CALCULATION OF VOLTAGES INDUCED BY NEARBY LIGHTNING ON OVERHEAD LINES TERMINATED ON DISTRIBUTION TRANSFORMERS

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Abstract - Medium-voltage lines are terminated on distribution transformers. The presence of these transformers must be taken into account if one wants to obtain a realistic evaluation of lightning-induced voltages. In the paper are compared induced voltages calculated assuming one of the simplest models for the transformer, a Π of capacitance, with those calculated assuming the more complex and accurate model recently introduced by Vaessen, based on modal analysis. Laboratory measurements are carried out on a sample transformer to determine the parameters of the two equivalent circuits. After identification, the two models are used to perform calculations of lightning-induced voltages. For this purpose use is made of a computer code developed in the framework of an Italian-Swiss collaboration, which has been recently linked to the EMTP. It is shown that, in general, the overvoltages calculated using the two models are different. The authors feel that work is needed in order to select or define the model representing the best compromise between simplicity and accuracy.

1. INTRODUCTION

Although in most studies on lightning-induced voltages transmission lines have been considered infinitely long [1,2] or matched [3,4], the optimization in number and position of distribution-lines protections requires the estimation of the induced voltages for more realistic line configurations. In particular, the presence of distribution transformers and of the relevant protection devices at the line terminations, as well as the presence of the surge arresters along the line, should be considered in the simulation.

The present contribution deals with distribution transformer models. In particular, we are interested in models which permit assessing the effect of the presence of the transformer on the induced voltages.

In this respect, a common practice is to model the transformer by means of a capacitance or of a Π of capacitance, two models particularly popular. These models can be easily integrated in computer programs for lightning-induced voltage calculations (e.g. [5,6]), and this is probably one of the reasons for their popularity.

It is not clear, however, whether the adoption of more complex models and more physically reasonable (e.g. [7-12]), might result in some differences in the calculated voltages when a realistic system configuration, as shown in Fig. 1, is considered.

The aim of the paper is to assess the differences of the induced voltages calculated using a) the model constituted by a Π of capacitance and b) the model proposed by Vaessen [7], based on modal analysis.

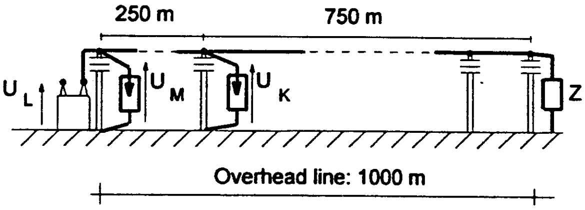

Fig. 1. Case-study system

The Vaessen model has been chosen because it is one of the models developed to better understand transient phenomena, and it gives good agreement between mesurements and theoretical predictions, though also the models described in [8,13] could have been chosen. Other models have been developed [9,12], but essentially for transformer design.

In Sect. II we shall briefly review the 'coupling' model we adopt for the calculation of the induced voltages and the computer program in which such a model is translated. In Sect. III we shall resume the main features of the two transformer models. Then we shall give the parameters of the equivalent circuits of the two models relevant to the sample transformer used for this study, which we have determined by means of laboratory measurements. In Sect. IV we shall describe the case-study system used for own analysis and discuss the results of our simulations. Sect. V will be devoted to the Conclusion.

2. CALCULATION OF LIGHTNING-INDUCED VOLTAGES ON OVERHEAD LINES

2.1. Coupling model. The voltage induced on an overhead line above a perfectly-conducting ground [1]

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[1] The ground has been assumed as perfectly conducting since we are interested essentially in the relative differences between the two transformer models considered.

by an indirect return-stroke can be calculated by means of the model by Agrawal et al. [14], which is described by the two following coupling equations (see Fig. 2 for the definition of the geometrical quantities)

$$\frac{\partial u^s(x,t)}{\partial x} + L' \frac{\partial i(x,t)}{\partial t} = E_x^i(x,h,t) \qquad (1)$$

$$\frac{\partial i(x,t)}{\partial x} + C' \frac{\partial u^s(x,t)}{\partial t} = 0 \qquad (2)$$

where

- $E_x^i(x,h,t)$ is the horizontal component of the incident electric field along the x axis at the conductor's height;
- $i(x,t)$ is the current induced along the line;
- L' and C' are the p.u. line inductance and capacitance respectively.

