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OVERVOLTAGES IN POWER TRANSFORMERS CAUSED BY NO-LOAD SWITCHING

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Abstract - When an unloaded power transformer is switched on via a relatively long cable, sometimes extreme high voltages appear at the secondary side of the transformer. These overvoltages are caused by a resonant phenomenon that occurs when the resonant frequencies of the transformer and the cable match. The resonant frequency of the cable feeder is equal to the reciprocal of 4 times its travel time τ. The resonant frequency of the transformer is determined by its short-circuit inductance and the capacitance which is connected to the secondary winding. In this paper a model of this phenomenon is presented and an example of this resonant phenomenon, leading to the insulation breakdown at the secondary side of a power transformer, is given.

Keywords: Switching Transients, Power Transformers, Cables, Resonant Phenomena.

INTRODUCTION

Damages to power transformers are unwelcome since continuity in power delivery may be seriously disrupted. Furthermore repair or replacement is expensive and time consuming. An example of an unknown silent killer of transformers is the switching on of unloaded transformers via a cable feeder. When the resonant frequencies of the cable feeder and transformer match, very high voltages may appear at the secondary terminals of the transformer. This can damage the insulation of the transformer winding, and finally lead to a flashover from winding to core. This occurred in one of the 120 MVA, 150/50 kV transformers situated in a Dutch steel company. Shortly after switching the power transformer on the 150kV grid, which is the regular procedure, the circuit breaker received a trip command from the transformer protection. The Buchholtz relays operated, and so did the distance protection from the utility serving the 150kV grid, since an earth fault was detected. Inspection of the transformer showed winding-insulation damage caused by a flashover between one of the 50kV phase windings and the transformer core. After a preliminary study, internal (ferro)resonance was disqualified as the originator of the problem. In addition, calculations taking the polespread of the 150 kV SF6-puffer circuit breaker into account did not lead to the expected overvoltages between the 50 kV winding and the core with a peak value of at least 320kV. Fig. 1 shows the topology of the relevant part of the network. The cable feeder consists of three 3 km long single-phase cables.

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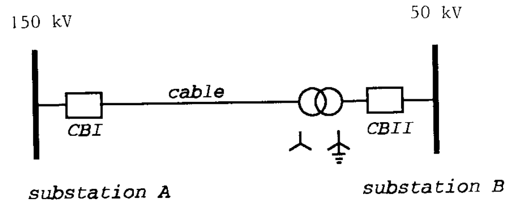

Figure 1: Cable-transformer connection

MATHEMATICAL MODEL

Upon modeling the 3-phase transformer, both the inductive and capacitive properties have to be considered. The inductive model as described in [1] is used. The necessary parameters can be calculated from factory data. For the description of the capacitive properties of transformers, several approaches are presented in the literature [2,3,4,5]. These papers introduce extended models of transformers. However, the calculation of transient phenomena is limited to severe overvoltages due to lightning discharges. For our purpose, the model as described in [2] will be used. In this model, the primary, secondary and cross-over capacities of transformer windings are concentrated at each end of the relevant winding or windings. The value of the capacitors in the model is half the value of the winding capacitances that can be measured. The schematic diagram of an Yy-transformer, where the neutral point of the secondary winding is grounded, is shown in Fig. 2.

Compared with the extended models, this model is very simple and therefore gives only information of the terminal voltages of the transformer. Very high frequency oscillations inside the transformer, which strongly depend on the type of windings can not be studied. On the other hand capacitor data, available from consumer tests, which include all internal para-

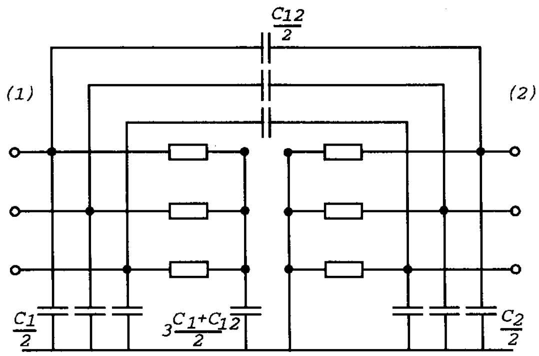

Figure 2: Three-phase model of Yy-transformer

sitic and bushing capacities related to the transformer terminals, can be obtained in a relatively simple way. When the transformer is switched on the 150 kV grid by the circuit breaker, initially the leakage field of the high voltage winding is excited. Subsequently the exciting current increases slowly to the magnetizing current of the main flux. The latter current is described by an exponential function with a time constant which is the sum of the eddy current flux time constant of the core and the ordinary time constant of the field coil proper. The value of this time constant is in the order of $20 - 50\mu s$, depending on the core material used [7,8]. The transformer saturation will play a neglectable role in the frequency phenomena studied and is therefore not taken into account in the model.

