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The Effect of Gibbs Factor on Transient Analysis in Underground Power Cables

Yılmaz Uyaroğlu[1], Selçuk Emiroğlu*[2]

Abstract

In this work, the transient overvoltage phenomena occurred at 34.5 kV AC underground cable transmission systems during the closure of the underground cables is to be studied and simulated by using the MATLAB program. Then, the transient voltage occurred at the underground cables is analyzed by using a modified Fourier transform. The studied system of underground cables is firstly modeled in the frequency domain. Transient voltages induced at the sending-end and receiving-end terminals of an underground cable of the transmission system are calculated in the frequency domain and using inverse Fourier Transform, the sending end and receiving end voltages are obtained by converting to the time domain. The effects of Gibbs factor on transients overvoltage phenomena considering cable length and source impedance are investigated. Numerical simulations are presented to demonstrate the transient voltages induced at the terminals of sending-end and receiving-end of an underground cable at the transmission system and the effects of Gibbs factor to eliminate Gibbs oscilllations.

Keywords: Transient analysis, underground cables, Fourier transforms, Gibbs oscillation

1. INTRODUCTION

Transient network analyzers used to measure and analyze the electromagnetic transients in power systems at early stages [1]. By using a digital computer, the transient analysis and the modeling of underground cables have been a considerably interesting subject in recent years. After using of the digital computer, many methods have been investigated to analyze the transient analysis of underground cables such as Fourier transform [2,3], z transform [4-6], weighting method [7], discrete wavelet transform [8], orthogonal projection approach [9], state variable approach [10].

Wedepohl who has firstly studied and investigated the transient analysis of cables has used Laplace transform and Bewley – Lattice techniques for transient analysis assuming that all parameters of cable do not depend on frequency [11]. After that, Indulkar and Dang have investigated the transient analysis of a cable

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system which has parameters depend on frequency [12].

In this work, the magnitude and waveform of the voltage in any point of the cable have been obtained in the time domain with inverse modified Fourier transform. The integral in inverse Fourier transform goes from minus infinity to infinity. But, the integral of the inverse Fourier transform does not go infinity and goes to the limited final value. So, Gibbs oscillations occur. In order to eliminate Gibbs oscillation, multiplier named as Gibbs factor is inserted in the calculations [13-15].

The transient overvoltages occurred during the switching operations are important phenomena for power system design and protection. To obtain transient voltages, all expressions have been transformed into the frequency domain. The magnitude and waveform of transient voltages have been calculated in the time domain by using the inverse Fourier transform. The cable parameters which depend on frequency such as series impedance, cable length, and effect of ground have been used in calculations.

Switching transient voltages reach the maximum values when the receiving end is open circuit. According to this state, in order to obtain the maximum value of voltage in the studied cable system, the system has been energized when the receiving end terminal of the line is open circuit. Also, the effects of source impedance and cable length on transient voltages have been investigated.

This paper is organized as follows. Section 2 briefly introduced the studied system of underground cables, and the parameter of cable is given. Mathematical formulations of the system are presented in section 3. Fourier transform and sigma factor are presented in section 4 and section 5 respectively. In section 6, simulation results are given. Conclusions are finally given in section 7.

2. ANALYSIS OF CABLE SYSTEM

The geometries of single cable are shown in Fig.1. The underground cable is made of core conductor, inner semiconducting layer, pure XLPE, outer semiconducting layer, sheath, aluminum foil, inner serving and outer serving as shown in Fig 1.

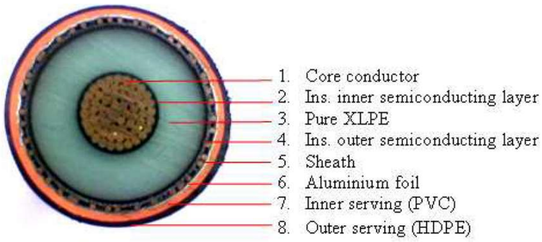


Fig. 1. The geometries of real single cable [16]

The radiuses of the conductor, inner sheath, outer sheath, and cable outer are shown in the cross-section of cable as shown in Fig. 2. Also, the parameters of the underground cable and ground resistivity are given in Table 1. The configuration of the cable system used in simulations is shown in Fig. 3.

