

Sensitivity Analysis of Maximum Overvoltage on Cables with Considering Forward and Backward Waves

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Abstract - lightning is known to be one of the primary sources of most surges in high keraunic areas. It is well-known fact that surge overvoltage is a significant contribution in cable failures. The other source of surge voltage is due to switching and it is pronounce on extra high voltage power transmission systems. The effect of both lightning and switching surges is weakening the cable insulation. The progressive weakening of such insulation will lead to cable deterioration and eventually its failure. Each surge impulse on the cable will contribute with other factors towards cable insulation strength deterioration and ultimately cable can fail by an overvoltage level below the cable basic impulse level (BIL). The maximum lightning overvoltage for a given cable depends on a large number of parameters. This paper presents the effect of model parameters (e.g., rise time and amplitude of surge, length of cable, resistivity of the core and sheath, tower footing resistance, number of sub conductors in the phase conductor (bundle), effect of surge arrester, length of lead, relative permittivity of the insulator material outside the core, power frequency voltage, stroke location, cable joints, shunt reactors, sheath thickness) on maximum cable voltage. The simulations show that the maximum overvoltage.

Keywords: Maximum overvoltage, Sensitivity analysis, Forward and Backward waves.

1. INTRODUCTION

power transmission network has developed during the last decades based on the use of over head line and cables [1]. The insulation of underground insulated cables is not self restoring and the BIL can experience a decrease as a result of aging. Lightning overvoltage can be a major cause of underground cable failure; therefore it must be taken into account when designing the insulation system of a cable. IEC specifies one, two, or three BIL levels for each system voltage, thus giving the customer some room for adapting the BIL to the actual lightning overvoltage conditions. The manufacturer is simply required to produce cables that satisfy the lightning test voltages. CIGRE WG B1-05 is currently undertaking a study to assess the maximum voltage stress on long cables. This study is motivated by the possibility of reducing the

required test voltage for long cables that are protected by arresters, as the cable attenuation may reduce the **maximum cable voltage well below the existing BIL's**. Therefore it is necessary to develop a technique which is able to estimate maximum overvoltage in power cables considering effective parameters. The resulting overvoltage at the cable ends has been subject to several investigations, e.g. [2-4] while in reality the maximum voltage may occur inside the cable [5, 6]. This maximum voltage can be found by calculating the voltage at selected positions along the cable (discretized model) [7]. This can be done by subdividing the cable into a number of small sections but error accumulation lead to inaccurate results. References [6,8,9] presents an improved approach where a regular line model is used for obtaining the voltages and currents at the line ends which are next used in the calculation at internal points using an off-line time step. However, in the case of steep-fronted lightning surges, the maximum voltage can only be determined with good accuracy if one of the selected positions is sufficiently close to the position of the maximum voltage. Article [10] is presented an analysis of the maximum voltage inside distribution cables from lightning strokes based on analysis by lattice diagrams. However, the technique does not cover the cable attenuation effects found in long transmission cables and the exact position of maximum voltage. In [11], maximum voltage is calculated by adding the peak value of the voltage wave in the forward and backward direction. The study presented in this paper is aimed at determining effect of model parameters on maximum lightning overvoltage (close back flashover) with the method which is explained in [11]. This goal is achieved by performing sensitivity analysis considering effective parameters on the maximum overvoltage. Simulation results show the importance of this study.

2. COMPUTATIONAL PROCEDURE

The maximum voltage was calculated based on the technique presented in [11]. The computation was carried out in three steps:

- 1) Calculation of the voltage at the exposed end of the cable assuming infinite cable length.
- 2) Calculation of the maximum incoming voltage wave at the remote end of the cable using the result from previous stage as a known voltage source at the exposed end.