With this model, the switching transients are calculated. By assuming a balanced three-phase voltage at the input terminals of the transformer, the single-phase or positive-sequence diagram as in Fig. 3 is obtained. R_S and L_S are the short-circuit resistance and inductance as seen from the primary side. The ideal transformer in Fig.3 represents only the transformer ratio n. In Fig. 3 the capacities C_I , C_T and C_0 are introduced as short notation.

$$C_I = C_1/2; C_T = C_{12}/2; C_0 = C_2/2$$

From Fig. 3 the following equations in the time-Laplace domain can be derived:

$$\begin{aligned} u_1 &= (R_S + pL_S)i_1 + u_2' \\ i_{CT} &= pC_T(u_1 - u_2) \\ i_{C0} &= pC_0u_2 \\ i_{CT} &= i_2 + i_{C0} \\ i_2 &= -ni_1 \quad u_2' = n.u_2 \end{aligned} \tag{1}$$

With $R_S = 0$ the ratio u_2/u_1 can be calculated :

$$\frac{u_2}{u_1} = \frac{C_T}{C_T + C_0} \cdot \frac{p^2 + \omega_1^2}{p^2 + \omega_2^2} \tag{2}$$

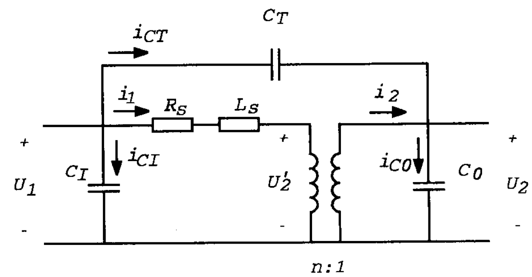

Figure 3: Single-phase equivalent model of Yy-transformer

where

$$\omega_1 = \frac{1}{\sqrt{nL_{S,SEC}C_T}} \qquad \omega_2 = \frac{1}{\sqrt{L_{S,SEC}(C_T + C_0)}}$$

$L_{S,SEC}$ is the short-circuit inductance related to the secondary winding of the transformer($L_S = n^2 L_{S,SEC}$).
Given the primary voltage:

$$u_1(t) = \hat{e}\cos\omega t$$

which, in the Laplace-domain, corresponds to

$$u_1(p) = \hat{e}\frac{p}{p^2 + \omega^2}$$

the secondary voltage becomes

$$u_2(p) =$$

$$\frac{\hat{e}C_T}{C_T + C_0} \cdot \left[\frac{\omega_1^2 - \omega^2}{\omega_2^2 - \omega^2} \cdot \frac{p}{p^2 + \omega^2} - \frac{\omega_1^2 - \omega_2^2}{\omega_2^2 - \omega^2} \cdot \frac{p}{p^2 + \omega_2^2}\right] \tag{3}$$

From relation (3) it is already clear that when $\omega = \omega_2$ the amplitudes of the power-frequency part with frequency ω and the transient part with frequency ω_2 becomes infinite in theory. In practice the power frequency is always much lower than the resonant frequency of the transformer. However, the frequency of the transient, which depends on the properties of the cable feeder, is normally much higher and may meet this constraint.
The feeder cable consists of three single-phase cables. These cables can be modeled by π-elements or, more acurately, by surge-impedances. The velocity v of a wave over the cable feeder can be written as:

$$v = \frac{1}{\sqrt{LC}}$$

where L and C are the inductance and capacitance per unit length.
Note that the inductance L is not the inductance measured or calculated for power frequency, but the inductance for transient frequencies. Given the cable capacitance C, L can be calculated from the foregoing formula, since the velocity of waves through cables

