Maximum Lightning Overvoltage along a Cable due to Shielding Failure

Thor Henriksen

Abstract--This paper analyzes the maximum lightning overvoltage due to shielding failure along a cable inserted in an overhead line. The cable is protected by surge arresters at both ends and the maximum voltage appears normally somewhere along the cable. The maximum voltage can for severe cases of lightning overvoltages be found by calculating the voltage at a limited number (e.g. 10) of equidistant positions along the cable.

Keywords: Lightning overvoltage, shielding failure, cable, maximum voltage

I. Introduction

THIS paper considers a cable inserted in an overhead line with surge arresters at both ends of the cable as shown in Fig. 1. The cable is exposed to lightning overvoltages due to the overhead line and the maximum lightning overvoltage is an important parameter regarding the design and the level of the test impulse voltage of the cable. This problem has recently been analyzed by a CIGRE WG (B1.05). The working group has completed its report [1], but it has not been published so far. The main conclusion from the work is that the standard lightning impulse test voltages in IEC 60071-1 are in most cases more severe than the expected lightning overvoltages, in particular for long cables.

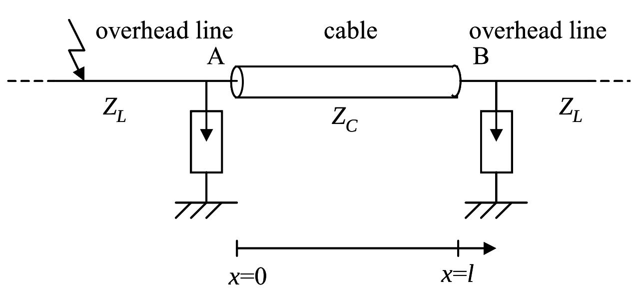

Fig. 1 Cable system

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T. Henriksen is with SINTEF Energy Research, N-7465 Trondheim, Norway (e-mail: Thor.Henriksen@sintef.no)

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The working group has analyzed in detail the overvoltages due to back-flashover. Overvoltages due to shielding failure can at a moderate cost be limited to a level below the one due to back-flashover. Those overvoltages were therefore not analyzed by the working group.

It is possible to limit the peak value of the current of strokes causing shielding failure by the design of the shield wires [2]. The purpose of this paper is to present a method for determining the maximum lightning overvoltage along the cable due to shielding failure for a given current peak value.

The method can be used to determine the peak current that causes the same maximum voltage along the cable as the one that must be expected due to back-flashover. The electro-geometrical model in [2] can then be used to determine the shielding angle that corresponds to that peak current. The shielding angle is the most important parameter when designing the shield wires.

II. Forward and Backward Voltage Wave

The voltage along the cable in Fig. 1 can be decomposed into a forward voltage wave $v_+(x,t)$ and a backward voltage wave $v\_(x,t)$. The forward wave is generated at the exposed end (x=0) and the backward wave is generated at the remote end (x=l). The maximum value of the two waves occurs at the location were they are generated. This gives the following upper limit for the voltage along the cable:

$$V_{cable\ \max} \le v_+(0,t)_{\max} + v_-(l,t)_{\max} \qquad (1)$$

Ref [3] shows that the maximum voltage in the vicinity of the remote end occurs within some kilometers from that end when considering severe cases of lightning overvoltages due to back-flashover. That maximum value is as a reasonable approximation equal to:

$$V_{\max} = v_+(l,t)_{\max} + v_-(l,t)_{\max} \qquad (2)$$

This maximum voltage must be compared with the maximum voltage at the exposed end when determining the maximum voltage along the cable.

It is based on [1] and [3] useful to point out some characteristic features of the backward wave, i.e. the wave generated due to reflection at the remote end of the cable. Fig. 2 shows the value of the reflected wave. v_(l,t) as a function of the value of the incoming wave $v_+(l,t)$.