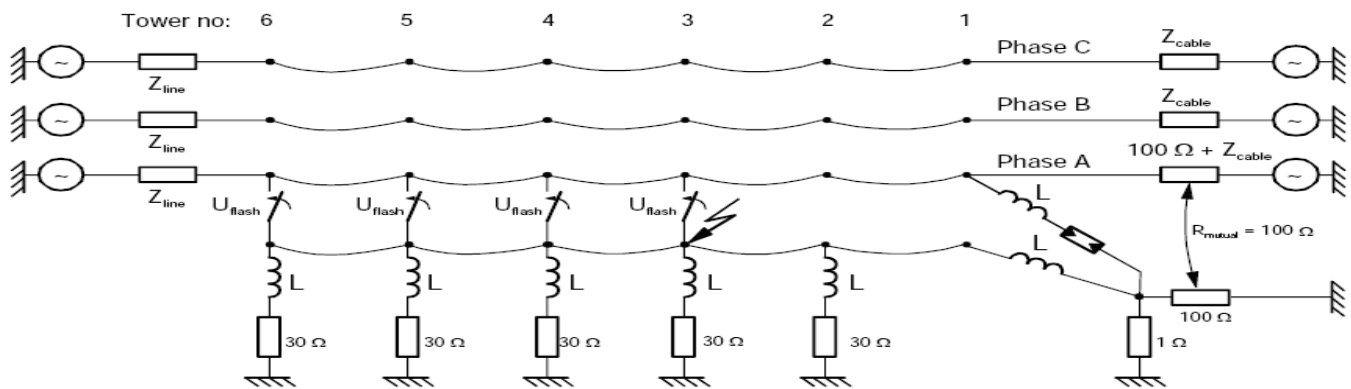


Fig -1: System configuration.

3) The maximum value of the reflected voltage wave at the remote end was calculated as outlined in [11]. The maximum value of the voltage along the cable in the vicinity of the remote end was set equal to the sum of the maximum incoming wave and the maximum Reflected wave at the remote end (This sum is greater than the voltage at the remote end when the two maxima do not appear simultaneously).

3. SYSTEM CONFIGURATION

The sample system considered for explanation of the proposed methodology is a 230 KV system shown in Fig.1. The situation considered is that a 200 kA lightning current with $1.2/50\mu s$ strikes the tower top in the third tower. This causes a back-flashover in the struck tower. (Note that the voltages are presented in p.u. of the system voltage in all sections, i.e. 1. p.u. equals $230\sqrt{2}/\sqrt{3}$ KV). The complete parameter model is given in Appendix.

4. SENSITIVITY ANALYSIS

The maximum lightning overvoltage for a given cable depends on a large number of parameters. In this part the effect of model parameters on the maximum overvoltage was investigated.

4.1 Effect of cable length

To study the effect of different cable lengths, simulations were carried out for cable lengths from 0.5 km to 14km. The results in Fig.2. Indicate that the maximum overvoltage along the cable is reduced with increasing cable length due to the cable attenuation and distortion effects combined with the finite duration of the impinging overvoltage at the exposed end. In the case of very long cables, the overvoltage level is limited to the arrester protective level at the exposed cable end plus the voltage drop along arrester leads. For shorter cables, the maximum voltage occurs within a few kilometers from the remote end where it may significantly exceed the arrester protective level.

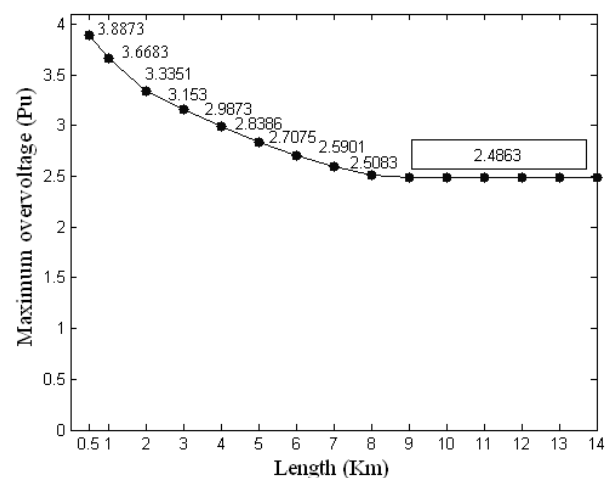


Fig -2: Maximum overvoltage as function of cable length.