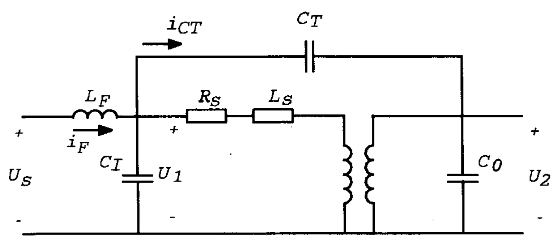

Figure 4: One-phase equivalent of Cable-Transformer-Cable system

is approximately half the speed of light [6].
The angular frequency of the transient is

$$\omega = \frac{2\pi}{4\tau} = \frac{\pi}{2.l.\sqrt{LC}}$$

The angular frequency of one π-element is

$$\omega = \frac{1}{l.\sqrt{LC/2}}$$

The frequency of the transient and the frequency of the π-element match when taking instead of C:

$$C' = \frac{8}{\pi^2}.C$$

In Fig. 4 the transformer is connected to the feeder cable. The cable is represented by one π-element, where $C_I = C_1/2 + C'.l/2$. Note that C_I differs from C_I used in Fig.3.
The secondary capacitor $C_0 = C_2/2 + C_C$, where C_C represents the total capacitance of the cable connected to the secondary winding of the transformer. The additional equations (4) are depicted in Fig. 4.

$$\begin{aligned} u_S &= pL_F i_F + u_1 \\ i_F &= i_{CI} + i_{CT} + i_1 \\ i_{CI} &= pC_I u_1 \end{aligned} \qquad (4)$$

From (1) and (4), the ratios u_2/u_S and u_1/u_S can be derived. When the transformer resistance R_S is ignored, the ratio u_2/u_S is:

$$\frac{u_2}{u_S} = \frac{C_T(p^2+\omega_1^2)}{a(p^4+bp^2+c)} \qquad (5)$$

where

$$a = L_F\{C_I(C_0+C_T)+C_0C_T\}$$

$$b = \frac{L_F\{n^2C_I + C_T(n-1)^2 + C_0\} + L_S(C_T+C_0)}{aL_S}$$

$$c = \frac{n^2}{aL_S}$$

The ratio u_1/u_S is calculated as:

$$\frac{u_1}{u_S} = \frac{(C_T+C_0)(p^2+\omega_2^2)}{a(p^4+bp^2+c)} \qquad (6)$$

These expressions are simplified, when it may be assumed that $C_I \gg C_T$ and $C_I \gg C_0$. The longer the cable feeder is, the more this is true. The constants a,b,c become

$$a = L_F C_I (C_0 + C_T)$$

$$b = \omega_F^2 + \omega_2^2$$

$$c = \omega_F^2 \omega_2^2$$

with

$$\omega_F = \frac{1}{\sqrt{L_F C_I}}$$

In this case, the ratios can be written as:

$$\frac{u_1}{u_S} = K_1 \frac{p^2+\omega_2^2}{(p^2+\omega_F^2)(p^2+\omega_2^2)} = \frac{K_1}{p^2+\omega_F^2} \qquad (7)$$

$$\frac{u_2}{u_S} = K_2 \frac{p^2+\omega_1^2}{(p^2+\omega_F^2)(p^2+\omega_2^2)} \qquad (8)$$

with

$$K_1 = \frac{1}{L_F C_I} = \omega_F^2$$

$$K_2 = \frac{C_T}{C_T + C_0}\omega_F^2 = \frac{\omega_F^2\omega_2^2}{n\omega_1^2}$$

For the determination of the maximum voltage, that can be observed when the transformer is switched on, a sinusoidal source voltage is assumed at the front end of the feeder cable, i.e.:

$$u_s(p) = \hat{e}\frac{p}{p^2+\omega^2}$$

The voltages at the primary and secondary terminals of the transformer become:

$$u_1 = \frac{K_1 \hat{e} p}{(p^2+\omega_F^2)(p^2+\omega^2)} \qquad (9)$$

$$u_2 = \frac{K_2 \hat{e} p (p^2+\omega_1^2)}{(p^2+\omega_F^2)(p^2+\omega_2^2)(p^2+\omega^2)} \qquad (10)$$

When is taken into account that $\omega \ll \min\{\omega_F, \omega_1, \omega_2\}$, the time-domain voltage signals become:

$$u_1(t) = \hat{e}\,(\cos\omega t - \cos\omega_F t) \qquad (11)$$

$$u_2(t) = \frac{\hat{e}}{n}\,(A\cos\omega t - B\cos\omega_F t - C\cos\omega_2 t) \qquad (12)$$

