Improved Calculations for No-Load Transformer Switching Surges

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***Abstract*—This paper deals with a modeling of components and calculation of transient overvoltages that build up on the transformer primary terminals after the transformer has been switched off by a vacuum circuit breaker (VCB). The transformer is connected to the circuit breaker by a cable. The transient overvoltages are calculated for different cable lengths, and the cumulative probability of different arc angles is investigated.**

In this study two cases are considered: transient overvoltages due to steady-state magnetizing current switching, and transient overvoltages due to inrush current switching. It is shown that the case of inrush current switching is worse, as virtual current chopping is possible. The cable is modeled by pi sections, whereas the transformer model is based on a terminal impedance. The VCB re-ignitions are modeled by means of withstand voltage characteristics and high-frequency quenching capability. Due to shortage of field tests, this work uses only literature references to compare the results with actual measurements.

***Index Terms*—Modeling, overvoltage, transformer, VCB.**

I. Introduction

THE LATEST developments in vacuum switching technology, vacuum processing and a new kind of contact material development are the reasons why vacuum switching devices are now widely applied. The main characteristics of these devices are: safety, quiet action, high reliability, low maintenance, small size and little weight. Especially the application of the VCBs to protect power distribution circuits has increased, and it is likely that VCBs will be the dominant technology in the first two decades of the 21st century.

However, some problems exist, especially when small inductive currents are to be switched. Transients with high overvoltages can occur when the current is chopped before the natural current zero at short arc angles. An arc angle is defined as the time interval between the opening of the VCB and the natural current zero.

At short gaps, the withstand voltage is small, and therefore a small transient recovery voltage (TRV) is needed for a re-ignition to occur.

Re-ignitions can lead to voltage escalation in the network containing many high-frequency components that cause the load side to show different behavior at different frequencies. Therefore, when modeling the re-ignition behavior and calculating the TRV significant efforts should be made not only for the VCB model, but also for the load side models of cables, motors or transformers.

The first maximum and the rate of rise of the TRV depend largely on current chopping. The magnitude of the chopping current determines the likelihood of the first re-ignition. This becomes clear when dealing with small inductive current switching in relation to the unstable arc burning around current zero. The chopping current is a parameter that has been extensively studied and the latest generation of VCBs have significantly reduced the mean chopping current level [12], [18]. In three-phase circuits the situation is more complicated because of the capacitive and inductive coupling of the load. The re-ignited high frequency current from one phase can be superposed on the load current in the other phases by means of the mutual coupling. The total current, which consists of the power frequency and the high-frequency component, can be chopped. This phenomenon is known as virtual current chopping (VCC) [11], [19], [20] and is a reason of high overvoltage generation.

The interruption of large nonlinear inductances, like transformers under no-load, are generally considered less of a problem. The amplitude of the magnetizing current is much lower than the VCB chopping level, so the current is chopped immediately. Transformer losses represent a large damping coefficient which reduces the theoretical maximum value significantly. The interruption of inrush currents can be very serious as it is a possible source of VCC. The maximal values of the generated overvoltages can become as high as 8 times the value of the transformer rated voltage.

This paper is a more detailed analysis of the switching of transformer under no-load. The switching of transformer magnetizing currents and inrush currents is studied, and the cumulative probability of the occurrence of overvoltage is calculated for the studied case.

II. Modeling the System Components

A. Modeling Re-Ignitions

The model that will represent the re-ignition phenomenon must take into account the chopping current, the cold withstand voltage and the behavior of a vacuum arc at high frequencies.

The chopping current is a parameter that has already been studied by several researchers. A number of formulas have been proposed for the estimation of the mean chopping level. Smeets [14] proposed an expression that calculates the mean chopping level. The value of the chopping current mainly depends on the contact material, but it also depends on the type of load and the characteristic impedance of the circuit that is switched.

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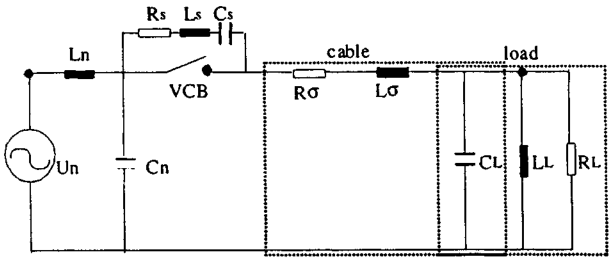

Fig. 1. Test circuit for re-ignition modeling.

