Propagation Characteristics and Overvoltage Analysis on Unconventional Submarine Cables

Paulo E.D. Rocha, Antonio C. S. Lima, Sandoval Carneiro Jr.

***Abstract*—There are some submarine cables also known as umbilical cables which are finding a growing use in the oil industry. One of the advantages of such cables is that they can combine both structural and electrical cables thus providing a more compact installation. From the electrical point of view these cables can be seen as a pipe-type inside another pipe-type. The electrical parameters, namely the impedance and admittance per unit of length of such cables cannot be calculated using conventional cable parameters subroutine available in Electromagnetic Transient (EMT) Programs such as EMTP-RV, ATP. However the procedures used in those subroutines can be expanded for the analysis of the umbilical cases.**

This paper presents a review of the basic procedures commonly used for evaluation of the cables impedance and admittance per unit of length as well as outlines the changes needed in order to represent the umbilical. The cable parameters are used in a Frequency Domain program to assess an overvoltage analysis as well as an analysis of the propagation characteristics of the submarine cable system.

***Index Terms*—Frequency-Dependent Pipe-Type Models, Electromagnetic Transients**

I. Introduction

Some industries, such as the oil companies are experiencing a large expansion and may need some unconventional power transmission networks. Furthermore, the environmental issues creates a great concern in the oil industries, so reliability is very important. Furthermore, electromagnetic transients studies are of paramount importance for the correct assessment of the Electrical Network performance and accurate models are needed to assure the accuracy of the simulations. In countries with deep oil wells the companies are using some unconventional cable that are considerably different from the ones usually found in underground power transmission. For instance, these unconventional cables may have several pipes with power conductors, cooling hoses, optical devices. The cost of an oil installation together with the need for reliability have placed a high demand on the accuracy of the electrical studies.

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These unconventional cables also present a technological challenge as one may be involved with the calculation of the electrical parameters of a pipe inside another. Furthermore, the evaluation of pype-type cables alone is not straight forward as in single-core (SC) cables or overhead transmission lines. This is due to the fact that a pipe may contain SC cables which are not concentric.

This work analyzes the propagation characteristics and the sheath, pipe overvoltages for this unconventional cable. The unconventional cable also known as umbilical cable is shown in Fig. 1. The detailed cable dimensions are shown in the appendix A. Umbilical cables can be understood as a pipe-type cable inside another pipe. Unfortunately, nowadays, this type of cable cannot be represented in EMTP type programs using the available Cable Constants (CC) routines. A stand alone program was build to calculate the cable parameters and the time domain responses were obtained using a Numerical Laplace Transform.

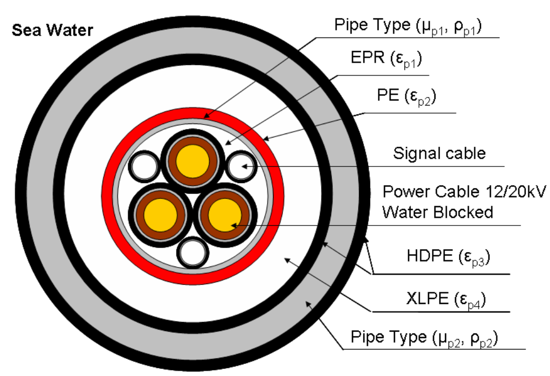

Fig. 1. Umbilical cable

II. Frequency Domain Analysis

An umbilical cable as any transmission system can be represented by the characteristic admittance Y_c and propagation function A, which are calculated from series impedance Z and shunt admittance Y, both per unit length, as follows:

$$\begin{aligned} A &= \exp\left[-l\sqrt{Z(\omega)\cdot Y(\omega)}\right] \\ Y_c &= Z^{-1}\sqrt{Z(\omega)\cdot Y(\omega)} \end{aligned} \tag{1}$$

where l is the length of the cable. As the umbilical cable is a system of n conductors, we have only $n\times n$ matrices. The series impedance, per unit length, is given by:

$$Z(\omega) = Z_{int}(\omega) + Z_{pipe}(\omega) + Z_{ext}(\omega) \tag{2}$$

where

- $Z_{int}(\omega) = Z_{skin}(\omega) + Z_{sol}(\omega) + Z_{prox}(\omega)$ includes skin, solenoid and proximity effects;
- $Z_{pipe}(\omega) = Z_p(\omega) + Z_c(\omega)$ represents the contribution of the first metallic layer of the surrounding pipe, as well as the coupling between the metallic layers in the pipe;
- $Z_{ext} = Z_{ideal}(\omega) + Z_{solo}(\omega)$ represents the mutual coupling between the conductors and external media.