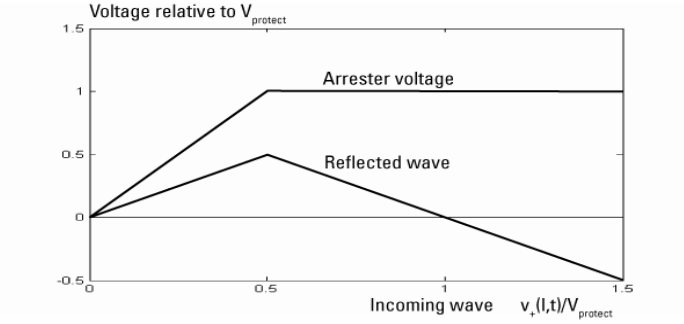

Fig.2. Reflected wave and arrester voltage as function of incoming wave

Fig. 2 is based of the following assumptions:

- The cable is lossless
- The overhead line is neglected
- The arrester has an ideal characteristic with protective level $V_{protect}$
- No ground potential rise is considered

The value of the reflected wave depends in Fig. 2 on the instantaneous value of the incoming wave only. The maximum value of the reflected and the incoming wave appears simultaneously if the peak value of the incoming wave does not exceed $0.5 \cdot V_{protect}$. The maximum voltage in the vicinity of the remote end appears then at the end of the cable.

Assuming that the incoming wave starts from zero and increases to a value well above $0.5 \cdot V_{protect}$ implies that the maximum value of the reflected wave appears before the maximum value of the incoming wave. The maximum voltage along the cable appears in this case at some distance from the remote end. This is explained in details in [3].

A rather typical shape of the reflected wave is that the maximum value is obtained after a short time followed by a rapid decay.

Fig. 2 is based on several simplifications that may have a significant influence on the reflected wave. However, the general shape of the reflected wave agrees reasonably well with the one obtained by the simplified model.

Ref.[3] shows how to determine two wave components at the remote end of the cable when applying a more sophisticated model. An example of the shape of the reflected wave can be found in Fig. 4.

III. Representative Worst Case

Lightning overvoltages exhibit considerable stochastic variations and the Monte Carlo simulation technique is in principle the most appropriate analysis method. However, limitations in the knowledge about the input data needed in such an analysis are frequently a serious problem. A simplified approach based on some worst case consideration is used to overcome this problem.

The CIGRE WG used such an approach where the stroke was assumed to hit the tower that caused the highest overvoltages along the cable. The selected time to half value of the lightning current was infinite and the front time was 1 µs. The computation was performed with three values for the peak value of the lightning current (100, 200 and 250 kA). The three values were used since it is not obvious which value is the most representative one.

The analysis of overvoltages due to shielding failure will here be based on the same assumptions as in [1] except for the following modifications: The stroke is assumed to hit the line/cable joint. This implies that there will be no flashovers. The time to half value of the lightning current is 300 µs since an infinite value may cause some unrealistic increase in the maximum overvoltage along the cable. The design of the shield wires is assumed to limit the peak value of the lightning current to at least 20 kA.

The 1 µs front time was in the case of back-flashover selected based on the rate of rise of the lightning current. A significantly lower front time is possible when the peak current is reduced to 20 kA. However, the value of 1 µs will still be used since the probability of having a smaller front time without a flashover is extremely small unless the stroke hits the line very close to the cable entrance. (The stroke location is of minor importance when there is no flashover).

The report from the WG shows that the most useful information is obtained by analyzing each particular case individually. A specific example is therefore used as a base in the work presented in this paper. This example is shown in detail in appendix A. A two-conductor model is used for the overhead line. (i.e. one phase conductor and one equivalent shield wire). It is possible to simplify this model when analyzing shielding failure without any flashover. The more complicated model was however selected because it allows a comparison with the overvoltages due to back-flashover.

IV. Impinging Voltage

The impinging voltage is the voltage at the exposed end of the cable when the incoming transient wave from the remote end (i.e. the backward wave) is neglected. It corresponds to the voltage at the exposed end for a semi-infinite cable. It is useful to consider this voltage as a first step when analyzing the maximum overvoltage along the cable.

Fig. 3 shows the impinging voltage for the representative worst case described in the section III and Appendix A. The figure covers both back-flashover and shielding failure.

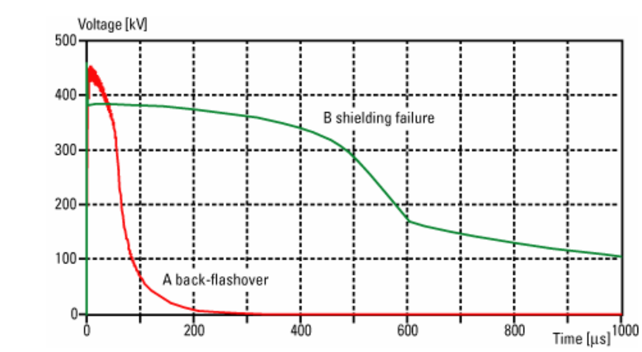

Fig. 3 Impinging voltage

The rated voltage is 145 kV. Voltage A is due to the back-flashover case. The peak value of the lightning current is here 200 kA. The peak value of the impinging voltage is 451 kV and the time to half value is about 55 µs.