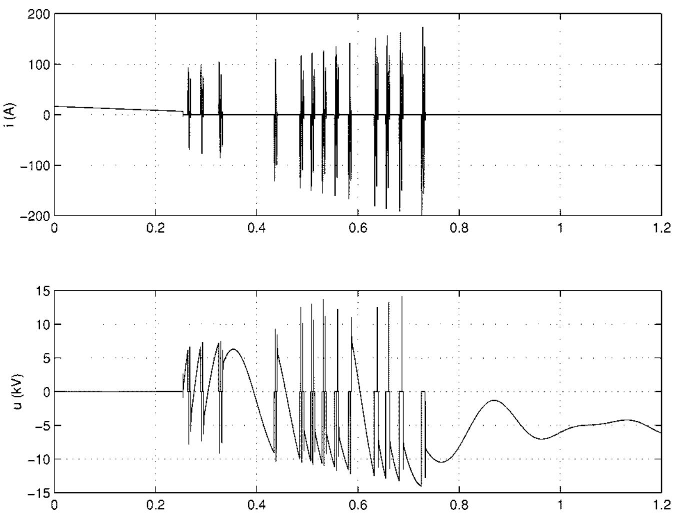

Fig. 2. Re-ignited current and voltage across the VCB.

The withstand capability of VCB is another parameter that influences the re-ignited overvoltage. The withstand voltage mainly depends on the contact distance. In many cases this characteristic can be considered linear. If a re-ignition occurs, a high-frequency current flows through the VCB. This current will be quenched if the slope of the high-frequency current is lower than the critical current slope. The critical current slope is also a characteristic that depends on the VCB. The research on these characteristics reported by Glinkowski, *et al.* [2] and Glinkowski and Greenwood [3] fully represents the VCB behavior at short gaps up to 1 mm. We analyzed the re-ignition behavior on a simple circuit shown in Fig. 1 and used the approach of [7], [21] for modeling the VCB.

The results of the calculation are shown in Figs. 2–4. Fig. 2 shows the current and voltage across the VCB, whereas Fig. 3 shows the current and voltage of the load. The complete description of the first re-ignition after chopping is given in Fig. 4. After the VCB contacts have opened, the current decreases to a value which is determined as the chopping current. Thereafter, the TRV is applied resulting in two different oscillations. Its frequencies depend on the type of load circuit. The first frequency is in the range of a few MHz, and it is determined by the capacitance of the cable and the load, the source side capacitance (in this case $C_n \gg C_L$), the capacitance of VCB gap, the cable inductance and the parasitic inductance of the gap. This frequency can be approximately calculated by means of the expression:

$$f1 \approx \left(2\pi\sqrt{L_\sigma \frac{C_S C_L}{C_S + C_L}}\right)^{-1}. \tag{1}$$

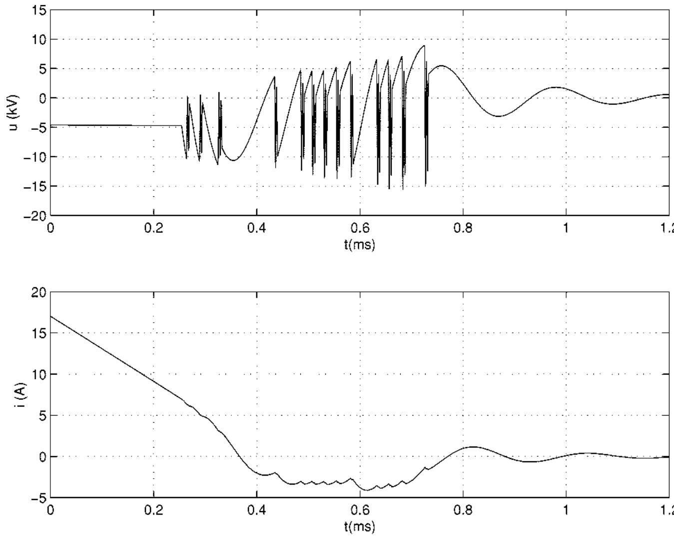

Fig. 3. Voltage and current of the load.

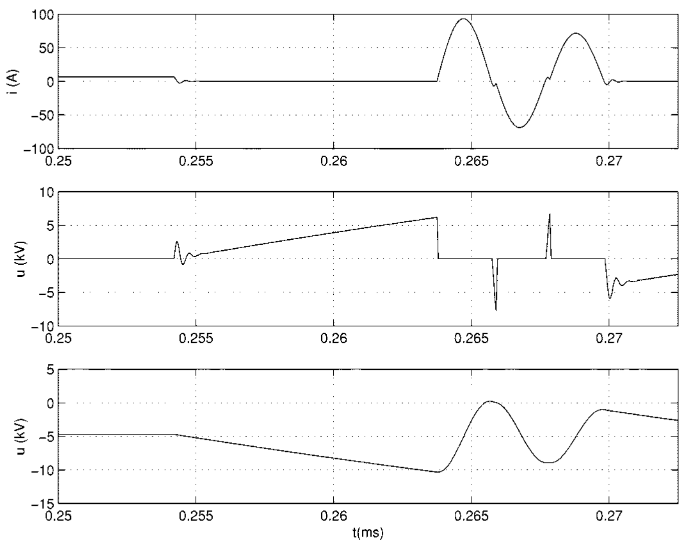

Fig. 4. VCB current, voltage and load voltage of the first re-ignition.