4.2 Effect of magnitude of lightning stroke

Fig.3. compares maximum overvoltage on cable with different magnitude of lightning strokes between 100 to 200kA with front time $1.2/50\mu s$. As seen from the simulation results in Fig.3. with decreasing magnitude of lightning stroke decreases the maximum overvoltage on cable.

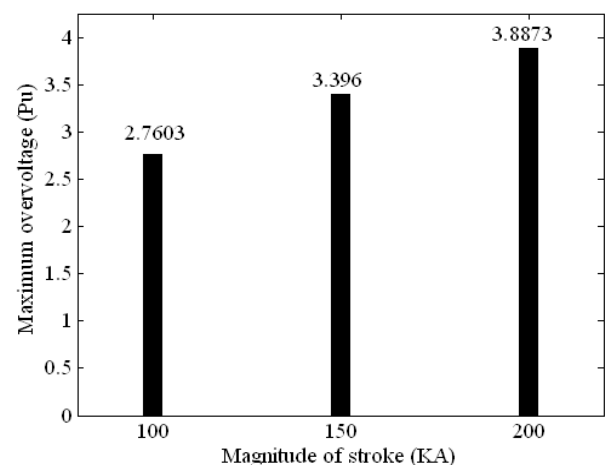


Fig -3: Maximum overvoltage as function of magnitude of stroke.

4.3 Effect of length of arrester lead

The magnitude of the transient voltage which propagates down the cable is mainly determined by arrester discharge voltage, the lead lengths on the arresters and the rate-of-rise of surge current. Approximately this voltage is the sum of arrester voltage and the arrester lead-induced voltage, which is a function of the lead length and rate-of-rise of current surge ($\frac{\partial i}{\partial t}$). Fig.4. shows maximum overvoltage on cable as function of arrester lead lengths (e.g., 3,9 and 16 m). As seen from the simulation results in Fig.4. with increasing arrester lead lengths, maximum overvoltage on cable is increases.

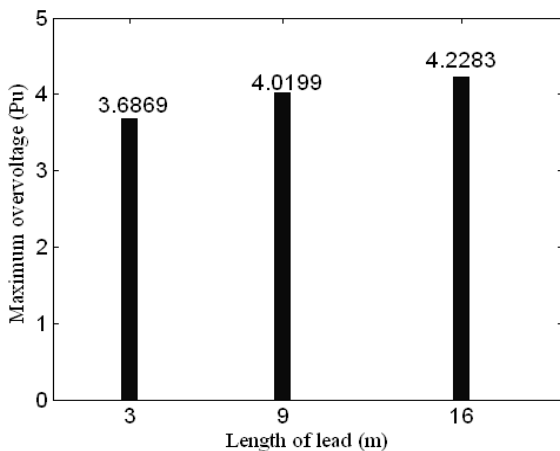


Fig -4: Maximum overvoltage as function of length of arrester lead.

4.4 Effect of number of sub conductors in the phase conductor (Bundle)

Fig.5. compares maximum overvoltage on cable with three different structures in phase conductor (simplex, duplex and quadruplex bundle) as seen from simulation results, maximum overvoltage in system with quadruplex bundles of over head line higher than system with simplex bundle of over head line. The reason is that, the over head line surge impedance decreases, it causes an increase in the ratio of the characteristic impedance of the cable and the line. This factor causes the peak value of the impinging voltage increase at exposed end. The change in the surge impedance of line is shown in Table 1.