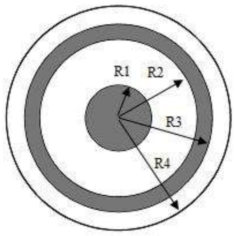


Figure 2. Single cable cross section area [16]

Table 1. The parameters of underground cable [17]

Conductor radius (R1)	3 mm
Sheath inner radius (R2)	14 mm
Sheath outer radius (R3)	15 mm
Cable outer radius (R4)	17 mm
Resistivity of core (ohm-m)	$1.72\ 10^{-8}$
Resistivity of sheath (ohm-m)	$1.72\ 10^{-8}$
Relative permittivity of core insulation	2.3
Relative permittivity of sheath insulation	7
Resistivity of ground (ohm-m)	20

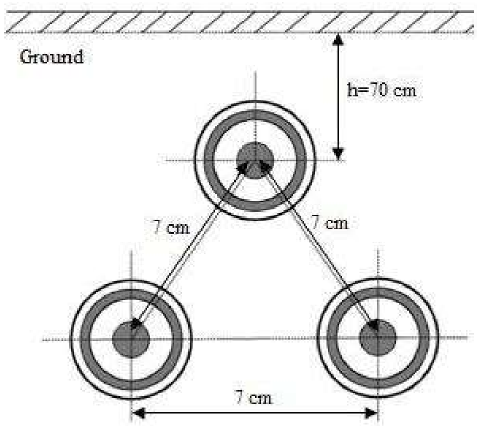


Figure 3. Configuration of cable system [18]

3. MATHEMATICAL FORMULATION OF SYSTEM

The voltage at the equivalent sheath is zero because the cable sheaths at the major part terminals are solidly earthed. So, the row and column elements of the series impedance matrices of cable related to cable sheath may be eliminated. Series impedance matrices are three order square matrices. So, the nodal parameters of two-port system A and B will be a matrix of 3x3 order. As it is shown in Fig. 4, V_S and V_R are sending-end and receiving-end voltage matrices of the 3x1 order. Also, the single line diagram of the studied system is shown in Fig. 5.

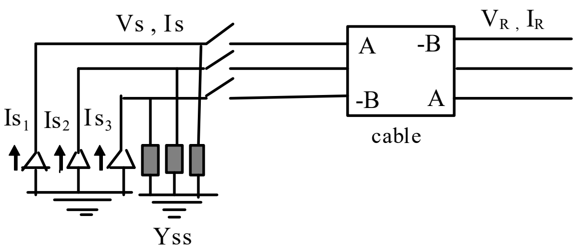


Figure 4. Norton equivalent circuit of cable system

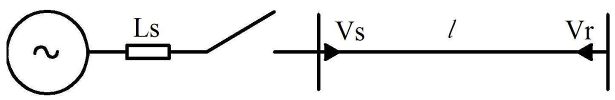


Figure 5. Single line circuit of studied system

The nodal equation of the cable system can be written as equation (1) [1].

$$\begin{bmatrix} I_S \\ I_R \end{bmatrix} = \begin{bmatrix} A & -B \\ -B & A \end{bmatrix} \begin{bmatrix} V_S \\ V_R \end{bmatrix} \quad (1)$$

Writing the Kirchhoff's current law at the sending-end terminal, it gives [1],

$$I_{ss} = I_s + I, I = Y_{ss} V_s \quad (2)$$

Using equation 1 and equation 4, matrix yields as below [1, 17].

$$\begin{bmatrix} I_{SS} \\ I_R \end{bmatrix} = \begin{bmatrix} A + Y_{SS} & -B \\ -B & A \end{bmatrix} \begin{bmatrix} V_S \\ V_R \end{bmatrix} \quad (3)$$