Equations (1) and (2) are in terms of *scattered* voltage $u^s(x,t)$. The total voltage $u(x,t)$ is given by the sum of the scattered voltage $u^s(x,t)$ and the so-called *incident* voltage

$$u^i = -\int_0^h E_z^i(x,z,t)dz \approx -E_z^i(x,0,t)\cdot h \qquad (3)$$

namely,

$$u(x,t) = u^s(x,t) + u^i(x,t) \qquad (4)$$

The boundary conditions, for resistive terminations, are

$$u^s(0,t) = -R_o\, i(0,t) - u^i(0,t) \qquad (5)$$

$$u^s(L,t) = R_L\, i(L,t) - u^i(L,t) \qquad (6)$$

The incident field appearing in (1)-(6) is given by the sum of the field radiated by the lightning channel and the ground reflected field, both considered in absence of the wire.

For the calculation of the incident field, one of the available return-stroke current models can be adopted, as discussed in [15].

The Agrawal model has been shown to give reasonably good agreement between theory and experimental measurements [6,16].

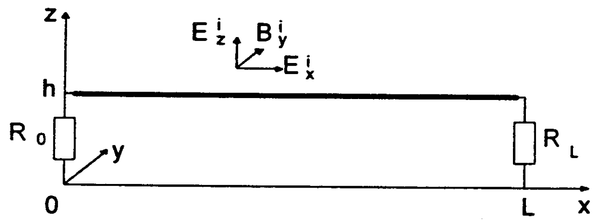

Fig. 2- Geometry used for the calculation of overvoltage induced on an overhead power line by an indirect lightning return-stroke

2.2. Coupling program. The above equations have been translated into a a coupling program, developed within the framework of an Italian-Swiss research collaboration [4].

The program, named LIOV (lightning-induced overvoltages), allows to calculate the induced voltages starting from the channel-base current. The latter is used to calculate the lightning electromagnetic field assuming the MTL return-stroke current model [17]; the electromagnetic field is then used to calculate the induced surges using the Agrawal coupling model.

The program was originally developed to deal with the case of a line with resistive terminations. In principle, the LIOV program can be suitably modified case by case in order to take into account the presence of the specific type of termination, or of the line-discontinuities (e.g. surge arresters across the line insulators along the line). This procedure, as discussed in [6], requires that the boundary conditions for the transmission-line coupling equations be properly re-written case by case. Therefore, it has been considered more convenient to link the LIOV program to the EMTP [18], leaving to the EMTP the task of solving the boundary conditions, in relation to the discontinuities and terminal conditions of the line [19]. In this way, all the models contained in the EMTP library become available for a more accurate evaluation of lightning-induced voltages. Further, as discussed in [19], the new code is particularly convenient for simulations of the type presented in the paper, namely for the case of overhead lines terminated on complex terminations.

3. THE TWO TRANSFORMER MODELS CONSIDERED.

In this section we give the details of the equivalent circuits relevant to the two transformer models mentioned in the Introduction. For each case, we will first summarize the theoretical background of the model, and then we will give the numerical values of the circuit parameters.

The latter have been determined by means of experimental measurements on a single-phase sample transformer of 40kVA rated power and 16/0.4 kV voltage ratio.

3.1. The Π-circuit model. As mentioned earlier, in lightning-induced voltage calculations, distribution transformers are frequently modelled by means of a Π-circuit of capacitance, as shown in Fig. 3.

In it, one can identify the capacitance bewteen the MV terminal and ground C_M, the one between the LV terminal and ground C_L, and the capacitance between the MV and LV terminals C_{LM}.