4.5 Effect of resistivity of the core material

Fig.6. compares maximum overvoltage on cable with three different values of resistivity of the core material (e.g., $1.7e^{-9}$, $1.7e^{-8}$ and $1.7e^{-7}$). As seen from the simulation results with increasing the value of resistivity of the core material, maximum overvoltage on cable decreases. The reason is that the attenuation coefficient was increases and causes the voltage peak value of a voltage wave transmitted along the cable are reduced. The change in the attenuation coefficient is shown in Table 2.

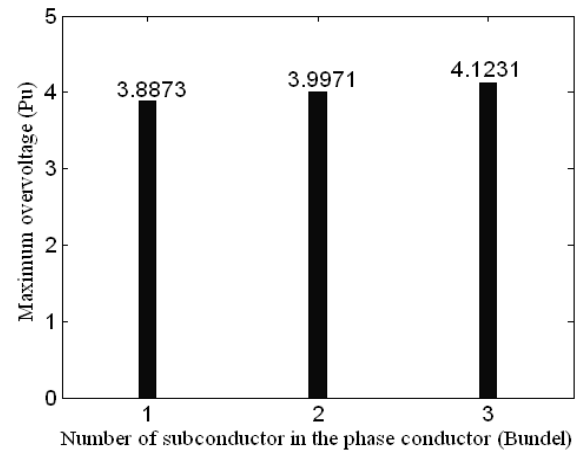


Fig -5: Maximum overvoltage as function of number of bundle.

Table -1: Impact of phase conductor design on characteristic impedance

Characteristic impedance [Ω]	
Conductor arrangement	Phase A,B and C
Simplex	435
Duplex	359
Quadruplex	310

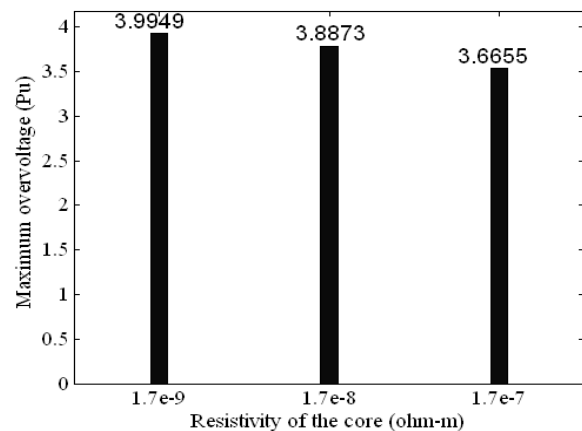


Fig -6: Maximum overvoltage as function of resistivity of the core material.

Table -2: Impact of resistivity of the core material on attenuation coefficient

Resistivity of the core material	Attenuation coefficient (db/km)
$1.7 * 10^{-9}$	0.365268
$1.7 * 10^{-8}$	0.467032
$1.7 * 10^{-7}$	0.788959

4.6 Effect of resistivity of the sheath material

Fig.7. compares maximum overvoltage on cable with three different values of resistivity of the core material (e.g., $2.8e^{-8}$, $2.1e^{-7}$ and $2.1e^{-6}$). As seen from the simulation

results with increasing the value of resistivity of the sheath material, maximum overvoltage on cable decreases. The reason is that the attenuation coefficient was increases and causes the voltage peak value of a voltage wave transmitted along the cable are reduced. The change in the attenuation coefficient is shown in Table 3.

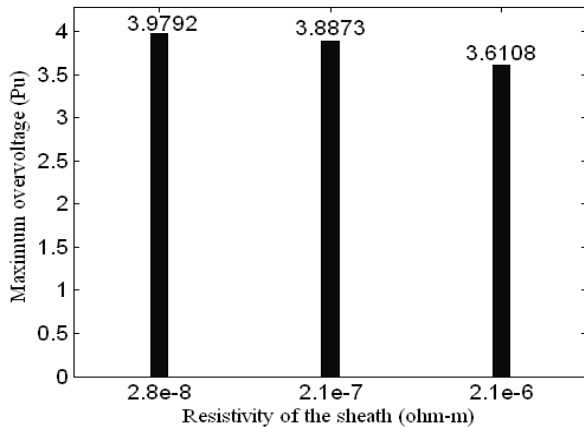


Fig -7: Maximum overvoltage as function of resistivity of sheath material.