where

$$A = 1$$

TABLE I
SYSTEM PARAMETER DATA

Parameter	Value
Transformer rated power	$120\ MVA$
Rated voltage	$150/50\ kV,\ Yy$
Rated frequency	$50\ Hz$
Short-circuit inductance $L_{S,SEC}$	$10.9\ mH$
Primary capacitance C_1	$0.8\ nF$
Secondary capacitance C_2	$3.4\ nF$
Cross-over capacitance C_{12}	$2.4\ nF$
Cable Feeder (primary)	$150\ kV, 400\ mm^2$
Length	$3.273\ km$
Resistance $R(50Hz)$	$0.066\ \Omega/km$
Capacitance C	$0.26\ \mu F/km$
v_{surge}	$158.10^3\ km/sec.$
Inductance L	$0.154\ mH/km$
Cable (secondary)	$50\ kV, 2*400\ mm^2$
Lenght	$12.5\ m$
Capacitance C	$0.63\ \mu F/km$
C_I	$0.344\ \mu F$
C_T	$0.0012\ \mu F$
C_O	$0.01745\ \mu F$

$$B = \frac{1 - \frac{\omega_F^2}{\omega_1^2}}{1 - \frac{\omega_F^2}{\omega_2^2}} \tag{13}$$

$$C = \frac{1 - \frac{\omega_2^2}{\omega_1^2}}{1 - \frac{\omega_2^2}{\omega_F^2}}$$

The maximum possible voltage at the secondary terminals of the transformer follows from these expressions, by taking the sum of the absolute values of the separate terms. This leads to:

$$u_{1,max} = 2\hat{e} \tag{14}$$

$$u_{2,max} = \frac{\hat{e}}{n}(|A| + |B| + |C|) \tag{15}$$

CALCULATIONS AND RESULTS

For model calculations, data of the damaged transformer and the cables connected as given in table I are used as an illustration.
From these we calculate with $f_x = \frac{2\pi}{\omega_x}$:

$$f_F = 12.1\,kHz, \quad f_2 = 11.1\,kHz, \quad f_1 = 25.4\,kHz.$$

For these values of f_F and f_2, resonance can be expected. This is confirmed by the value of $u_{2,max}$ (15), which becomes:

$$u_{2,max} \;=\; 3.73\,\hat{e} \;=\; 455\,kV$$

The separate coefficients are:

$$A = 1,\ B = -4.6,\ C = 5.6$$

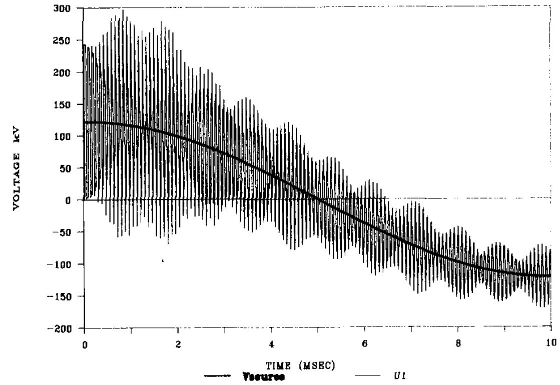

Figure 5: Primary transformer voltage, secondary cable: 12.5m

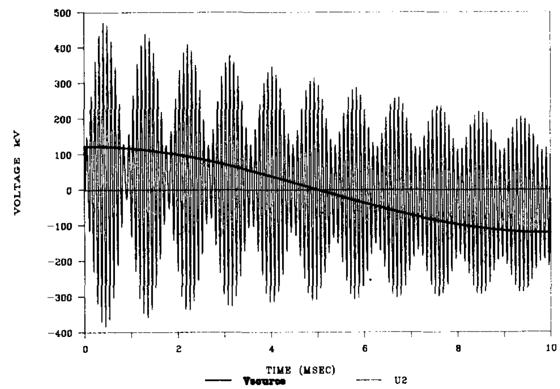

Figure 6: Secondary transformer voltage, secondary cable: 12.5m

To verify of this solution, three-phase computations have been made using the transformer model in Fig. 2. This model contains, besides the capacities and the winding resistances all self and mutual inductances of the three phase transformer.
The cable feeder in the three-phase model is a distributed line. The worst-case situation occurs in phase A, since the voltage in phase A is at maximum when the transformer is switched on. Figs. 5 and 6 show phase A of the calculated terminal voltages at the primary and secondary of the transformer, as well as the source voltage. From Fig. 5 it can be seen that the amplitude of the primary voltage is higher than calculated with the simple expressions (14) and (15). The influence of the secondary frequency can also be observed at the primary side. However, the amplitude of the secondary terminal voltage u_2 agrees well with the simple calculation. The secondary voltages in phases B and C stay below $200kV$.
From the analytical expression for the voltages, it is clear that this resonant phenomenon can be avoided by changing one oor both of the frequencies f_F and f_2. Since the secondary cable is much shorter under these circumstances, changing the length of this cable is the most effective and inexpensive alternative.