C_M, C_L and C_{LM} can be inferred from the values of the three following capacitance:

1) the capacitance between the MV terminal and the ground when the MV winding is short-circuited and the LV winding is short-circuited and connected to ground (which gives C_M in parallel

with C_{LM});

2) the capacitance between the LV terminal and the ground when the LV winding is short-circuited and the MV winding is short-circuited and connected to ground (which gives C_L in parallel with C_{LM});
3) the capacitance between the MV and LV terminals when both MV and LV windings are short-circuited and connected together (which gives C_M in parallel with C_{LM}).

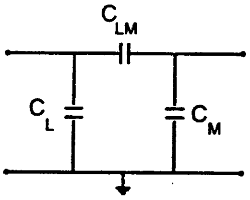

Fig. 3. The Π-circuit model

Although, the three capacitances are sometimes measured at industrial frequency, we have measured them at the frequency of 100 kHz, considered more adequate for our problem.

The results inferred from the above measurements are the following: $C_L = 0.645$ nF, $C_{LM} = 0.395$ nF, and $C_M = 0.255$ nF.

3.2. The Vaessen model. The model presented by Vaessen in 1988 [7] is based on modal analysis.

For a no-load transformer, the proposed expression for the transfer function $H(j\omega)$ and the input impedance function $Y(j\omega)$ in the frequency domain are the following [7]:

$$H(j\omega) = \frac{V_2}{V_1} = \gamma - \sum_{k=1}^{M} A_k \frac{\omega_k^2}{\omega_k^2 - \omega^2 + j\omega 2\delta_k} \qquad (7)$$

$$Y(j\omega) = \frac{I_1}{V_1} =$$

$$= \frac{1}{R_0} + \frac{1}{j\omega L_0} + j\omega C_0 + \sum_{k=1}^{M} j\omega C_k \frac{\omega_k^2}{\omega_k^2 - \omega^2 + j\omega 2\delta_k} \qquad (8)$$

where:

γ is the capacitive transformation ratio;
M number of the resonance frequencies;
A_k is the amplitude of the k-th mode shape at this terminal;
$\omega_k = 2\pi f_k$, where f_k is the k-th resonance frequency;
δ_k is the k-th damping factor.

The values for R_0, L_0 and C_0 are relevant to iron-losses, no-load inductance and input capacitance respectively. In this study the first two quantities have been disregarded, while C_0 is 1nF.

The modal parameters of the model described by (7), (8), are determined from the measured transfer function and admittance (see [7] for further details).

The equivalent circuit proposed by Vaessen, which transforms the modal model into an electric network suitable for EMTP [7], is shown in Fig. 4.

To identify the parameters of the Vaessen model, the transformer have been excited by means a 0.2/0.5 μs impulse voltage, with a crest value of 65 V, applied at the high-voltage terminal.

The values of the Vaessen model parameters, which result from processing the measured data, are given in Table I.

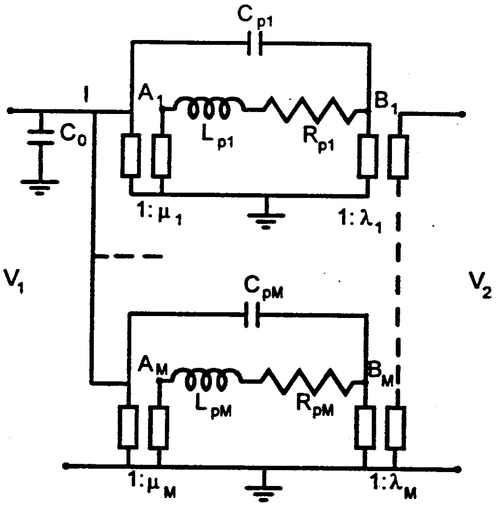

Fig. 4. Equivalent EMTP-circuit for the Vaessen model.