Table -3: Impact of resistivity of the sheath material on attenuation coefficient

Resistivity of the sheath material	Attenuation coefficient (db/km)
$2.8 * 10^{-8}$	0.268066
$2.8 * 10^{-7}$	0.467032
$2.8 * 10^{-6}$	1.3182

4.7 Effect of resistivity of stroke location

Fig.8. compares maximum overvoltage on cable with three different locations (tower number 2, 3 and 4). The results show that the stroke location is very important. A very low peak value is obtained when the stroke hits on tower 4 because the peak value of the impinging voltage at exposed cable end is strongly reduce.

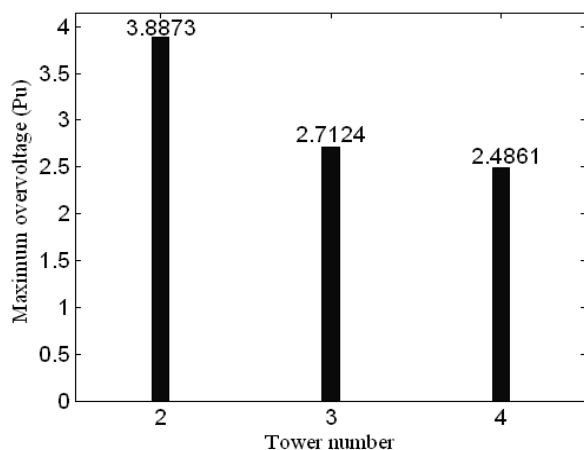


Fig -8: Maximum overvoltage as function of stroke location.

4.8 Effect of power frequency voltage

Fig.9. compares maximum overvoltage on cable with three different values of power frequency voltage (-200, 0 and 200KV). As seen from the simulation results with increasing the value of power frequency voltage, maximum overvoltage on cable decreases. The reason is that the value of the reflected wave is strongly influenced by the power frequency voltage and the maximum value of the reflected wave decreases when power frequency voltage increases.

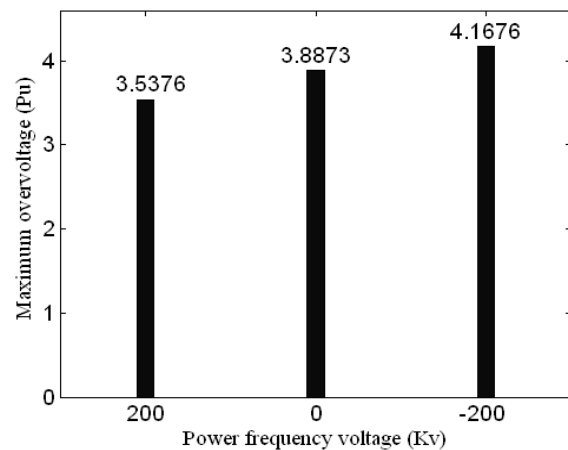


Fig -9: Maximum overvoltage as function of power frequency voltage.

4.9 Effect of surge rate-of-rise

The rate-of-rise of lightning current has significant influence on the level of maximum overvoltage at the cable and one of factors that effected on back flashover voltage. We investigated this influence with 200 KA lightning current waveform with rise times varying from 0.1 to 3 μs (0.1, 1.2, 3 μs). As seen from the simulation results presented in Fig.10. The maximum overvoltage will increase when the front time of surge decreases. It means that, increasing the front time of surge cause reduction the peak value of the impinging voltage.