As the receiving end of the cable is not loaded, $I_R=0$. From equation (3),

$$V_R = A^{-1} B V_S \quad (4)$$

Substituting V_R into the matrix (Eq.3), V_S and V_R can be written as [2, 12]

$$V_S = [(A + Y_{SS}) - BA^{-1}B]^{-1} I_{SS} \quad (5)$$

$$V_R = A^{-1} B[(A + Y_{SS}) - BA^{-1}B]^{-1} I_{SS} . \quad (6)$$

As a result, the terminal voltages at receiving-end and sending-end in the cable system are calculated by expressions (5) and (6), respectively [2, 12].

4. FOURIER TRANSFORM

Inverse modified Fourier transform is given below [19].

$$f(t) = \frac{1}{2\Pi} \int_{-\infty}^{+\infty} F(\omega) e^{j\omega t} d\omega \quad (7)$$

where $F(\omega)$ is a Fourier transformation and given as

$$F(\omega) = \int_{-\infty}^{+\infty} f(t) e^{-j\omega t} dt. \quad (8)$$

So that all pole of integral expression is real and stable, assume that new angular frequency is ω'. Real axis slipped with ω to the negative side; yields $\omega' = \omega - j\alpha$. So, inverse modified Fourier transform express as below [1, 20].

$$f(t) = \frac{1}{2\Pi} \int_{-\infty - j\infty}^{+\infty - j\infty} F(\omega' - j\alpha) e^{j(\omega' - j\alpha)t} d\omega' \quad (9)$$

or

$$f(t) = \frac{e^{\alpha t}}{2\Pi} \int_{-\infty - j\infty}^{+\infty - j\infty} F(\omega' - j\alpha) e^{j\omega' t} d\omega' \quad (10)$$

The real part of integral can be written as

$$f(t) = \frac{e^{\alpha t}}{\pi} Re \int_{0}^{\infty - j\alpha} F(\omega' - j\alpha) e^{(j\omega' t)} d\omega'. \quad (11)$$

Writing this integral in the discrete form [15]

$$f(t) = \frac{2\omega_0}{\pi} e^{\alpha t} Re \sum_{n=1}^{N} F[(2n-1)\omega_0 - j\alpha] e^{j(2n-1)\omega_0 t}. \quad (12)$$

5. GIBBS OSCILLATION AND SIGMA FACTOR

Equation 11 can be calculated with numerical integral (Eq.12) in computer. Frequency harmonics named as Gibbs oscillation have been occurred because of the numerical integral from zero to limited end value.

Lanczos has proposed the method to reduce Gibbs oscillation [13]. So, Gibbs oscillation has been reduced with sigma factor as given below.

$$\sigma = \frac{sin(\pi\omega/\Omega)}{(\pi\omega/\Omega)} \quad (13)$$

where Ω is cutting frequency of top limit of integral. Including sigma factor to Fourier function,

$$f(t) = \frac{e^{\alpha t}}{\pi} Re \int_0^{\Omega} \sigma F(\omega' - j\alpha) e^{(j\omega' t)} d\omega' \quad (14)$$

can be written. Sigma factor has a low effect on low frequency and high effect in high frequency for reducing Gibbs oscillation.

6. SYSTEM STUDIES AND SIMULATION RESULTS

The transient voltages induced at the underground cable system on account of simultaneous switching are investigated by using a computer in the MATLAB program [21]. Also, the simulation results are compared with and without the sigma factor. Effects of source impedance and cable length on the transient voltages are also taken into consideration.

6.1. Effect of Cable Length

Effects of cable length on the transient voltage's magnitude owing to simultaneous closure have been investigated by performing three-phase simultaneous switching to the line from the generator which has source impedance.

Sending-end and receiving-end voltage waveforms got with three different cable lengths for low and high source impedances are given in Fig. 6 and Fig. 8. The maximum receiving-end and sending-end voltages for different cable lengths and source impedance are tabulated in Table 2 and Table 3.