Upon enlarging the length of the secondary cable

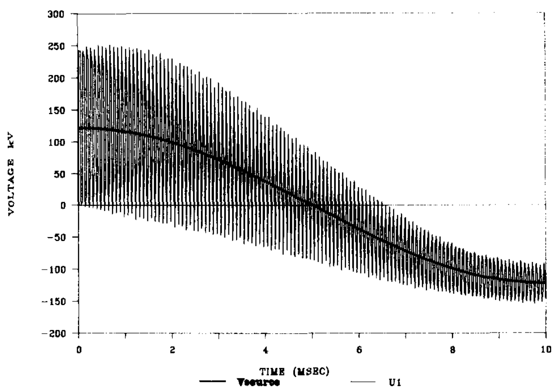

Figure 7: Primary transformer voltage, secondary cable: 25m

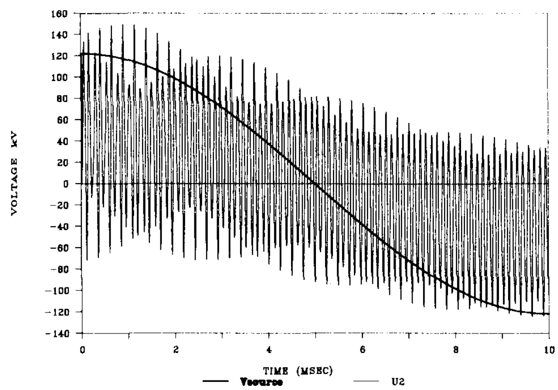

Figure 8: Secondary transformer voltage, secondary cable: 25m

twice we calculate:

$$C_0 = 34.4nF,\ f_2 = 8.22kHz.$$

which yields

$$B = -0.69,\ C = 5.6,\ u_{2,max} = 1.12\,\hat{e} = 137.2kV$$

In Figs. 7 and 8, the result of the three-phase calculation is given.
Extending the cable to four times its original length gives:

$$C_0 = 65.9nF,\ f_2 = 5.94kHz,$$

$$B = -0.25,\ C = 1.25,\ u_{2,max} = 0.83\,\hat{e} = 101.8kV$$

which tends toward a normal situtation, where two times the secondary peak voltage is about $82kV$. Figs. 9 and 10 present the result of computer simulations. From this picture and the analytical calculations, it is clear that at the primary side of the transformer the transient has the frequency f_F and at the secondary side f_2. In case of resonance both frequencies show up at each side.

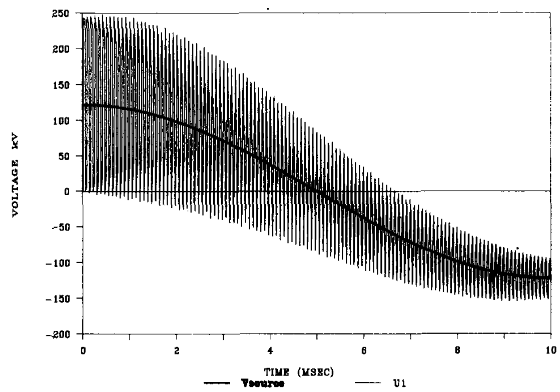

Figure 9: Primary transformer voltage, secondary cable: 50m

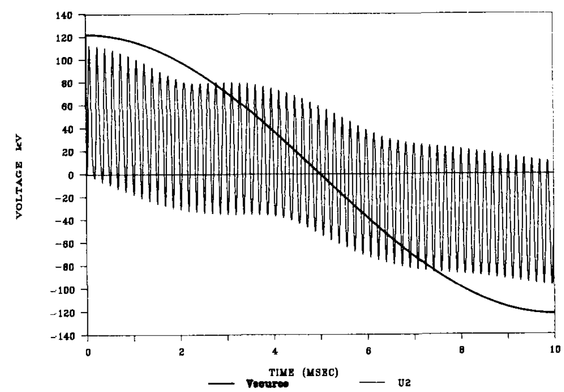

Figure 10: Secondary transformer voltage, secondary cable: 50m

CONCLUSIONS

Not only overvoltages due to lightning discharges, but also overvoltages caused by switching can cause high overvoltages at transformer terminals. When an unloaded transformer is switched on via a cable feeder with a critical length, overvoltages can appear at the secondary terminals of the transformer which reach several times the peak value of the primary voltage. The critical length of the connected cables is determined by the travel time or the resonant frequency of the primary cable and the resonant frequency of the transformer and secondary cable. Therefore, with the help of elementary parameters from the transformer, namely the short-circuit inductance and the winding capacitances, and the capacitances of the cables connected, a potentially critical situation can be predicted with relatively simple formulas. Measures to avoid critical situations consist of changing the values of the cable capacitances. This can be done by either changing the length of the cables or in case of low secondary nominal voltages, by the installation of extra capacitors at the secondary terminals. Finally the installation of surge arrestors at the secundary terminals of the transformer can be considered.