Voltage B is due to shielding failure where the peak value of the lightning current is 20 kA and no flashover occurs. The peak value of the impinging voltage is 459 kV. This voltage appears more or less as a spike at the beginning and it is not possible to observe this spike in Fig. 3. It can however be seen in Fig. 4. The maximum level after the spike is 384 kV. The time to half value is about 550 µs. (The slope of the current is assumed piecewise constant and that is the reason for the distinct change in the impinging voltage at 600 µs).

The limited duration of the impinging voltage in the case of back-flashover is **not** related to the duration of the lightning current since it is assumed to have an infinite time to half value. The current hits a conductor or tower that has a galvanic connection to ground. The lightning current is therefore gradually diverted to ground and this is the reason for the decay of the impinging voltage.

The most severe overvoltages due to shielding failure occur when there is no flashover. The duration of the impinging voltage is then closely related to the duration of the lightning current. The shape of the voltage and the current is roughly the same except for the limitation of the voltage due to the surge arrester. The time to half value of the impinging voltage becomes greater than the time to half value of the current as a result of this limitation.

V. Determining Maximum Overvoltage Along the Cable

Ref [3] describes a simplified method that has shown to give sufficiently accurate results when analyzing the overvoltages due to back-flashover. The method ignores the losses between the remote end and the position of the maximum voltage in the vicinity of that end. However, experience has shown that this distance is short (typically less than 2 km). The limited duration of the impinging voltage is an important reason for this result.

The duration of the impinging voltage is much longer in the case of shielding failure and an alternative method is therefore needed. One possible approach is to calculate the maximum voltage at selected points along the cable. This method introduces in principle a discretization error both regarding the location of the peak voltage and the peak value. The spatial error is easy to control, but it is not very important. The error in the peak value is on the other hand important unless it can be kept sufficiently low.

The variation in the maximum voltage in the vicinity of the position that gives the highest voltage is moderate if at least one of the two waves has a long duration (e.g. the interval where the value is at least 98% of the peak value). The reflected wave has a short duration. However, the forward wave has a rather long duration in the case of shielding failure. It is therefore reason to assume that it is possible to determine the maximum overvoltage due to shielding failure by calculating the voltage at a limited number of positions along the cable.

VI. Computational Results Maximum Voltage

A. 4.2 km cable

This cable is rather short and the attenuation along the cable is moderate except for high frequency components. Fig. 4 shows voltage at the exposed end and the incoming and the reflected wave at the remote end. The initial spike of the impinging voltage is almost completely damped out in the forward wave arriving at the remote end. The backward wave shows a rather significant spike at the beginning.

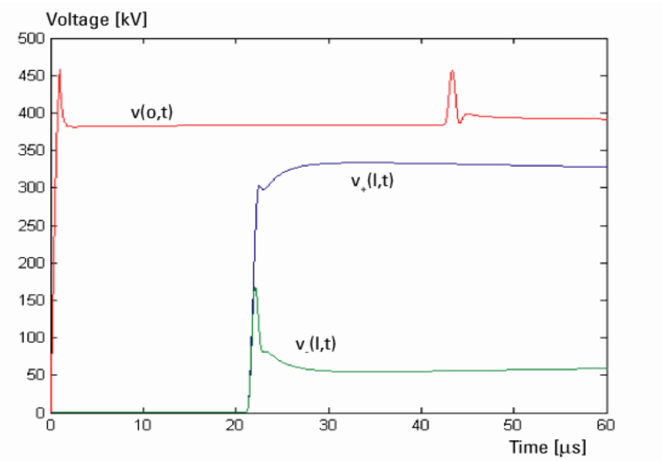

Fig.4.Voltage at exposed end and incoming and reflected waves at the remote end, 4.2 km cable

The voltage was calculated at 11 equidistant points along the cable. Fig. 5 shows the voltage at the two ends of the cable and at the point where the maximum voltage appears. The voltage at the two points adjacent to that point is shown by dotted lines. The maximum voltage appears before the forward wave is influenced by the backward wave generated at the exposed end of the cable.