As it can be seen from Table 2 and Table 3, the magnitude of the maximum sending-end and receiving-end voltage of the first phase reduces with the rise of cable length.

Table 2. The maximum magnitudes of overvoltages for different cable length (L_s:0.189 mH)

Cable length l(m)	Maximum magnitude of the sending-end voltages (p.u)		Maximum magnitude of the receiving-end voltages (p.u)	
	with sigma factor	without sigma factor	with sigma factor	without sigma factor
5000	1.2802	1.4187	1.9817	2.0710
30000	1.0146	1.0880	1.8189	1.8964
80000	1.0079	1.0901	1.5517	1.5694

Table 3. The maximum magnitudes of overvoltages for different cable length (L_s:9.47 mH)

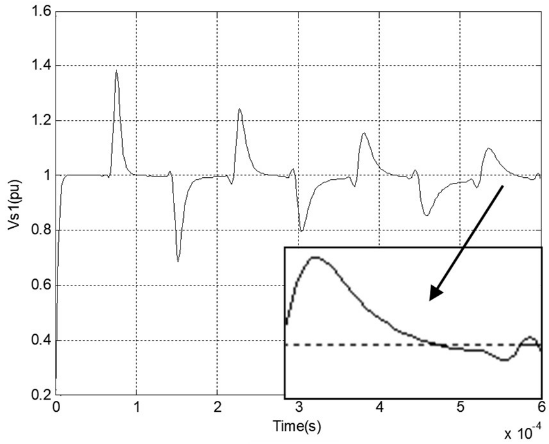
Cable length l(m)	Maximum magnitude of the sending-end voltages (p.u)		Maximum magnitude of the receiving-end voltages (p.u)	
	with sigma factor	without sigma factor	with sigma factor	without sigma factor
5000	1.8639	1.8664	2.0699	2.0727
30000	1.5692	1.6022	2.0386	2.1235
80000	1.3168	1.3404	1.6398	1.6677

6.2. Effect of Source Impedance

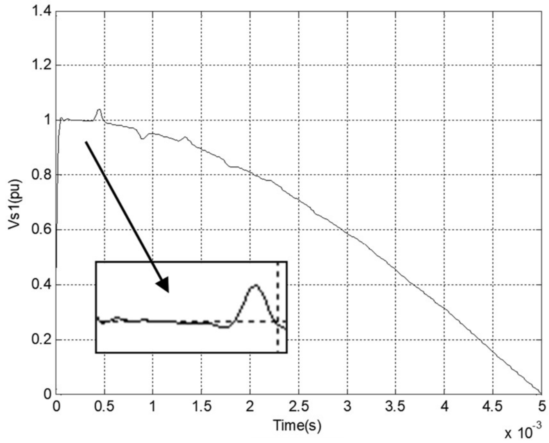
Sending-end and receiving-end voltage waveforms obtained for low and high source impedance are shown in Fig. 6 and Fig. 8. The maximum receiving-end voltage for low and high source impedance is given in Table 4.

Table 4. Maximum magnitudes of overvoltages for different source inductance (l =30 km)

Source inductance (mH)	Maximum sending-end voltage(pu)		Maximum receiving-end voltage(pu)	
	with σ	without σ	with σ	without σ
0.189	1.0146	1.0880	1.8189	1.8964
9.47	1.5692	1.6022	2.0386	2.1235



(a)