All the parameters in $Z(\omega)$ are frequency dependent. The shunt admittance per unit length $Y = G + j\omega C$, can be determined directly from Maxwell potential matrix. Usually the conductance G is neglected and $Y = j\omega C$. The capacitance C is frequency independent.

In order to simplify the analysis, any saturation effect in the piper is neglected, and proximity and solenoid effects are neglected. As the main goal is the analysis of submarine cables, the external media is assumed homogeneous, linear, and unbounded with a relative magnetic permeability $\mu_r = 1$ constant throughout the whole frequency span considered for the analysis. All the losses in the dielectrics are neglected.

The technical literature has already presented both accurate and approximate formulae for the evaluation of single-core cables [1]. For the analysis considered here two main "structures" are considered either considering more "exact" impedance expressions as well as approximate formulae as shown in Table I where the acronym reflects the different methodology to deal with the parameters. Therefore the WAWB configuration was compared against the results obtained using SASB using the data given by [2]–[4].

TABLE I
EVALUATED FORMULAE

Submarine Cable			
Method	**Internal impedance**	**Pipe impedance**	**Sea impedance**
SASB	Schelkunoff	Ametani + Schelkunoff	Bianchi
WAWB	Wedepohl	Ametani + Wedepohl	Bianchi

A. Unconventional Submarine Cables

Applying the methodology proposed in [3] to the umbilical cable system shown in Fig. 1, the impedance matrices per unit length in (2) are given by:

$$Z_{int}(\omega) = \begin{bmatrix} \mathbf{Z}_{i_{SC_{(nxn)}}} & 0 & 0 & 0 \\ 0 & \mathbf{Z}_{i_{FO_{(mxm)}}} & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \end{bmatrix} \quad (3)$$

$$Z_p(\omega) = \begin{bmatrix} \mathbf{Z}_{p_{SC_{(jxk)}}} & \mathbf{Z}_{p_{SC,FO}} & 0 & 0 \\ \mathbf{Z}_{p_{FO,SC}} & \mathbf{Z}_{p_{FO_{(pxq)}}} & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \end{bmatrix} \quad (4)$$

$$Z_c(\omega) = \begin{bmatrix} & & & Z_{c_2} & Z_{c_4} \\ & \mathbf{Z}_{c_1} & & Z_{c_2} & Z_{c_4} \\ & & & Z_{c_2} & Z_{c_4} \\ Z_{c_2} & Z_{c_2} & Z_{c_2} & Z_{c_3} & Z_{c_4} \\ Z_{c_4} & Z_{c_4} & Z_{c_4} & Z_{c_4} & Z_{c_5} \end{bmatrix} \quad (5)$$

$$Z_{ext}(\omega) = \mathbf{Z}_{0_{(NxN)}} \quad (6)$$

where n and m are the numbers of metallic layers in SC and communication cables (optical fiber OF cables) respectively, (in this case $n = 6$, $m = 3$). The indexes j, k in (4) represents the number of conductor in SC cables where as the indexes p, q represent the number of communication cables. $\mathbf{Z}_{i_{SC_{(nxn)}}}$ and $\mathbf{Z}_{i_{FO_{(mxm)}}}$ are the internal impedance matrices of tubular conductors and can be obtained using the "exact" [2] or the approximate formulations [1]. There are as many columns of zeroes in $Z_{int}(\omega)$ and in $Z_p(\omega)$ as the number of metallic layers in the surrounding pipe.