The second frequency component of the voltage is much lower and depends on the load parameters. This is the natural frequency of the load and its value is in the range of kHz. It is estimated as:

$$f2 \approx \left(2\pi\sqrt{L_L C_L}\right)^{-1}. \tag{2}$$

When the TRV has become greater than the withstand voltage of the gap, the VCB re-ignites. This is followed by a high-frequency current flow through the VCB. The re-ignited current contains two high-frequency components and one power frequency component. The first has a value of:

$$f3 \approx \left(2\pi\sqrt{L_\sigma C_L}\right)^{-1}. \tag{3}$$

The other high-frequency component is due to the parasitic capacitance and the inductance of the gap:

$$f4 \approx \left(2\pi\sqrt{L_S C_S}\right)^{-1} \tag{4}$$

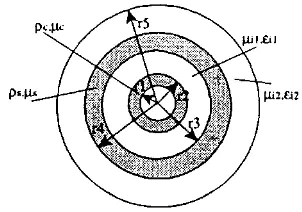

Fig. 5. Cross section of one phase of the cable.

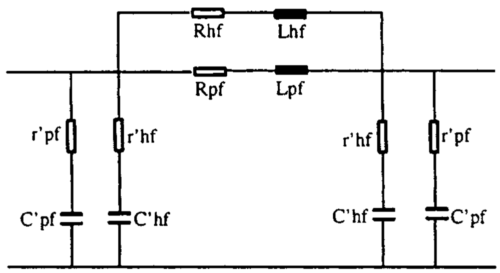

Fig. 6. Cable pi section.

and it is in the range of a few tens of MHz. Measurements [13] show that the VCB switching can cause additional high-frequency components at high-frequency current zero. If these high-frequency components are to be taken into account, their characteristics must be measured in a great detail and very small time steps must be used in the calculations.

B. Cable Modeling

The cable we used in our calculation is a three-phase 20 kV cable without an external shield. The cross section of one phase is shown in Fig. 5.

The parameters of the cable are calculated by means of ATPs Cable Constants and the cable itself is modeled by pi sections, as shown in Fig. 6. Each pi section has a length of 1 m. The cable dielectric losses are included by using its $\tan\delta$ at power frequency and at frequency of 1 MHz. In order to test the validity of the applied model, we calculated the frequency response of the impedance of one phase of the cable and compared it with the frequency response calculated by the ATP J-MARTI frequency-dependent Cable Constants and Cable Parameters routine. Figs. 7 and 8 show the dependence of the impedance amplitude and the phase angle versus the frequency. It can be seen that there is good agreement between the ATP calculation and the applied model and measurements [6]. It should be pointed out that the mutual coupling in the cable model does not contain a loss component. This is very hard to determine due to the influence of the cable shields.

C. Transformer Modeling

Having shown that the re-ignition of VCB causes electromagnetic transients in a wide range of frequencies, we must take these frequencies into account by using a transformer model, just as we did for the cable. If no re-ignition in the system occurs, however, the electromagnetic transients are in the low-frequency domain, and the unloaded transformer behaves as a reactor which is strongly nonlinear. This nonlinearity is the result of the magnetic saturation and transformer hysteresis. Furthermore, due to the saturation, inrush currents can occur when the transformer is energized. They can reach values a few times higher than the transformer rated current. Switching off the inrush currents can lead to VCC. When the transformer is switched off, a re-ignition may or may not take place. The first case requires the wide frequency transformer representation. At high frequencies, for fast flux variations, the saturation and hysteresis of the transformer core can be neglected. The second case requires only the saturation and hysteresis [23], [24]. In order to calculate the electromagnetic transients accurately, one should consider the residual flux, because of its influence on the generation of overvoltage.

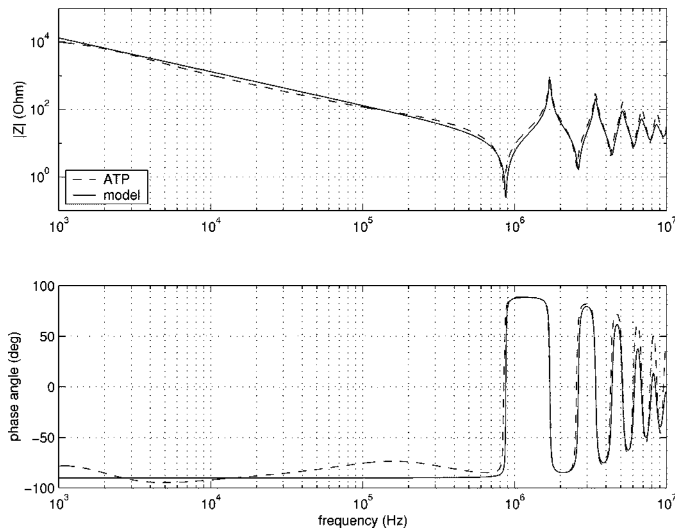

Fig. 7. Frequency response of the impedance absolute value and phase angle with the receiving end open.