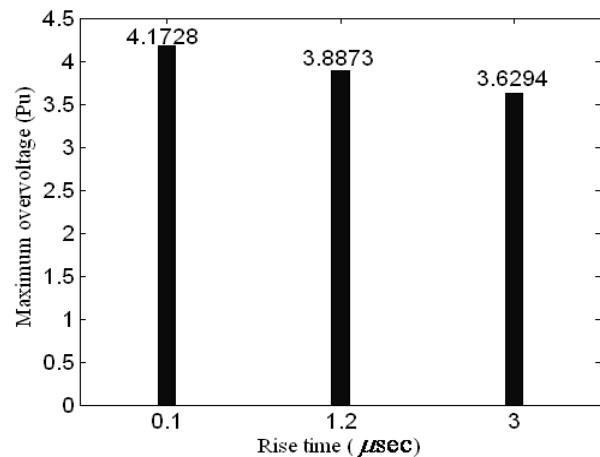


Fig -10: Maximum overvoltage as function of rise time.

4.10 Effect of arrester

Fig.11. compares maximum overvoltage on cable with and without considering arrester as function of cable length. As seen from the simulation result, maximum overvoltage on cable significantly reduced by the presence of surge arrester.

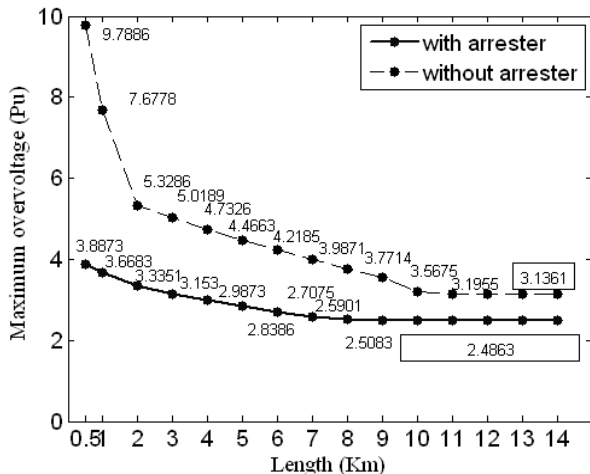


Fig -11: Maximum overvoltage as function of cable length with considering arrester and without arrester.

4.11 Effect of tower footing resistance

The tower footing resistance is one of factors that effected on back flashover voltage. During a back flashover, the major part of the stroke current flows in to ground via the over head shield wires and towers. And therefore, maximum overvoltage on the cables can be reduced by using an effective tower footing resistance. Simulation results in Fig.12. with different tower footing resistance (e.g., 10,40 and 90Ω) shown that the maximum overvoltage on cable decrease significantly when the tower footing resistance decreases. And the overvoltage stresses on the cables can be reasonably controlled for tower footing resistances of 10 Ω or lower.

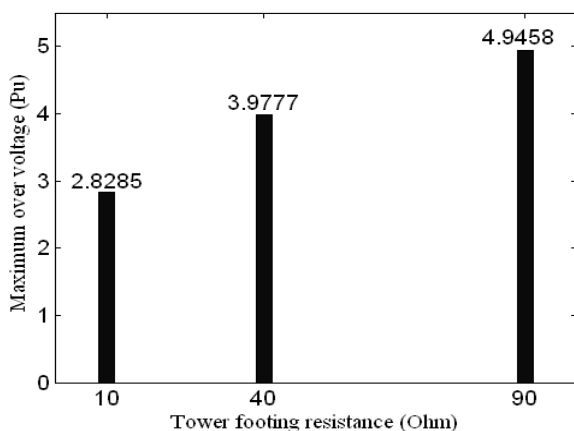


Fig -12: Maximum overvoltage as function of tower footing resistance.

4.12 Effect of thickness of sheath

Fig.13. compares maximum overvoltage on cable with three different values for thickness of sheath (e.g., 1, 2 and 3 mm).