In (6) N stands for the number of metallic elements in the umbilical and all elements are equal to a value Z_0 (sea return impedance) which is obtained assuming an unbounded, homogeneous, media in which the internal media (sea) is given by the outermost umbilical radius and an infinite external radius. The expression for Z_0 is given by [4], [5]

$$Z_0 = \frac{\rho\,\eta_w}{2\pi R}\frac{K_0(\eta_w R)}{K_1(\eta_w R)} \quad (7)$$

As the umbilical cable (UC) has a second metallic layer the expression in (5) the elements are slightly different from the classical approach propose in [3] and are given by

$$\begin{aligned} Z_{c1} &= z_{p1_e} - 2z_{p1_m} + z_{p1_{is}} + z_{p2_i} \\ &\quad + z_{p2_e} - 2z_{p2_m} + z_{p2_{is}} \\ Z_{c2} &= z_{p1_e} - z_{p1_m} + z_{p1_{is}} + z_{p2_i} \\ &\quad + z_{p2_e} - z_{p2_m} + z_{p2_{is}} \\ Z_{c3} &= z_{p1_e} + z_{p1_{is}} + z_{p2_i} + z_{p2_e} \\ &\quad - 2z_{p2_m} + z_{p2_{is}} \\ Z_{c4} &= z_{p2_e} - z_{p2_m} + z_{p2_{is}} \\ Z_{c5} &= z_{p2_e} + z_{p2_{is}} \end{aligned} \quad (8)$$

where z_{pi}, z_{pe} and z_{pm} are the internal, external and mutual pipe impedances. The pipe impedances are basically the same as the internal surface sheath impedance, the mutual impedance between layers and the external surface sheath impedance given by [1], [2], [5]. The approximate expressions given in [1] present suitable accuracy just when the condition $(r_e - r_i)/(r_e + r_i) < 1/8$ is respected, where r_e and r_i are the external and internal radius of a tubular conductor.

III. Modal Propagation Funtions

For the analysis of propagation characteristics, the umbilical cable shown in Fig. 1 was analyzed from 10 Hz to 1 MHz. The propagation constants are obtained from the square root of eigenvalues of the $Z(\omega)Y(\omega)$. To avoid artificial eigenvalue/eigenvector switch-over a switch back procedure was used [8]. The modal propagation velocities are shown in Fig. 2 while the modal damping is depicted in Fig. 3.

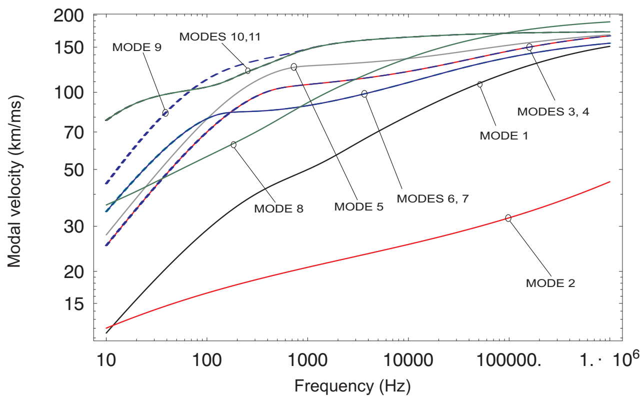

Fig. 2. Modal propagation velocity

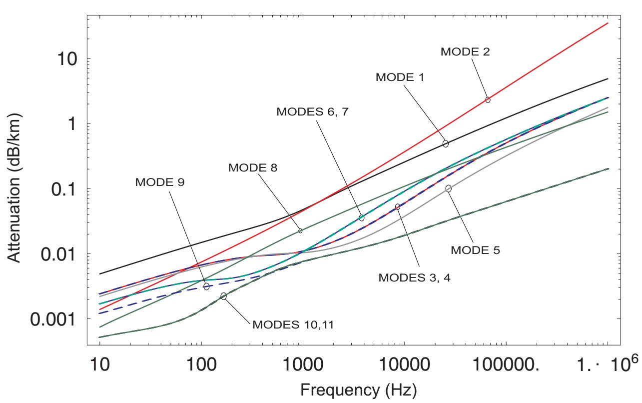

Fig. 3. Modal damping

As the umbilical cable has a peculiar structure it is interesting to evaluate how the modal currents are distributed in such cable. This can be done by an analysis of the current transformation matrix, T_i, relating modal and actual currents. Unfortunately, the modal transformation matrix has a strong frequency dependence. The common procedure is such cases it to approximate as the following

$$T_{iapp} \cong \Re[T_i]|_{\omega \to \Omega} \tag{9}$$

where Ω is the high (or highest) angular frequency value. As suggested in [6] a value of $\Omega = 2\pi 10^6$ was adopted. Therefore, using T_{iapp} calculated at 1 MHz, the modes present the following characteristics:

- mode 1 is an inter-sheath mode, it propagates in the inner metallic layer of the first pipe and returns in the sheathes of SC and communication cables. It is a "slow" mode and has the higher damping due to the magnetic permeability of the pipe type;
- mode 2 is sea return mode, the current propagates through the outermost metallic layer of the umbilical and returns through the sea. It has also a high damping and lowest propagation speed due to the high capacitance of the cable and the high inductance of the external path;
- modes 3 and 4 are also inter-sheath modes that relates SC and OF cables. These two modes present basically the same characteristics beacuse the SC and OF cables are symmetrically distributed inside the pipe;
- in mode 5 the current propagates through the sheathes of SC cables and return through the sheathes of the nearest OF cable with a small fraction of the current returning through the pipe. Although it has the same behavior as modes 3 and 4, this mode presents a higher speed and smaller damping;
- modes 6 and 7 are similar to modes 3 and 4 although they possess a smaller speed and a higher damping;
- mode 8 is a inter-pipe mode where the current propagates through the internal metallic layer and return through the external layer of the pipe
- modes 9, 10 and 11 are purely coaxial ones as the current propagates in one core and return in the sheath of the same or the nearest SC cable. As the SC cable are symmetric inside the pipe the three modes present the same behavior, these modes have the higher propagation velocities and smaller damping.

IV. Time-domain Analysis

For the time domain three configurations were considered. The umbilical cable was modeled in the frequency domain and a Numerical Laplace Transform was used to obtain the time-domain responses. The numerical Laplace Transform used in this work is summarized in Appendix B while the data for the umbilical cable are shown in Appendix A. In all test cases, the system was simulated using SASB ("exact" impedance formulation) and WAWB (approximate impedance formulation).

The first test is shown in Fig. 4 where the input is a 60 Hz, symmetric, balanced three-phase sinusoidal voltage and the other conductors are grounded on the source side. The sheathes voltages at the receiving end of the umbilical cable obtained using SASB and WAWB formulation are shown in Fig. 5. The agreement between the two formulation is very good. The highest value of the mismatch found in this case is of 0.009 pu.

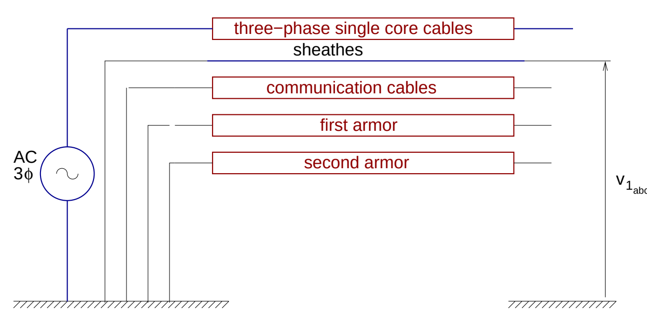

Fig. 4. Test Case # 1

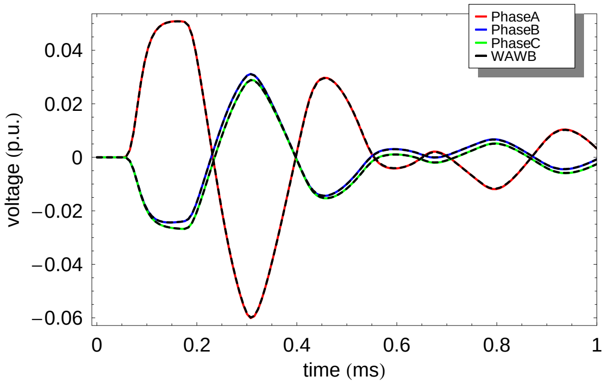

Fig. 5. Sheath voltages for the first test

The second test case is similar to the first one, but now there are no grounded conductors. The sheathes voltages at the receiving end are shown in Fig. 6. Again there is a good match between SASB and WAWB formulations. The highest mismatch found for this case was of 0.001 pu.