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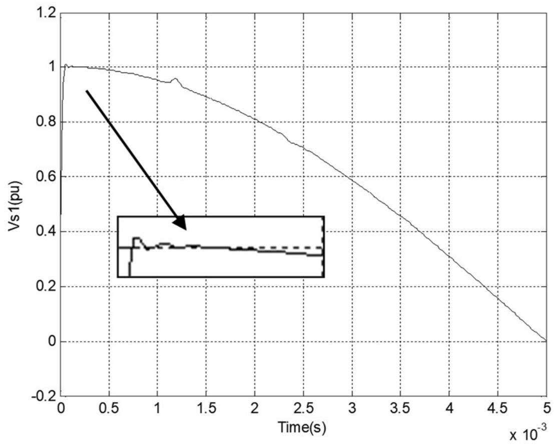
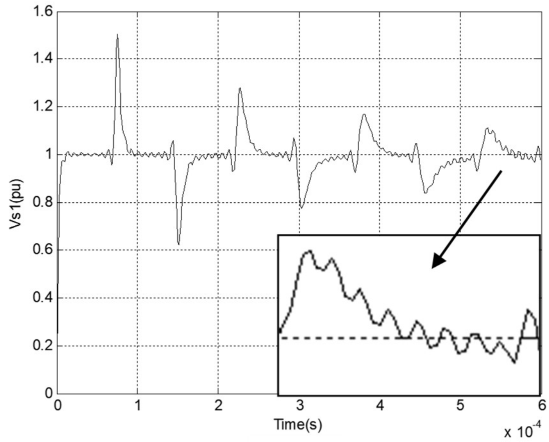


(c)

Figure 6. The waveform of transient voltages induced at sending-end with sigma factor when L_S: 0.189 mH l= a) 5000 m, b) 30000 m, c) 80000 m

The waveform of sending-end and receiving-end voltages including sigma factor when source inductance L_S:0.189 mH, with cable length (l) 5000 m, 30000 m, and 80000 m are shown in Fig. 6 (a,b,c) and Fig. 8 (a,b,c) respectively.



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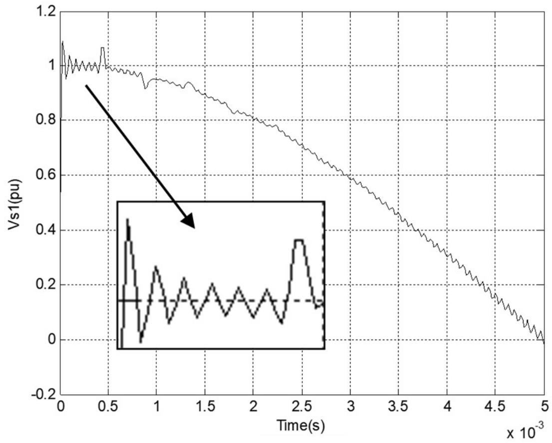

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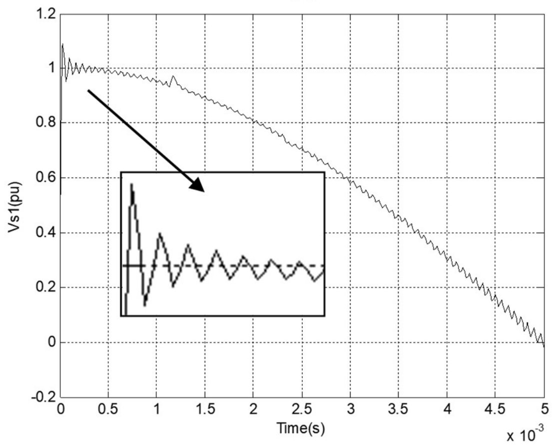
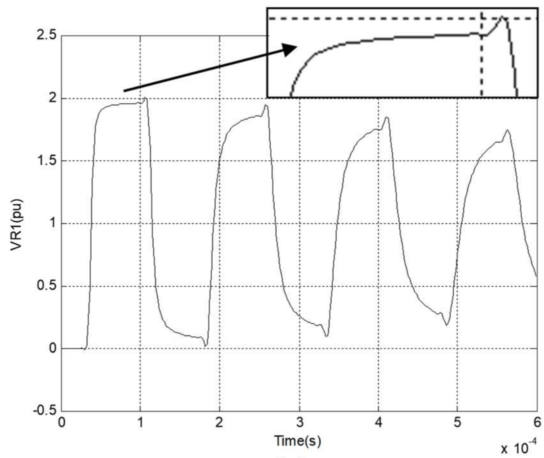