Table I. Parameters of the EMTP circuit for the Vaessen model.

k	f_k [kHz]	R_{pk} [Ω]	L_{pk} [mH]	C_{pk} [nF]	μ_k	λ_k
1	240	4695	10.8	0.0406	-6.54	0.007
2	312	8000	31.8	0.0081	2.82	0.007
3	423	3425	4.65	0.0304	0.597	0.007
4	735	4760	6.31	0.0074	-0.854	0.007
5	869	7860	11.7	0.0029	-1.85	0.007
6	1163	5000	11.4	0.00166	1.77	0.007
7	1247	2857	3.8	0.0043	2.09	0.007
8	1428	2777	3.7	0.0034	1.96	0.007

4. NUMERICAL SIMULATIONS AND DISCUSSION.

4.1. Case study system. We consider a 1 km-long, 10 m-high, overhead distribution line terminated at one end on a distribution transformer protected by a surge arrester. The other end of the line is matched. A second surge arrester is located at 250 m from the MV terminal of the transformer (see Fig. 1).

The incident electric field appearing in (1)-(6) is calculated using the MTL return-stroke current model [17], assuming a return-stroke velocity of 1.5×10^8 m/s, a decay constant $\lambda = 2$km[2], and a channel-base current with a peak-amplitude of 50 kA and a maximum front steepness of 43 kA/μs.

We assume that the differential coupling among the three phases of the distribution line is negligible, so that the line can be studied as single-phase.

The surge arresters, is modelled as a non-linear

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[2] The MTL model has been shown to reproduce, with reasonable approximation, fields from natural and triggered lightning [15].

EMTP element with the V-I characteristic shown in Table II.

Table II. Assumed non-linear characteristic of the surge arrester

I [A]	V [kV]
0.0015	34.7
0.002	43.3
0.01	48.5
0.1	51.9
1	55.5
5 000	79.1
10 000	85.0
20 000	94.4

We consider two stroke locations: stroke location A (equidistant from the overhead line terminations and at 50 m from the line center) and stroke location B (at 50 m from the transformer along the direction perpendicular to the line).

4.2. Simulation results. The calculated voltages for the two considered stroke locations are shown in Figs. 5 (stroke location A) and 6 (stroke location B). Those predicted by assuming the Vaessen model are reported in the left-side column of both figures, while those obtained making use of the Π-model are shown in the right-side column. For each case, the voltages at three different positions along the line are shown: at both sides of the transformer (points M and L in Fig. 1), and 250 m far from it (point K in the same Figure).

When no surge arrester is considered in the simulation, the difference in the voltages resulting from the use of the two different models is quite evident. By using the Π-circuit model, the maximum value of the voltage at points along the MV line is about 1.5 times bigger than that of the same voltage calculated using the Vaessen-model, and this independently of the stroke location. Note, also, that the voltage at point M calculated using the Vaessen model exhibits two 'bumps', contrary to the voltage predicted by using the Π-circuit, which are due essentially to the inductances present in the equivalent circuit of the Vaessen model. On the LV side, always neglecting the presence of the surge arresters, the ratio between the two voltages increases up to about 23.

The presence of one or two surge arresters acts in decreasing these differences (in this case, clearly, the voltage at point M is practically independent of the adopted transformer model). However, at the LV side, even when two surge arresters are considered in the simulation, some differences can still be observed: the ratio between the maxiumum values of the induced surges is of the order of 10 (stroke location A) or 7 (stroke location B).

5. CONCLUSIONS

The overvoltages calculated using the two transformer models examined in the paper (Π-circuit, and Vaessen, respectively) differ. This means that the simple model of a Π network of capacitance is probably not adequate for the problem of interest. These differences, however, are smoothed by the presence of the protection devices relevant to the transformers.

The simulations have been carried out considering a no-load configuration, according to the Vaessen model used in the paper. Extension of the results presented here to loaded transformers is of importance.

The authors feel that work is needed in order to select or define a model representing the best compromise between simplicity and accuracy.