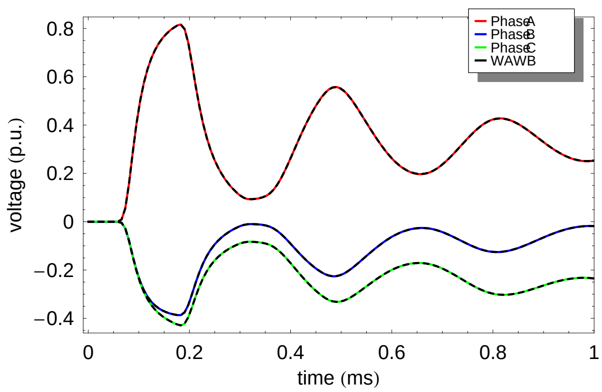

Fig. 6. Sheath voltages for the second test

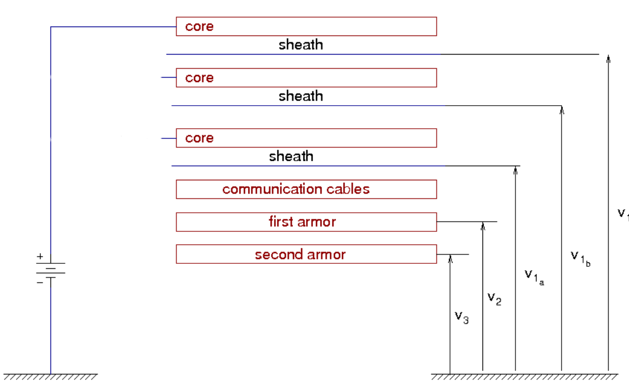

Fig. 7. Test case # 3

The third test is a step voltage applied to one of the core conductors while the other terminals remain open as shown in Fig. 7. In this case is interesting to analyze the voltages induced on the pipes due to a sudden change in the system input voltage. Fig. 8 presents the sheath voltages and Fig. 9 depicts the pipe voltage. Again in this case, the mismatch between simulated results was very small, the highest value was below 0.001 pu.

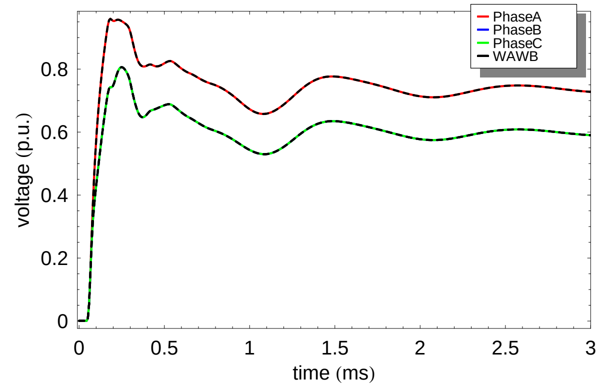

Fig. 8. Sheath voltages – test case # 3

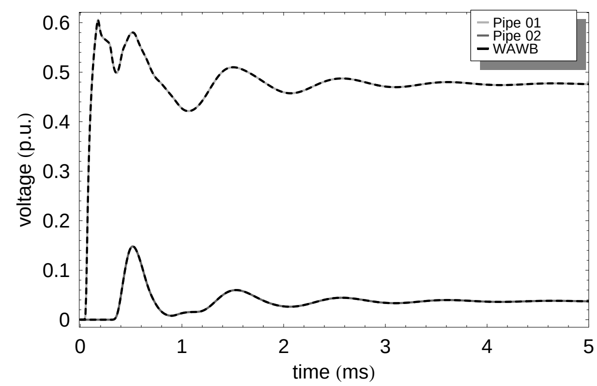

Fig. 9. Pipe voltages – test case # 3

V. Conclusions

This paper has presented analyzes of propagation characteristics and a time domain transient response of an unconventional cable system used in the oil industry. Unlike, underground cable systems, an umbilical cable system has not be implemented directly in EMT type programs. So a stand alone CC routine was created in order to analyze the overall performance of the system.