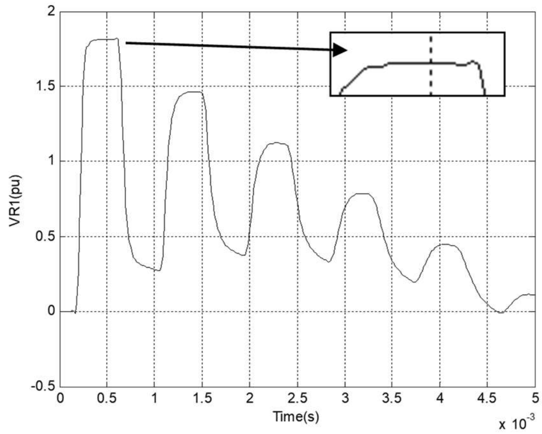
(c)

Figure 7. The waveform of transient voltages induced at sending-end without sigma factor when L_S: 0.189 mH l= a) 5000 m, b) 30000 m, c) 80000 m

The waveform of sending-end and receiving-end voltages without sigma factor when source inductance L_S:0.189 mH, with increasing cable length 5000 m, 30000 m, and 80000 m are shown in Fig. 7 (a,b,c) and Fig. 9 (a,b,c) respectively.



(a)



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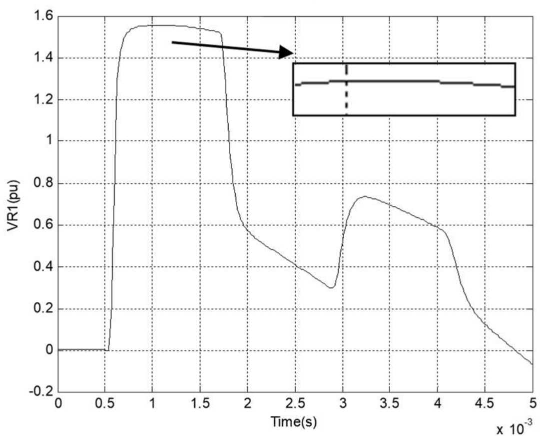

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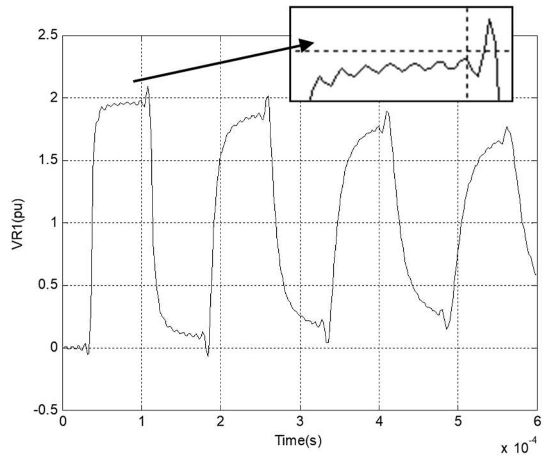
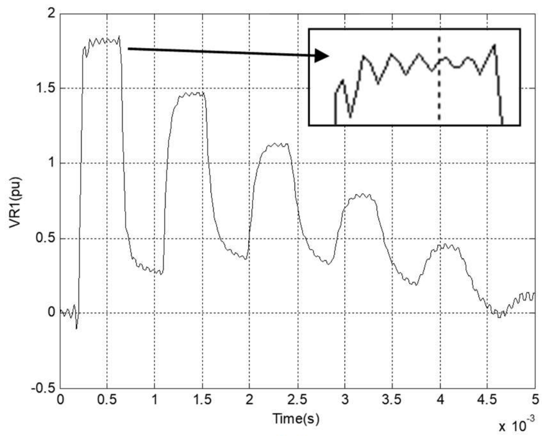
Figure 8. The waveform of transient voltages induced at receiving-end with sigma factor when L_S: 0.189 mH l= a) 5000 m, b) 30000 m, c) 80000 m



(a)