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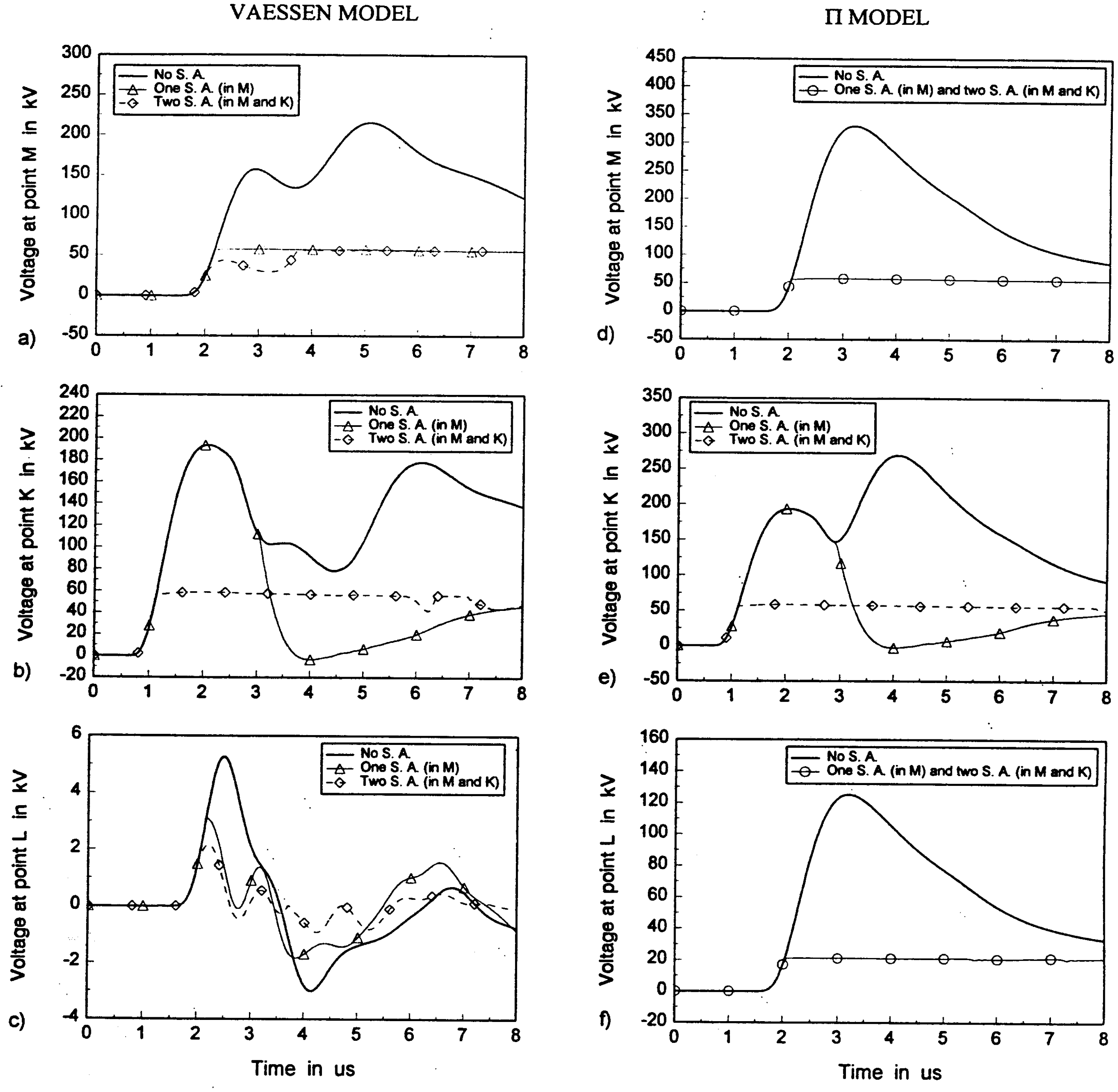

Fig. 5. Induced voltages calculated at three different positions (M, K, L of Fig. 1) making use of the two transformer models: Vaessen (a, b, c) and Π (d, e, f). (Stroke location A: equidistant from line termination and at 50 m from the line center).