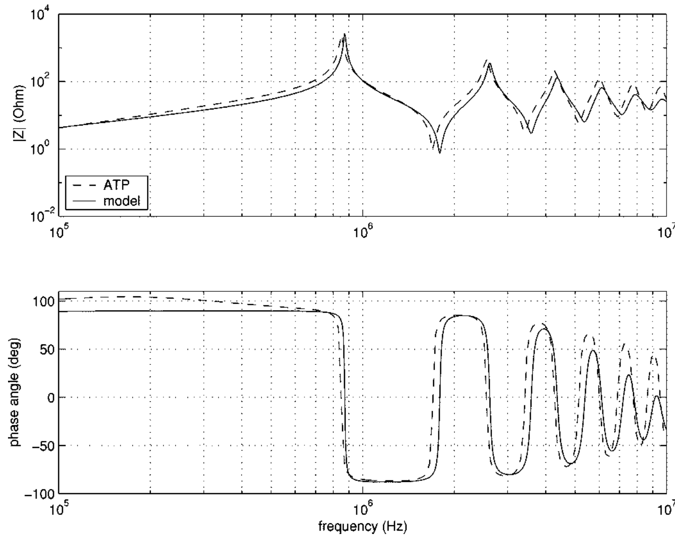

Fig. 8. Frequency response of the impedance absolute value and phase angle with the receiving end short circuited.

A terminal impedance characteristic gives enough information about the frequency response of transformers and rotating machines. Such tests were performed by Soysal [15], and he shows that when a transformer secondary winding is open, the presence of an iron core affects the frequency response below 100 kHz considerably as it shifts the resonant frequencies and

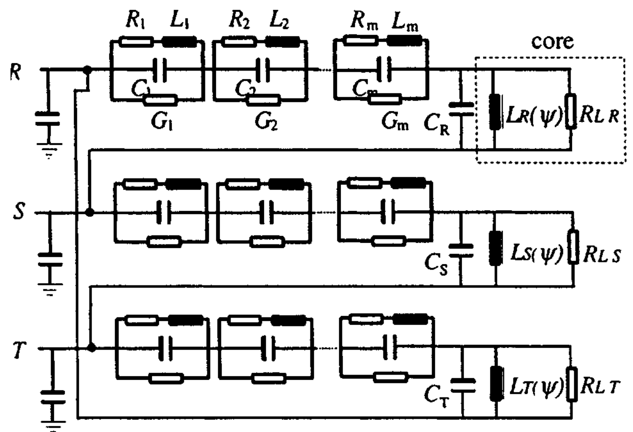

Fig. 9. Representation of the transformer in a wide range of frequencies.

increases the magnitude of the impedance. In our study, we model the transformer by using the saturation in one of the Foster sections of terminal impedance, as can be seen from Fig. 9.

The reason for including the saturation is that it is important to take into account the inrush currents at energization. If a re-ignition occurs while the transformer is switched off, it is no longer the magnetizing branch that is dominant, but the transformer winding described by RLCG Foster sections. The terminal impedance can be expressed as:

$$Z(s) = \frac{V(s)}{I(s)} = \frac{a_0 s^m + a_1 s^{m-1} + \cdots + a_{m-1}s + a_m}{b_0 s^n + b_1 s^{n-1} + \cdots + b_{n-1}s + b_n} \quad (5)$$

where $m = n - 1$. If we consider that $s = j\omega$ then:

$$Z(j\omega) = \sum_{i=1}^{n/2} \frac{\beta_i \delta_i + \alpha_i \gamma_i \omega}{\delta_i^2 + \gamma_i^2} + j \sum_{i=1}^{n/2} \frac{\alpha_i \delta_i \omega - \beta_i \gamma_i}{\delta_i^2 + \gamma_i^2} \quad (6)$$

where $\delta_i = \sigma_i^2 + \omega_i^2 - \omega^2$ and $\gamma_i = 2\sigma_i \omega$. Thus, the problem consists of the solution of $2n$ nonlinear equations and the determination of the same number of unknown parameters, namely $\alpha_i, \beta_i, \sigma_i$ and ω_i. Each pair of these four parameters determines one RLCG Foster section. Expression (6) represents two nonlinear equations for each selected value of the frequency ω. Each impedance amplitude characteristic contains $n/2$ maximum and $n/2 - 1$ minimum. So we need only one more condition, which is normally taken from the impedance characteristic at power frequency. In order to provide the necessary parameters, one must measure the characteristics of the transformer. The solution of the equations is provided by Newtons method [1]. The equations are rather complex and if the initial solutions are too far from the exact solution, the convergence might fail. Therefore, the intervals should be investigated where the roots of the equations might be. According to [4], reducing the value of σ_i in (6) makes the peak of the characteristic sharper, whereas increasing ω_i moves the peak to the right. Furthermore, a change of α_i changes the vertical scale of the characteristic. By such adjustments it is possible to select equivalent circuit component values to provide a response that closely matches any measured peak. Having estimated the parameters, the Newton's method can be used to minimize the error.