As seen from the simulation results reducing the thickness of the sheath from 2 to 1 mm leads to a strong increase of the attenuation, where as a reduction from 3 to 2 mm has little effect. The change in the attenuation coefficient is shown in Table 4. This can be understood by considering that the dominant frequency component of the transient is about 10 KHZ. At this frequency, according to [12] the penetration depth in sheath is 2.4 mm, thus, increasing the thickness of the sheath beyond 2.4 mm will not lead to a significant change in the maximum overvoltage.

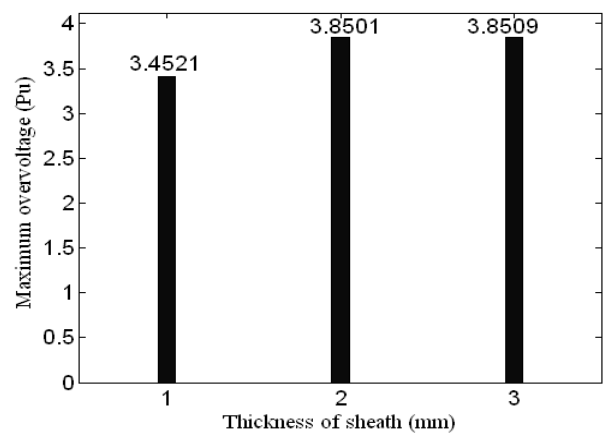


Fig -13: Maximum overvoltage as function of thickness of sheath.

Table -4: Impact of thickness of sheath on attenuation coefficient

Thickness of sheath (mm)	Attenuation coefficient (db/km)
1	0.625473
2	0.445879
3	0.445601

4.13 Effect of Relative permittivity of the insulator material outside the core

Fig.14. compares maximum overvoltage on cable with three different values of relative permittivity of the insulator material outside the core (e.g., 2.3, 4.2 and 8). As seen from the simulation results with increasing the value of relative permittivity, maximum overvoltage on cable decreases. The reason is that the attenuation coefficient was increases and causes the voltage peak value of a voltage wave transmitted along the cable are reduced.

4.14 Effect of Shunt reactors

A long AC cable will normally have shunt reactor compensation at both cable ends. Such reactors will not affect the impinging overvoltage due to their high series inductance. For a specific investigation involving a 54 km cable and 230 kV nominal voltage with 50% compensation

at each cable end, the effect of the reactors was only a 2 kV change to the maximum overvoltage.

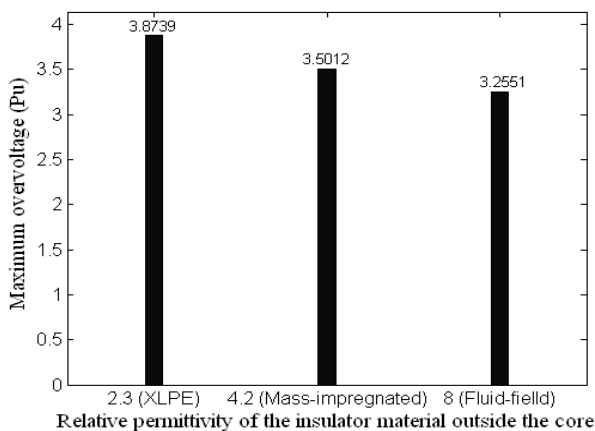


Fig -14: Maximum overvoltage as function of relative permittivity of the insulator material outside the core.

4.15 Effect of Cable joints

Cable joints can have significantly higher surge impedance than the cable and may therefore result in a higher cable overvoltage. The cable voltage increases with increasing value for the joint/cable surge impedance ratio and with increasing joint length. In practice, the joint/cable surge impedance ratio will be smaller than 1.45 and joints are usually shorter than 5 m. In order to assess the effect of joints on the cable overvoltage, calculations were done assuming 5 m joint length and 1.45 for the joint/cable surge impedance ratio the maximum voltage increase was found to be smaller than 1%.