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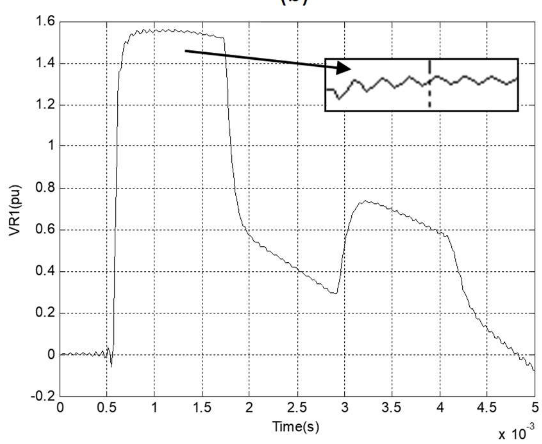

(c)

Figure 9. The waveform of transient voltages induced at receiving-end without sigma factor when L_S: 0.189 mH l= a) 5000 m, b) 30000 m, c) 80000 m

Voltages exponentially increase with a time constant. Besides, it is directly proportional to the source inductance. Also, the frequency of oscillations that are superimposed on nominal voltage frequency reduces with the rising source impedances as shown in Table 5 and Table 6. The voltage frequency of oscillations reduced at receiving-end decreases with the increasing the cable length. Table 5 and Table 6 shows approximately the voltage frequency of oscillations reduced at receiving-end with source impedance 0.189 mH and 9.47 mH respectively. The approximate values are used in Table 5 and Table 6.

Table 5. The oscillation frequency of the receiving end overvoltages for different cable length (L_S:0.189 mH)

Cable Length (m)	Frequency	Oscillation
5000	5 kHz	6.5 cycle (in 1 ms)
30000	1 kHz	5.5 cycle (in 5 ms)
80000	357 Hz	2 cycle (in 5 ms)

Table 6. The oscillation frequency of the receiving end overvoltages for different cable length (L_S:9.47 mH)

Cable Length (m)	Frequency	Oscillation
5000	2.5 kHz	2.5cycle (in 1 ms)
30000	835 Hz	4 cycle (in 5 ms)
80000	335 Hz	1.8 cycle (in 5 ms)

7. CONCLUSIONS

In this study, the magnitude and waveform of the transient overvoltages have been obtained using numerical Fourier transform. This paper investigated the source impedance and effect of cable length on the transient voltages induced at terminals of sending end and receiving end. The maximum magnitude transients overvoltages depend on cable length and source impedance etc. Source impedance and cable length have a significant effect on the waveform and magnitude of the transient voltage. Simulation results show that the magnitude of sending end and receiving end voltages decreases with the increasing the cable length. Also, as the source impedance rises, both the sending end and receiving end maximum magnitude of overvoltages rise. Also, the oscillation frequency of overvoltages decreases with the increasing source impedance and increasing the cable length.

This paper also presented the effect of sigma factor on transient analysis. In the transient analysis, because the Fourier integral has a limited final value, the Gibbs oscillation has occurred. Simulation results show that Gibbs oscillations have been reduced and eliminated with including sigma factor in Fourier integral.

8. REFERENCES

[1] Y. Uyaroğlu, Switching Transients Analysis in Underground Power Cables. M.Sc. Thesis, Sakarya University, 1997. (in Turkish)

[2] L. M. Wedepohl and C. S. Indulkar, “Switching Overvoltages in Long Crossbonded Cable Systems Using the Fourier Transform,” IEEE Transactions on Power Apparatus and Systems, pp. 1476-1480, July/August 1979.

[3] Ana Isabel Brito, V. Maló Machado, M.E. Almeida, M. Guerreiro das Neves, “Skin and proximity effects in the series-impedance of three-phase underground cables,” Electric Power Systems Research,130,132-138, 2016.

[4] W. D. Humpage, K. P. Wong, T. T. Nguyen, and D. Sutanto, “Z-transform electromagnetic transient analysis in power systems,” Proc. Inst. Elec. Eng., C, Gen. Trans. Dist., vol. 127, pp. 370-378, Nov. 1980.

