	0.0014
0.8	2.17	0.0015
0.9	2.17	0.0016
1.0	2.16	0.0016
1.1	2.17	0.0017

Excitation Pulse

The structures will be excited with **Gaussian pulse**. Gaussian pulse is defined as built-in TDS excitation. In TDS, used Gaussian pulse is explained in Figure 6.
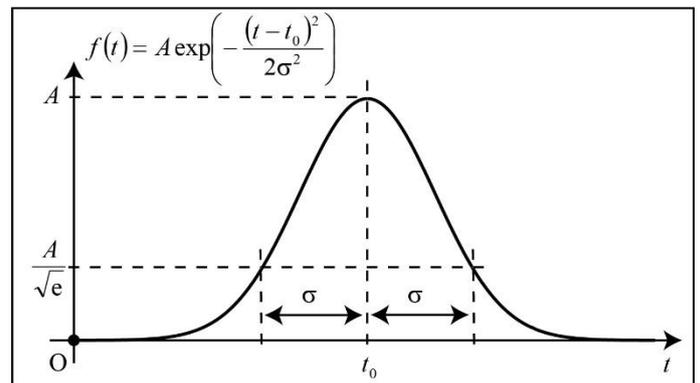

$$f(t) = A\exp\left(-\frac{(t-t_0)^2}{2\sigma^2}\right)$$

Figure 6. Graphical representation of Gaussian pulse excitation found in TDS

Parameters used for defining Gaussian pulse shown in Figure 6 are presented in Table 2.

Table 2. Numerical representation of parameters used in Gaussian pulse defining

TDS Parameter	Value
A [V]	1
sigma [s]	5e-10
t0 [s]	2.5e-9
Stop Time [s]	6e-8
Time Samples	1,024

Simulations

All cables were simulated **in frequency domain** before applying the Fourier transform. The frequency band for the simulation is obtained using TDS, according to Gaussian pulse settings (it is from about 0.01665 GHz to about 1.04897 GHz in 63 frequency points). This, relatively small number of frequency points appears as a result of applying *Zero padding* option, found in TDS. All WIPL-D project settings are kept as defaults, except *Maximum Patch Size* which was set to 0.4 wavelengths.

Computer used for the simulations was Intel® Core® i7-7700 CPU @ 3.60 GHz with 64 GB RAM and NVIDIA GeForce GTX 1080 GPU card. GPU is used both for matrix fill and matrix inversion.

For the case of cables filled with dielectric, a number of unknowns and a number of elements depend on parameters of dielectric used and they vary with the frequency. However, as the variations are small, the number of unknowns and number of elements as obtained for the first simulation frequency are adequate to represent calculation efficiency at all frequencies.

Number of elements, number of unknowns, and simulation time, for the first frequency, are presented in Table 3. Simulation time mainly consists of time required to perform matrix filling-in and time used for matrix inversion. Usually, it is recommended that matrix fill-in is performed on CPU, while matrix inversion is performed on GPU. In this scenario, however, the optimal settings are as follows: matrix filling-in should be performed on GPU and matrix inversion should be performed on CPU.

Table 3. Number of elements, number of unknowns, and simulation time at the first frequency.

Model	Number of elements	Number of unknowns	Simulation time per frequency [sec]
Straight coaxial cable (filled with air)	1,610	1,845	7.67
Curved coaxial cable with fault	4,070	4,645	15.44
Curved coaxial cable without fault	4,014	4,591	14.14

Results and Comparison with Theory

Results obtained using WIPL-D Pro will be used to mimic the process of locating a cable fault. The calculated location of the fault will be compared with the exact location of the fault edge closer to the generator end. Location of the edge used in all cable models is 4000 mm from the beginning of the cable (Figures 3-4).

Time domain generator current calculated for the model of the straight cable is presented in Figure 7.