5. CONCLUSIONS

In this paper considering from sensitivity analysis that the maximum overvoltage on cable:

- 1) Is significantly reduced by the presence of surge arresters.
- 2) Increases when increasing the grounding impedance of towers.
- 3) Increases when increasing the number of sub conductors in a bundle.
- 4) Increases when decreasing the rise time of lightning stroke.
- 5) Increases when increasing the magnitude of lightning stroke.
- 6) Decreases when increasing the length of cable.
- 7) Increases when increasing the length of arrester lead.
- 8) Increases when power frequency voltage decreases.
- 9) is strongly dependent on which tower the back flashover takes place
- 10) is reduced when decreasing the sheath thickness
- 11) is reduced when decreasing the conductivity of the sheath material
- 12) is reduced when decreasing the conductivity of the core material

- 13) is reduced when increasing the relative permittivity of the insulator material outside the core
- 14) The presence of shunt reactors and joints has only a minor effect on the maximum cable overvoltage.

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APPENDIX

A. System configuration

System that shown in Fig.1, Contain a lossless distributed parameter line model represents each span with four conductors .The two shield wires are assumed to have the same potential and they are considered as a fourth conductor. The phase conductors are at the remote end of the last span terminated by a resistance which is equal to the equivalent characteristic impedance ($z_t = 412\Omega$) when neglecting the presence of the other conductors. Each tower is represented by an inductance L . Five possible flashover locations are considered, each represented by a switch that closes when the absolute value of the voltage across the switch exceeds the voltage U_{flash} ($U_{flash} = 1000KV$).

B. Surge arrester

The arrester is modeled as a series connection of an inductance L and a non-linear static arrester characteristic. Table 5 shows the applied surge arrester current-voltage characteristic. The leads are represented by inductances based on $1\mu H/m$.

Table -5: Surge arrester current-voltage characteristic

Current(A)	Voltage(V)
0.1	0.1
500	374000
1000	388000
1500	414000
3000	430000
5000	439000
10000	463000
20000	506000
40000	589000

C. Cable

A full frequency-dependent transmission line model is used for the cable when calculating the voltage at remote end of the cable. Cable arrangement and physical data of a cable are shown in Fig.15. and Table 6.

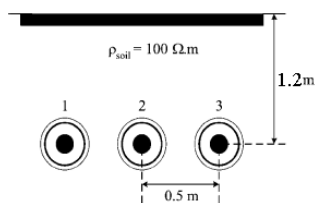


Fig -15: Cable configuration.

Table -6: Physical data of 230 KV cable

Name	Value
Inner radius of core (cm)	0.0
Outer radius of core (cm)	2.34
Inner radius of sheath (cm)	3.85
outer radius of sheath (cm)	4.13

Outer insulator radius (cm)	4.84
Core resistivity ($\Omega-m$)	$0.017 * 10^{-6}$
sheath resistivity ($\Omega-m$)	$0.21 * 10^{-6}$
Inner insulator ϵ_r	3.5
Outer insulator ϵ_r	8.0
All relative permeability μ_r	1.0
Earth resistivity ($\Omega-m$)	100
Inner insulator $\tan \delta$	0.001
Outer insulator $\tan \delta$	0.001
Length (m)	500

BIOGRAPHIES



Hamed Touthidi was born in Bam, Iran, in 1981. He received the B.S. in electrical engineering from Shahid Bahonar University, Kerman, Iran, in 2005 and the M.S. degree in electrical engineering from Shahid Bahonar University, Kerman, Iran, in 2008. His main fields of research are image processing, high voltage, electrical insulation and power system transient.



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Seyed Hossein Hosseini was born in Iran in 1961. He received the B.Sc. and M.Sc. degrees from the Electrical Engineering Department of Amirkabir University of Technology (AUT), Tehran, Iran, in 1985, and 1988, respectively, and the Ph.D. degree in the Electrical Engineering Department, University of Newcastle, New Castle, U.K., in 1995. Presently, he is a Professor of the Electrical Engineering Department at AUT. His special fields of interest include transient in power systems, power quality, restructuring and deregulation in power systems.