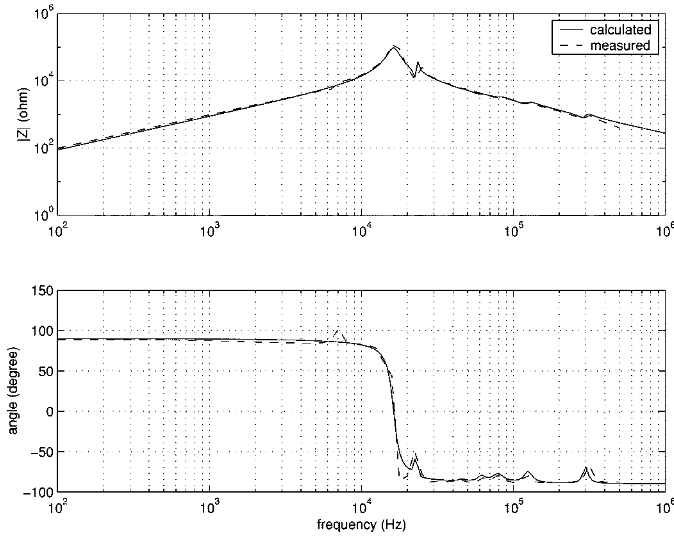

Fig. 10. Comparison of the calculated transformer absolute value and phase angle with the measurements.

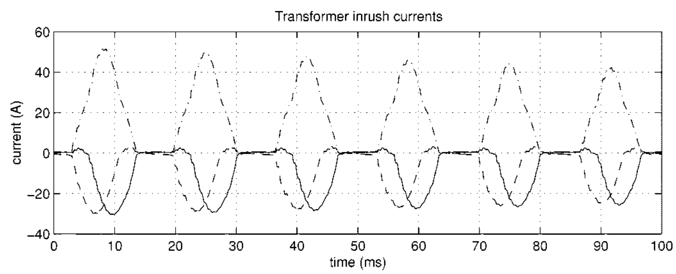

Fig. 11. Calculated transformer inrush currents.

The validity of this approach is shown for a generator step-up transformer Yd5, 144 MVA, 230/16 kV. The calculated characteristic is modeled by 7 Foster sections with a total number of 24 parameters; the results of the calculation are shown in Fig. 10.

The model of transformer that will be used in our study will consider only the saturation that has an influence when the transformer is energized [22]. The model resulting from this approach will only provide information about the primary side overvoltages. To obtain the transformer secondary side responses more data are needed and the model should consider the cross-over capacitance of the transformer. In our calculation the terminal impedance characteristic of [16] is used.

The re-ignition in one phase through the mutual transformer and cable capacitances can be superposed on the currents in the other phases which have not cleared the arc yet. Whether or not a VCC will occur depends on the amplitude of the power frequency arc current and the re-ignited current. Therefore it is important to know the accurate variation of the transformer currents. The calculated inrush currents and steady-state magnetizing currents are shown in Figs. 11 and 12.

III. Calculation of the Transformer Switching Overvoltages

The applied models of the system components are included in the circuit depicted in Fig. 13. The rated system voltage is 13.8 kV, 60 Hz. The source side circuit contains busbars which

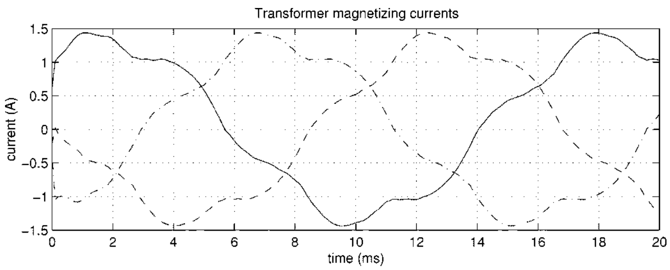

Fig. 12. Calculated transformer magnetizing currents.

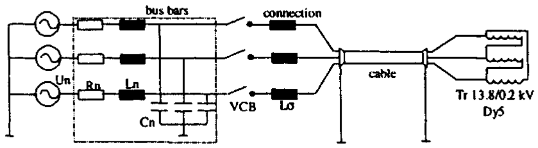

Fig. 13. System configuration for transient analysis.