This paper has also investigated whether the approximate formulae commonly used in underground cable system is suitable for the analysis of such a cable. The results indicate that it is possible to use these approximated expressions as long as they are used only for tubular conductors. Nevertheless, a check of validity is also implemented. In other words, the use of approximate formula implies that one check whether the condition of validity of the expressions is possible.

The use of approximate expression is particularly useful for frequency domain analyzes where one may need several frequency samples. For instance, using the approximate expressions for the time-domain analysis the total simulation time was 28.7% of the total time to evaluate the system using the "exact" expressions. In the case of modal propagation analysis as less frequency samples are involved the total time to express the expression using approximate formulae was 45.95% of the time needed to run the “exact” expressions.

Appendix A
Cable Data

The cable presented in the Fig. 1 is an umbilical cable composed of three SC power cable system, a communication system and two metallic layers. The space between the two metallic layers is filled with two layers of EPR. Inside this dielectric filling there are also non-metallic hydraulic hoses.

- Power cable - $r_c = 9.15 \cdot 10^{-3}\, m$, $r_{i1} = 15.35 \cdot 10^{-3}\, m$, $r_s = 16.42 \cdot 10^{-3}\, m$, $r_{i2} = 17.92 \cdot 10^{-3}\, m$, $\rho_c = \rho_s = 1.7241 \cdot 10^{-8}\, \Omega.m$, $\epsilon_{r1} = 3.0$ e $\epsilon_{r2} = 3.72$.
- Signal cable - $r_{ai} = 6.50 \cdot 10^{-3}\, m$, $r_{ae} = 6.85 \cdot 10^{-3}\, m$, $r_e = 8.55 \cdot 10^{-3}\, m$, $\rho_a = 1.7241 \cdot 10^-8\, \Omega.m$ e $\eta_3 = 2.3$.
- First Pipe Type - $r_{p1} = 38.63 \cdot 10^{-3}\, m$, $r_{p2} = 39.43 \cdot 10^{-3}\, m$, $r_{p3} = 43.43 \cdot 10^{-3}\, m$, $\rho_a = 0.171 \cdot 10^{-6}\, \Omega.m$, $\mu_{p1} = 200$, $\eta_{p1} = 3.0$ e $\eta_{p2} = 2.3$(HDPE - High density polyethylene).
- Inter-pipes - $r_{p4} = 69.83 \cdot 10^{-3}\, m$ e $\eta_{p4} = 2.3$.
- Second Pipe Type - $r_{p5} = 75.63 \cdot 10^{-3}\, m$, $r_{p6} = 87.63 \cdot 10^{-3}\, m$, $r_{p3} = 92.63 \cdot 10^{-3}\, m$, $\rho_{p2} = 0.171 \cdot 10^{-6}\, \Omega.m$, $\mu_{p2} = 400$ e $\eta_{p3} = 2.3$(HDPE).
- Transmission system - $length = 10 \cdot 10^3\, m$, $\rho_w = 0.2\, \Omega.m$(HDPE).

Appendix B
Numerical Laplace Transform

There are several possibilities to obtain the inverse transform of a frequency domain data. Firstly, the system was modeled in the frequency domain using real frequencies and the inverse transform was approximated by an infinite series. However, this procedure was very time-consuming and the series had a slow convergence rate thus a large number of frequency samples were needed. Wilcox in [9] presented an elegant and efficient procedure to obtain the time-domain responses. It uses a complex frequency $s = \alpha + j\omega$ so the samples are calculated in an axis parallel to the imaginary one, i.e. instead of a real angular frequency ω a complex one given by $\omega - j\alpha$, $\alpha > 0$ is used. Thus if $G(s)$ is the response of a particular system in the complex frequency domain s, its time-domain counterpart $g(t)$ is given by

$$g(t) = \frac{\exp(\alpha t)}{\Delta t} \mathcal{F}^{-1}(G(s)) \tag{10}$$

If $G(s)$ has uniformly spaced samples with respect to the angular frequency ω it is possible to replace

$$\mathcal{F}^{-1}(G(s)) \rightarrow \text{IFFT}(G(s))$$

where IFFT indicates the Inverse Fast Fourier Transform.

The observation time considered was 15 ms and 4096 frequency samples were used. To minimize Gibbs effects a Hanning Windows was considered, the damping coefficient was chosen based on the procedure used in [10], [11].

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