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BIOGRAPHIES

Gerardus Chr. Paap (SM'92, M'90) was born in Rotterdam, the Netherlands, on February 2, 1946. He received his M.Sc. degree from Delft University of Technology in 1972, and his Ph.D. degree from the Technical University of Lodz in 1988.

Since 1973 he has been with the Department of Electrical Engineering at Delft University of Technology. From 1973 to 1985, he was with the Division of Electrical Machines and Drives, where he lectured on the fundamentals of electrical machines; since 1985 he has been
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Dr. Paap's main research interests include power system transients and the dynamics of electrical machines.

Abraham A. Alkema was born in Marrum, the Netherlands, on December 17, 1962.
He recieved his M.Sc. degree from Delft University of Technology in 1991. Since that time he has been with the IJsselmij Utility.

Lou van der Sluis (SM'86) was born in Geervliet, the Netherlands on July 10, 1950. He obtained his M.Sc. degree in Electrical Engineering from Delft University of Technology in 1974. He joined KEMA's High-Power Laboratory in 1977 as a test engineer and has been involved in the developement of a data acquisition system for the High-Power Laboratory, computer calculations of test circuits and analysis of test data by digital computer.

Since 1990 he has been part-time professor in the Power Systems Laboratory at Delft University of Technology. At present his main research interest is arc-circuit interaction of power-circuit breakers in the electrical grid, the study of transient recovery voltages and the application of neural networks in Power Systems.

Discussion

C. S. Indulkar (Dept. of Electrical Engg., Indian Institute of Technology, New Delhi, India and **M. S. Thomas** (Dept. of Electrical Engg., Delhi College of Engg., Delhi, India): We congratulate the authors for their excellent paper on Transformer Switching Transients. The paper is easily understandable and the presentation is very clear.

We have done some studies on Transformer switching transients and also on the effect of having cables and lines connected to the transformer on the transformer transients. In the light of our works, we would like to have some clarifications.

1. The present paper takes a simple model with the primary, secondary and crossover capacitances of the transformer windings concentrated at each end of the relevant winding. Is such a model enough to handle the complicated transformer transients accurately? From our studies, we have found that for a 350 MVA, 230/138 KV transformer, 10 sections/phase gives accurate transient waveforms.
2. It is mentioned that this model only gives information about terminal voltages of the transformer. But for the transformer insulation design, the transient voltage distribution along the windings are equally important. Can the authors specify how their existing model could be modified for this purpose?
3. The transformer considered is a star/star 3-phase transformer, which is one of the most commonly used winding connections. Can the model developed by the authors handle other transformer connections, like star/delta, delta/star and delta/delta?

We would be grateful if the authors could clarify the above points.

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G. C. PAAP, A. A. ALKEMA, L. VAN DER SLUIS: The authors would like to thank Prof. C.S. Indulkar and Dr. M.S. Thomas for their kind comments on the paper and the interest they have shown in it.

In reply to their questions we would like to start with the comment that the aim of this study was to identify dangerous transformer switching transients. In order to be able to explain a serious accident, which took place in the Dutch steel works, we started with a simplified model of a cable-transformer-cable connection.

In this particular case the model can explain the high overvoltages at the secundary side of the transformer which is connected with a short cable. The available cable and transformer data are used as input parameters for our simplified model. A preliminary studie with a more complex model as decribed in [5] has been used to verify the frequencies of the transients. These frequencies match with the resonant frequencies of the model used in the paper.

We agree with the discussers that for accurate transient waveforms more complex models should be used. In particular for the calculation of the transient voltage distribution along the windings. In stead of the simple model we use, these extended models, [2], [3] and [5], can also be implemented in electromagnetic transient programs. However, in that case much more transformer data are necessary.

In the paper a star-star connection is considered. However, for our simplified model, all other transformer connections including grounded neutral points can be handled in the same way by taking the lumped stray capacitances at each side of the transformer windings into account.

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