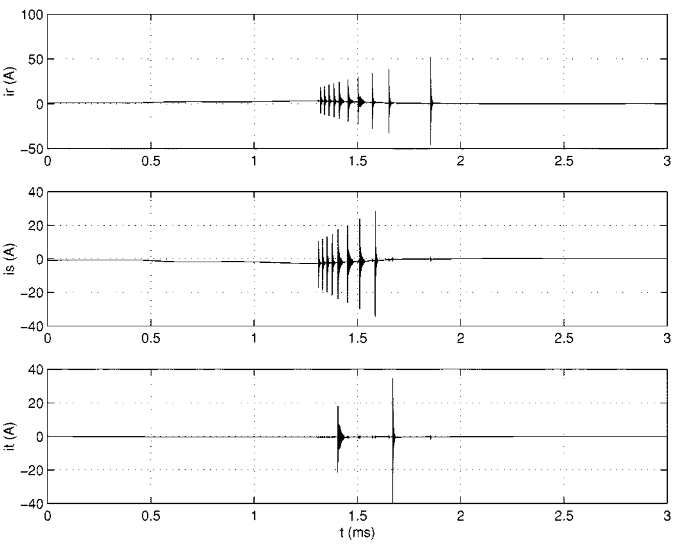

Fig. 14. Line currents at transformer terminals.

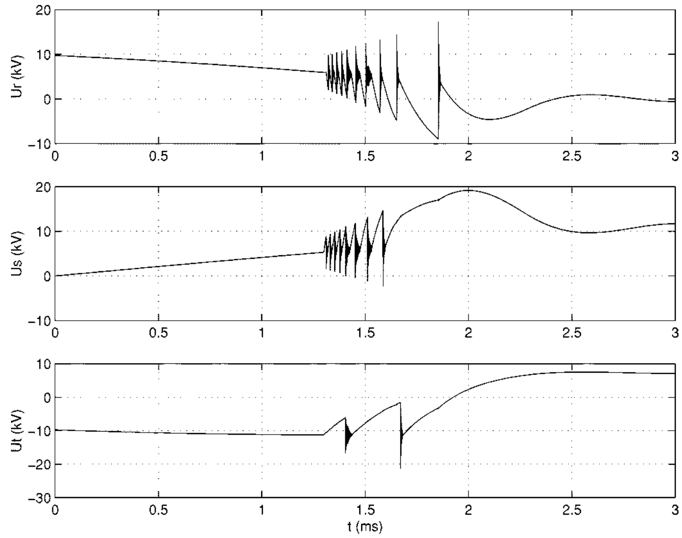

Fig. 15. Transformer terminal voltages—magnetizing current switching.

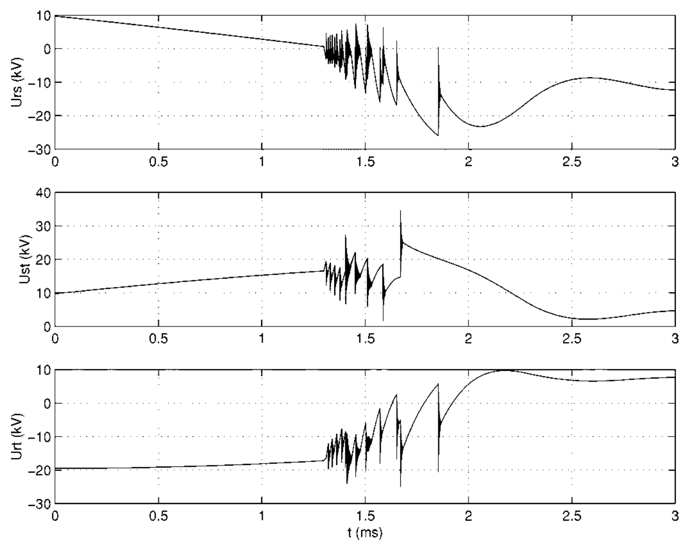

Fig. 16. Transformer phase-to-phase voltages—magnetizing current switching.

in practice are also frequency dependent. Due to lack of information they are represented only with a 50/60 Hz model. The transformer under no-load is connected to the VCB by a cable. The influence of the length of the cable on the generated overvoltages is also observed.

A. Switching Off Magnetizing Currents

The first case is switching off magnetizing currents. The CB opens at maximal current in phase R. Shortly thereafter a re-ignition takes place, as can be seen in Fig. 14. The calculated phase-to-ground and phase-to-phase overvoltages for a cable length of 20 m are shown in Figs. 15 and 16, respectively. When the steady-state currents are switched off, the maximal overvoltages do not reach very high values; in our case not more than 40 kV. The length of the cable has a significant influence on the generated overvoltages. It increases the total capacitance and the travel time of the surge impulse, which in its turn decreases the peak overvoltage [10].