Distance from the generator to the cable fault can be calculated using time delay of reflected Gaussian pulse:

$$dist = c_{diel} \cdot \frac{\Delta t}{2} = \frac{c_0}{\sqrt{\varepsilon_r}} \cdot \frac{\Delta t}{2} .$$

For straight cable (which is filled with air), we obtain:

$$dist = \frac{299792458 \, [m/s]}{\sqrt{1}} \cdot \frac{(29.2080 - 2.5220) \cdot 10^{-9} [s]}{2},$$

$$dist = 4.000 \, [m].$$

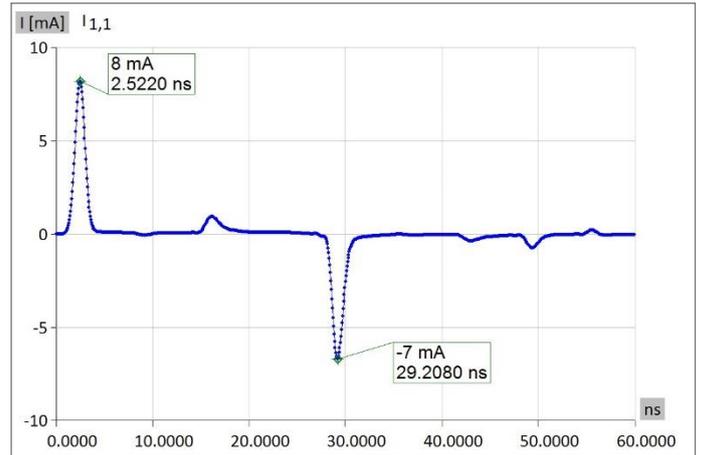This result coincides with the exact position of cable fault.

Figure 7. Current – straight cable filled with air

The next step is locating position of discontinuity in the curved cable. Since dielectric parameters depend on frequency, we will consider that used dielectric permittivity should be equal to average relative permittivity (Table 1). The average permittivity will be determined as sum permittivity values at all frequencies divided with 12. Thus, we will use relative dielectric permittivity of 2.196667.

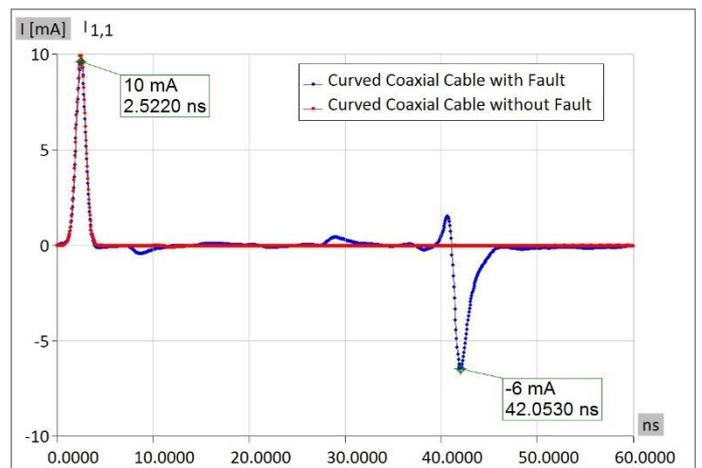Time domain generator current for curved cable is shown in Figure 8.

Figure 8. Currents - curved cable with and without fault

Similarly, as for the case of straight cable, using formulas from above, the calculated fault distance for the curved cable is:

$$dist = 3.998 \, [m].$$

Comparing the exact locations of cable faults as presented in Figure 3-4 with the calculated ones it can be concluded that the locations of the cable faults are found with high accuracy. The

3

difference appearing between calculated and exact distance due to an approximation of related to relative dielectric permittivity.

Conclusion

This application note presented successful usage of WIPL-D Pro together with an add-on tool, WIPL-D Time Domain Solver for modelling and simulation of various coaxial cables. Some of the coaxial cables were simulated as if they had a damaged outer conductor ("the cable fault"). The location of the cable fault was successfully determined by postprocessing WIPL-D results.

The verification of successful usage of WIPL-D is empowered with comparison between simulated results and the results obtained using EM theory. The location of the cable fault obtained with WIPL-D simulation and the one calculated based on EM theory are in excellent agreement.

In addition, it is shown that WIPL-D Pro model can include a dielectric with frequency dependent characteristics. As the simulation requirements for computer resources are moderate regarding both, the time and the memory required, All simulations were carried out using a standard workstation.