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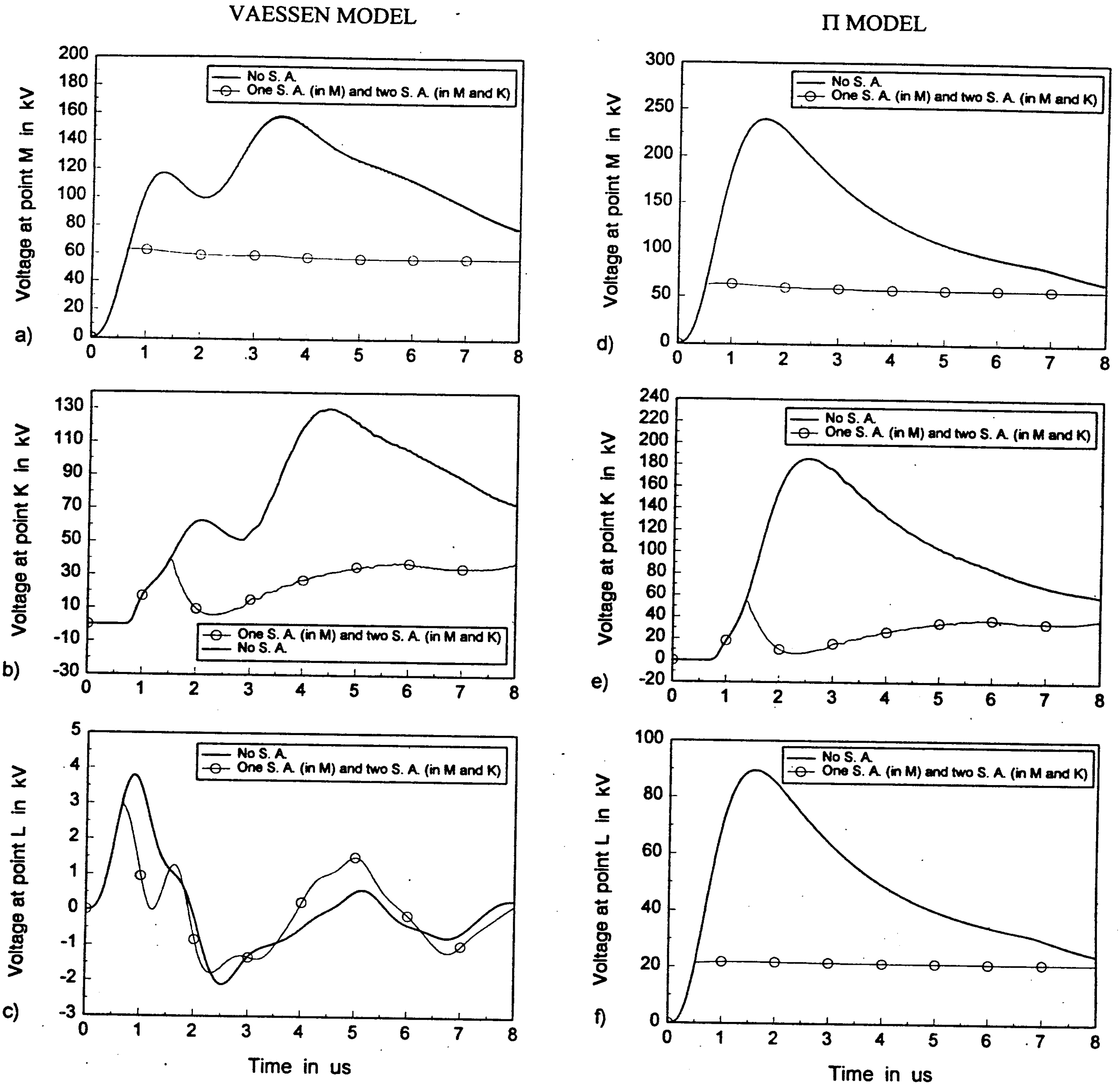

Fig. 6. Induced voltages calculated at three different positions (M, K, L of Fig. 4) making use of the two transformer models: Vaessen (a, b, c) and Π (d, e, f). (Stroke location B: at 50 m from the transformer, along the direction perpendicular to the line).

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