During the switching of steady-state currents, a re-ignition occurs at almost all instants of switching. Generally this depends mostly on the amplitude of chopping overvoltages, which are determined by the chopping current and the rate of rise of the dielectric withstand capability of the gap. The magnetizing current is chopped immediately and in this case it is not the chopping behavior of the VCB, but it occurs because the amplitude of the magnetizing current is well below the chopping level. In this case we have VCC, especially when the contacts open shortly before current zero. Fig. 17 shows an example of the calculated voltages in phase R, phase S and between phases R and S when the current in phase T clears first. Normally, the switching occurs in the second or third loop after 30–50 ms, but in order to reduce the computation time, the switching is done within 20 ms. In this case, the generated overvoltages are strongly affected by the arc angle. The greater the arc angle, the smaller the probability that a re-ignition will occur.

B. Switching Off Inrush Currents

Transformer inrush current switching is rare, but it might happen, particularly during an improper relay tripping immediately after energizing or in arc furnace supply systems

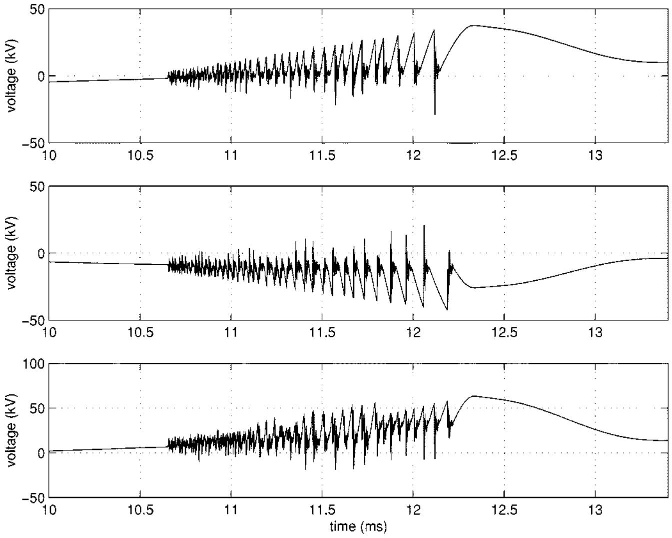

Fig. 17. An example of inrush current switching with VCC for a cable length of 40 m; upper trace: terminal voltage in phase R; middle trace: terminal voltage in phase S; lower trace: voltage between terminals R and S.

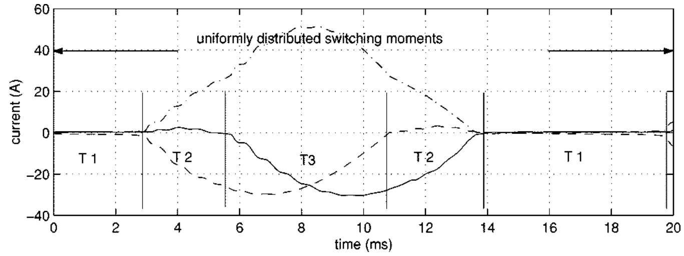

Fig. 18. Interval of randomly chosen switching instants for inrush current switching.

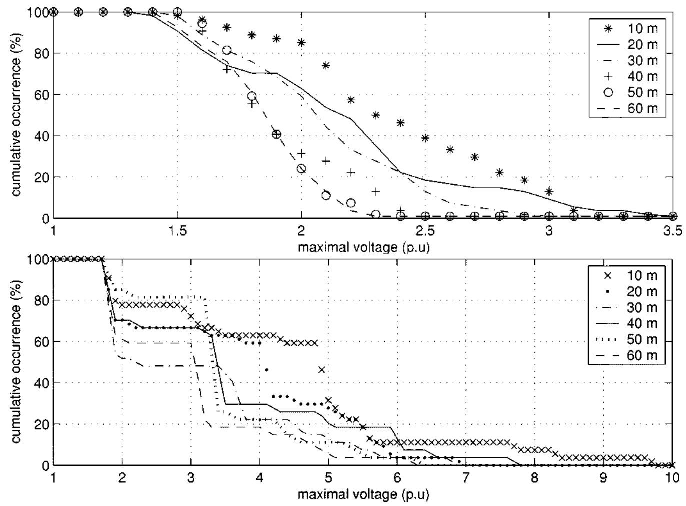

Fig. 19. Cumulative probability of overvoltage occurrence; upper trace: magnetizing current switching, lower trace: inrush current switching.

where switching occurs many times a day [5], [8]. Unlike distribution transformers, where the low-voltage terminals are mainly connected by a cable that leads to the load, arc furnace transformers have their secondary terminals opened.