[5] W. D. Humpage, K. P. Wong, T. T. Nguyen, “Z-transform electromagnetic transient analysis in crossbonded cable transmission systems,” Proc. Inst Elec. Eng, C, Gen. Trans. Dist., vol. 128, pp. 55-62, 1981.

[6] T. Noda, A. Ramirez, “Z-transform based methods for electromagnetic transient simulations,” IEEE Trans.on Delivery, vol. 22, no. 3, July 2007.

[7] I. Kocar, J. Mahseredjian, G. Olivier, “Weighting Method for Transient Analysis of Underground Cables,” IEEE Transactions on Power Delivery, vol. 23, no. 3, July 2008.

[8] B.A. Suleimanov, O.A. Dyshin, “Application of discrete wavelet transform to the solution of boundary value problems for quasi-linear parabolic equations,” Applied Mathematics and Computation 219 7036–7047, 2013.

[9] Heng-Xu Ha, Yu-Zhen Tan, Bo Chen, and Z. Q. Bo, “A Novel Electro-Magnetic Transient Analysis Method Based on

Orthogonal Projection Approach," Progress In Electromagnetics Research Symposium Proceedings, Moscow, Russia, August 18 - 21, 2009.

[10] A. Semlyen and Mansour H. Abdel-Rahman, "A State Variable Approach for the Calculation of Switching Transients on a Power Transmission Line," IEEE Trans. on Circuits and Systems, vol. cas. 29, no. 9, pp. 624-633, September 1982.

[11] L.M. Wedepohl, S.E.T. Mohamed, "Multiconductor Transmission Lines, Theory of Natural Modes and Fourier Integral Applied to Transient Analysis," Proc.IEE, Vol. 116., No 9., September 1969.

[12] L.M. Wedepohl, C.S. Indulkar, "Switching Overvoltages in Short Crossbonded Cable Systems Using the Fourier Transform," Proceedings of the Institution of Electrical Engineers, Vol. 122, No 4, 1975.

[13] C. Lanczos, "Applied Analysis", Prentice-Hall 539 pp., 1956.

[14] Ali Abdi, Seyed Mohammad Hosseini, "An investigation of resolution of 2-variate Gibbs phenomenon," Applied Mathematics and Computation 203, 714–732,2008.

[15] E. Berriochoa, A. Cachafeiro, J. Díaz, "Gibbs phenomenon in the Hermite interpolation on the circle," Applied Mathematics and Computation, 253, 274-286, 2015.

[16] Daud, Muhamad Zalani, Transient behaviour modelling of underground high voltage cable systems, Masters by Research thesis, School of Electrical, Computer and Telecommunications Engineering - Faculty of Informatics, University of Wollongong, 2009. https://ro.uow.edu.au/theses/2032

[17] U. Ünver, "Transient Analysis of Cable Systems Including the effect of Nonlineer Protective Devices," PhD. Thesis, University of Manchester Institute of Science and Technology, 1979.

[18] Y. Uyaroğlu, U. Ünver, "Yeraltı Enerji Kablolarında Oluşan Manevra Aşırı Gerilimlerinin Geçici Rejim Analizi: Kablo Uzunluğunun ve Şönt Reaktörlerin Etkisi," SAÜ Fen Bilimleri Enstitüsü Dergisi, 2, 119-123, 1997.

[19] N. Mullineux, J. Day, J.R. Reed, "Developments in obtaining transient response using Fourier transforms: use of the modified Fourier transform," Int. J. Elec. Eng. Educ, 4, pp. 31-40, 1966.

[20] U. Ünver, "Enerji Nakil Hatlarının Kısa Devre Analizi: Çift Taraftan Beslenen Hatlar," Elektrik Mühendisliği 6. Ulusal Kongresi, pp. 180-196, 1995.

[21] The MathWorks. (1993). MATLAB User's Guide. The MathWorks, Inc., Natick, MA