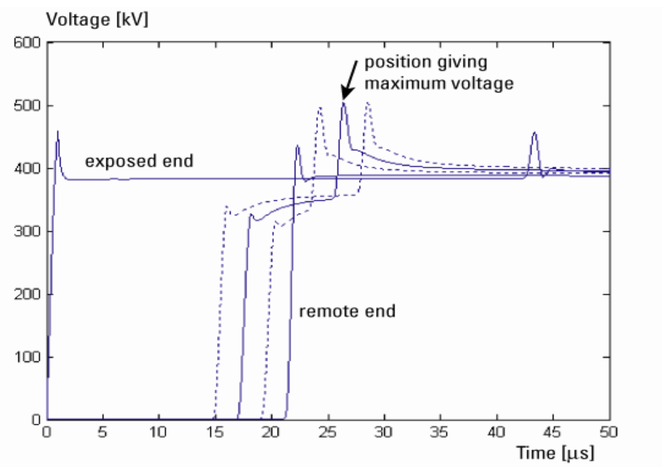

Fig.5 Voltage at cable ends and at the position with the maximum. voltage, 4.2 km cable

Fig. 6 shows the voltage profile (i.e. the maximum voltage as a function of position). The figure includes the profile due to back-flashover as well. The relative variation of the maximum voltage along the cable is much stronger in the case of back-flashover due to the shorter duration of the impinging voltage.

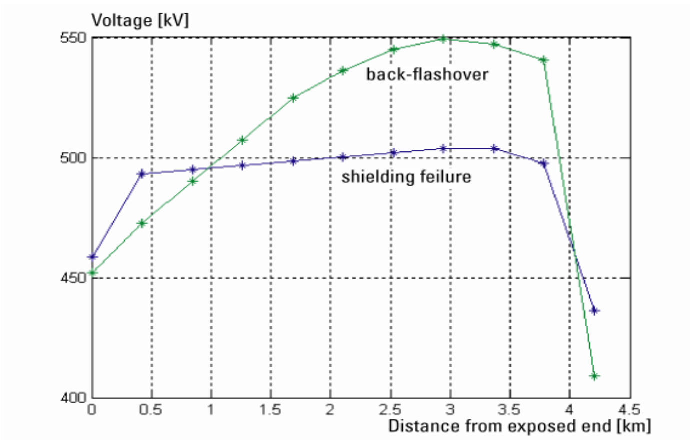

Fig. 6 Voltage profile, 4.2 km cable

B. 42 km cable

This cable is rather long and the incoming wave at the remote end is significantly reduced compared to the impinging voltage as can be observed in Fig. 7. The maximum value of the incoming wave is slightly above the value that corresponds to the maximum value of the reflected wave. This is the main reason why there is no significant initial spike in the reflected wave

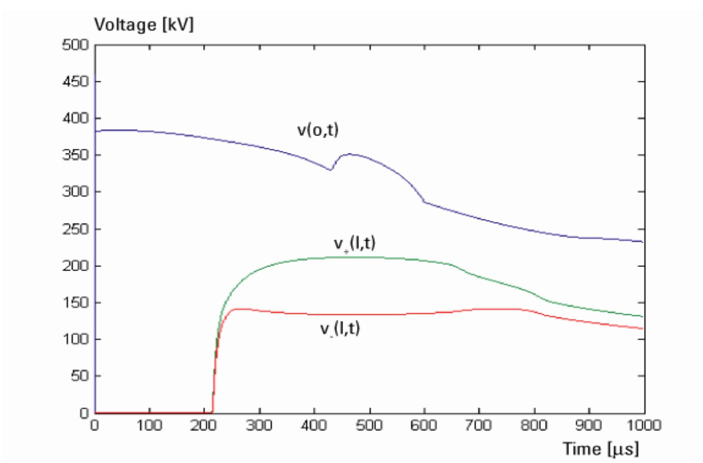

Fig.7. Voltage at exposed end and incoming and reflected waves at the remote end, 42 km cable

The voltage was calculated at 11 equidistant points along the cable. Fig. 8 shows the voltage at the two ends of the cable as well as the voltage at the location where the maximum voltage appears. The voltage at the adjacent locations is shown by dotted lines as well. The voltage at the exposed end contains at the beginning the same spike as in Fig. 5. It is however not possible to observe this spike in Fig. 7 due to the compressed time scale.