A complete analysis was carried out for different cable lengths for both switching cases. The cumulative probability of the generated phase-to-phase overvoltage between the phases R and S is calculated in the following way. The instant of switching is chosen randomly. For steady-state currents because of a symmetry all switching moments are within a time interval of 6.6 ms. For inrush current switching there is no symmetry because the inrush current amplitude decreases aperiodically. Therefore the random switching instant is chosen between 0 ms and 20 ms. If m is the total number of energizations, then for each energization we can determine the maximum value of the switching overvoltage. If ν is the number of energizations where a maximum value of $V_{\max}$ is $V < V_{\max} < V + dV$, then the probability of an overvoltage $V_{\max}$ which is in particular interval $[V, V + dV]$ is ν/m [4]. The cumulative occurrence of a particular voltage being exceeded is calculated as

$$Q(V_{\max}) = \int_{V_{\max}}^{\infty} f(V)\, dV. \tag{7}$$

The same method can be applied if measured data from a number of tests are known by a previous determination of the maximum values from each test. During inrush current switching we distinguish three intervals. This can be seen from Fig. 18, which represents the inrush currents during the first 20 ms.

T_1 is an interval where the instant values of the phase currents are not high in amplitude. This situation is similar to the case of magnetizing current switching; the currents are cleared immediately, re-ignitions do sometimes occur, but the overvoltages reach no high values. In the intervals T_2 and T_3 the currents are higher than the steady-state currents and due to a VCC higher overvoltages occur. In the interval T_2 in almost each case of switching a re-ignition with a VCC occurs, while in the interval T_3 this happens only when the contacts open shortly before the first current to clear. If no re-ignition takes place, only chopping overvoltages exist and they depend only on the chopping current level and on the transformer residual flux. However, they can also reach high values as reported in [25].

Fig. 19 shows the calculated cumulative probability for different cable lengths. Note that 1 p.u. denotes the maximum phase-to-ground voltage; that is $13.8\sqrt{2}/\sqrt{3} = 11.24$ kV.

During the inrush current switching, the maximum overvoltages occur when the contacts open in the intervals T_2 or T_3. However, less than 20% of the overvoltages are higher than 5 p.u. and for longer cable lengths the probability is even lower. The studied voltage transients are between phase R and phase S. The voltages in terminals R and S are approximately half the value of these voltages.

Measurements performed by Daalder and van den Heuvel [17] show that the maximum overvoltage for their transformer is 3.5 p.u. during steady-state and 7 p.u. during transient condition. The amplitudes of the magnetizing and inrush currents were 0.5 A and ~700 A, respectively. Ohashi, *et al.* [9] measured 3 p.u. and 4 p.u. during steady-state and transient current interruption respectively, with magnetizing currents of 1.5 A and inrush currents of ~33 A.

IV. Conclusion

Overvoltages are investigated for a system configuration that consists of a VCB, a cable and an unloaded transformer. The system components are represented by models based on available data and the results are compared with measurements and simulations in order to prove the validity of the approach.

A statistical distribution of the overvoltage that builds up across the transformer winding is studied. Due to possible VCC, the voltage in the phases which have not cleared the arc yet can reach a similar value but different polarity and therefore a delta-connected winding might be exposed to a value twice the phase-to-ground voltage.

The maximum calculated overvoltages in the steady-state situation are as high as 3 times the rated voltage. The transformer core affects the local maximum of the inrush currents, which might influence the overvoltage due to VCC. The maximum overvoltages at inrush current switching can reach values up to 8 times the rated voltage. The cable length also affects the generated overvoltages. It can be seen that when the cable length is increased, the overvoltage decreases.

This study presents results on a particular circuit with particular characteristics of the system components, so the results can not be applied to similar systems because many parameters influence the re-ignition overvoltages. There is no general rule that shows which of the parameters that influence the possible overvoltages are the most important. Therefore, the voltage transients in systems similar to the one studied here might be different. Many parameters must be considered in order to draw a reliable conclusion about the overvoltage level of a particular case.

Despite the huge computational effort, we believe that the used models are still simplified. The reason for this is the lack of measured data for transformer, cable and VCB which are important for accurate modeling. If measured characteristics of cable terminal impedances are known the same approach as for the transformer modeling can be used for fitting the characteristics. The transformer model should be refined by taking into account the hysteresis [25], mutual impedances and frequency-dependent losses.

The analysis of switching overvoltages that might occur during de-energization of unloaded transformers and other highly inductive loads are important for insulation co-ordination. These overvoltages have different origins. The potential insulation failure can be caused by their amplitude, rise time or both. For the transformer, the magnetizing current interruption does not produce high overvoltages, but the interruption of inrush currents might be a problem in some cases. This type of switching is unusual but not impossible. Transformers because of their high BIL can withstand these overvoltages. But if the VCB is used to perform many switching operations, the possible steep fronted surges can accelerate the deterioration of the transformer insulation. Therefore, the transformers should be protected with R-C suppression branches to damp the voltage oscillations and reduce the possible overvoltages. Advanced pole switching [26] to avoid the VCC is also recommended.

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