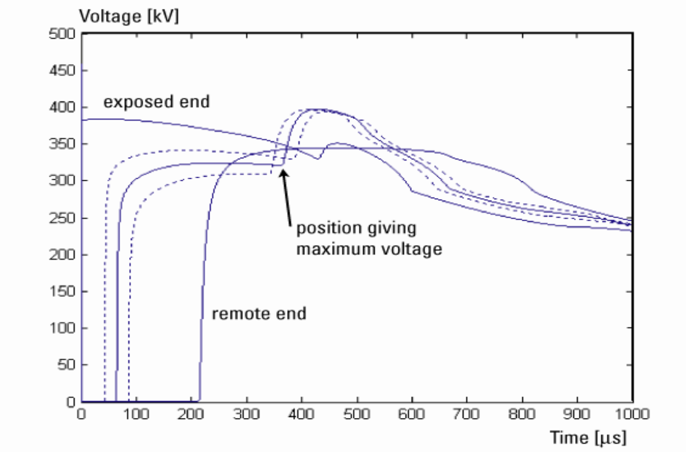

Fig.8 Voltage at cable ends and at the position with the maximum voltage, 42 km cable

The voltage profile is presented in Fig. 9 and it is seen that the position causing a maximum in the voltage profile in the case of shielding failure represents a local maxima. It is anyhow clear that the maximum voltage along the cable appears at the exposed end both during shielding failure and back-flashover

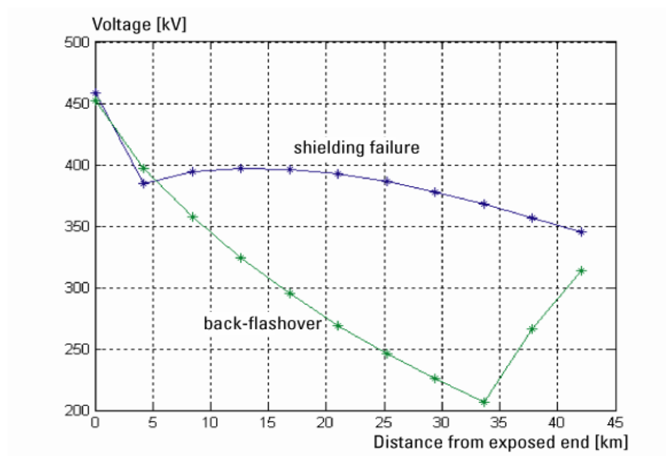

Fig.9. Voltage profile, 42 km cable

C. Other cable lengths

The results presented in sections 6.A and 6.B are obtained by calculating the voltage at selected positions along the cable. This method can due to the shape of the incoming wave at the remote end be expected to work well for any cable length between 4.2 km (section 6.A) and 42 km (section 6.B). It is further worth to note that the maximum voltage will remain constant if the length is increased above 42 km.

There is a spike at the beginning of the impinging voltage (see Fig. 4). This spike should be considered more carefully for short cables where it may contribute to the maximum value of the incoming wave at the remote end. Some additional computations showed that this occurs if the cable is less than 2.1 km. It is for shorter cables recommended to use the same method as in sections 6.A and 6.B, but also to consider (1) and (2). Eq.(2) applies to the maximum voltage in the vicinity of the remote end and the distance from the remote end can be calculated as shown in [3]. Eq.(2) is not valid when the cable is shorter than this distance. It is, however, for such cables reason to believe that the variation in the voltage profile along the cable is rather moderate. Computation of the voltage at a limited number of selected points can for such cases be expected to give a satisfactory result.

VII. LIMITING OVERVOLTAGES DUE TO SHIELDING FAILURE

A method has been presented suitable of calculating the maximum lightning overvoltage along the cable due to shielding failure for a given peak current

The maximum voltage should normally be kept below the corresponding value obtained due to back-flashover. The peak value of the lightning current causing shielding failure should, if necessary, be reduced and the computation of the maximum overvoltages repeated until the result becomes satisfactory.

The design of the overhead line should be modified in such a way that the peak value of the lightning current causing shielding failure does not exceed the value obtained in the previous point.

It is recommended to repeat the complete analysis of the lightning overvoltages based on the modified design of the overhead line.

VIII. CONCLUSIONS

The maximum voltage along the cable due to severe cases of shielding failure can be found by calculating the voltage at equidistant points along the cable. It is sufficient to use a rather limited number of points due to the long duration of the impinging voltage. The applied examples showed that a good accuracy was obtained by using 11 points.

Special attention may be needed for very short cables. It is anyhow rather easy to find an upper limit for the maximum voltage based on the forward and the backward voltage wave generated at each end of the cable.

It has been shown how to limit the overvoltages due to shielding failure below the level that can be expected due to back-flashover

IX. APPENDIX

A. Simulation Model

Fig 10 shows the basic configuration. Stroke location A and B correspond to back-flashover and shielding failure respectively. Four spans of the exposed overhead line are assumed lossless and they are represented by a two conductor distributed parameter model (phase conductor and two ground wires in parallel). The associated characteristic impedance is

$$\begin{bmatrix} Z_{ph} & Z_m \\ Z_m & Z_g \end{bmatrix} = \begin{bmatrix} 451.39 & 91.73 \\ 91.73 & 313.28 \end{bmatrix} [\Omega] \qquad (3)$$

A flashover is assumed to take place at each tower except for the tower closest to the cable entrance, when the magnitude of the voltage between the phase conductor and the tower exceeds 600 kV. The voltage drop along the corresponding towers is not taken into account, but a constant footing resistance equal 30 Ω is included as shown in the figure.

No flashover occurs in the right part of the line and the ground wires are neglected in that part of the line.

A single phase single core model is used for the cable based on the following data:

	Outer radius[mm]	Relative permittivity	Resistivity [Ω·m]
Conductor	5.6		2.01 ·e-8
Insulation	12.0	2.3	
Sheath	12.5		3.0 ·e-8

The sheath was assumed to be at zero potential and a distributed parameter frequency dependent model (JMARTI) was used in the computations that were made by the ATP version of EMTP.

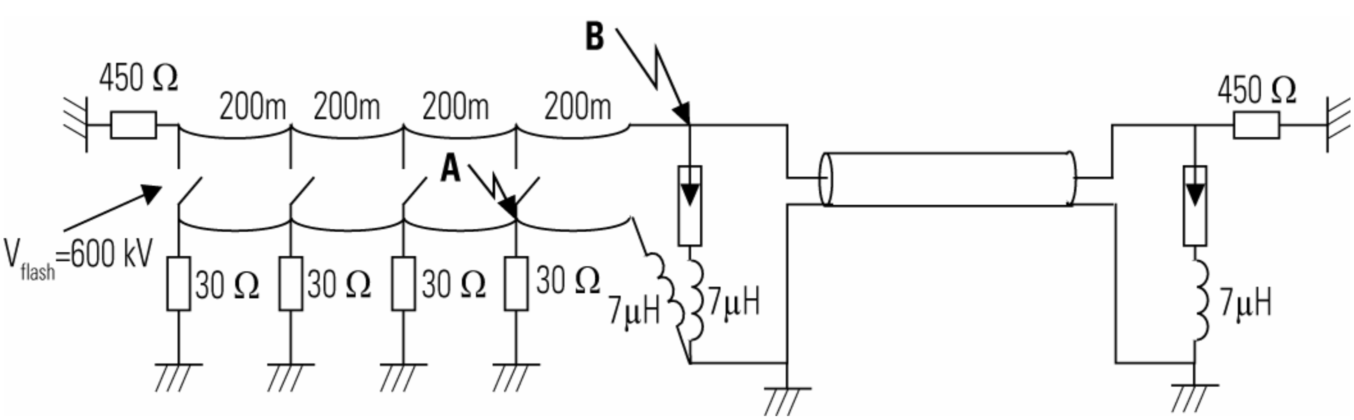

Fig.10. System configuration

The arrester characteristic is shown in Table I and the leads are represented by inductances based on 1 μH/m and 7m length.

TABLE I

SURGE ARRESTER CURRENT-VOLTAGE CHARACTERISTIC

Current [A]	Voltage [kV]
1.0000*E*–004	172.02
9.9996*E*–004	194.52
9.9981*E*–003	206.65
1.0002*E*–001	218.82
9.9991*E*–001	234.59
2.5000*E*+002	308.67
1.0000*E*+003	331.03
4.9998*E*+003	369.53
1.0000*E*+004	395.00
2.0000*E*+004	435.99

X. REFERENCES

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XI. BIOGRAPHY

Thor Henriksen was born in Trondheim, Norway in 1946. He received the M.Sc. degree in Electrical Engineering from the Norwegian Institute of Technology in 1970, and the Dr.ing. degree in 1973. He is presently working at SINTEF Energy Research Norway as a senior research scientist, mainly in the field of transient studies.