Circuit Breaker Switching Transients at Arc Furnace Installation

Miloš Maksić, Dejan Matvoz, Janko Kosmač, Igor Papič

Abstract — **Large number of vacuum circuit breaker switchings in installations supplying arc furnace transformers make these systems especially susceptible to overvoltage transients. This paper studies the role of a vacuum circuit breaker in a local arc furnace installation that suffered several transformer outages. Emphasis is given on voltage and current transients arising from the circuit breaker switching. Digital simulation of circuit breaker operation proves that the lack of a voltage suppression circuit was the primary cause of overvoltages affecting the arc furnace transformer and further shows its effect on the suppression of these transients.**

Keywords: **arc furnace, transients, transformer, overvoltage, surge suppressor.**

I. Introduction

FREQUENT outages of an arc furnace transformer in a local steelmaking installation have repeatedly forced operators to shut down production for long periods of time. These events necessitated a study of the source of these outages and of adequate protective measures. A detailed inspection revealed a severely degraded insulation on the arc furnace transformer, most likely as a consequence of overvoltages. Adequate construction of the transformer as well as the role of a vacuum circuit breaker (VCB) during switching was investigated. The latter is discussed in this paper.

Field measurements of overvoltages and current transients arising in arc furnace installations have been extensively investigated in the past [1]-[3]. Investigations proved that VCBs are a primary source of such transients where even tripping of small transformer magnetizing currents occasionally led to high overvoltages. Moreover, research into new phenomena such as virtual current chopping in three phase networks led to major improvements in overvoltage protection. Subsequent revisions in protection schemes improved overall performance of arc furnace installations.

Development of VCB models used in transient simulation programs [4]-[6] eased investigations into such phenomena and suitable protective measures.

The article presents the results of simulations of VCB switching in a local arc furnace facility. A VCB simulation model includes dynamic characteristics of a real breaker. Suitable parameters of the model were obtained based on a number of measurements performed on the actual VCB [7].

Simulations showed that VCB closing does not generate dangerous transients that could damage transformer windings or insulation. VCB opening however, results in high overvoltages experienced on the arc furnace transformer. A suitable solution to damp these overvoltages is achieved with the use of surge suppressors.

The investigation clearly pinpointed the reasons for several outages experienced in the arc furnace installation and also provided sufficient solutions to eliminate problems.

II. Transients in Vacuum Circuit Breaker Switching

Vacuum circuit breakers are commonly used in medium-voltage (MV) arc furnace installations with a high number of no-load interruptions, primarily because of their excellent interruption and dielectric recovery characteristics. Switching maneuvers can however result in overvoltages at the interrupted part of the circuit. These transients differ depending on whether VCB is opened or closed.

A. Transients during VCB closing

Closing of a VCB in a MV arc furnace installation shown in Fig. 1 is studied. Cable is represented as a Π section model.

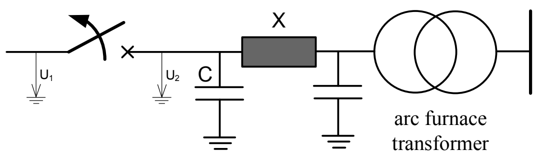

Fig. 1. A circuit breaker switching an arc-furnace transformer.

As the breaker poles gradually close, the dielectric withstand between the contacts at one point breaks, as is depicted in Fig. 2. A prestrike occurs as the voltage between the contacts falls abruptly establishing an electric arc which serves as a conducting path for a high-frequency current. Current levels gradually fall and at a certain slope in (A/μs) at current zero the VCB cuts off the current (current quenching),

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a phenomenon characteristic for the vacuum. Consequently, transient recovery voltage rises and as it exceeds the dielectric withstand between contacts another prestrike occurs. The process is repeated and several prestrikes occur before the contacts reach final closed position.

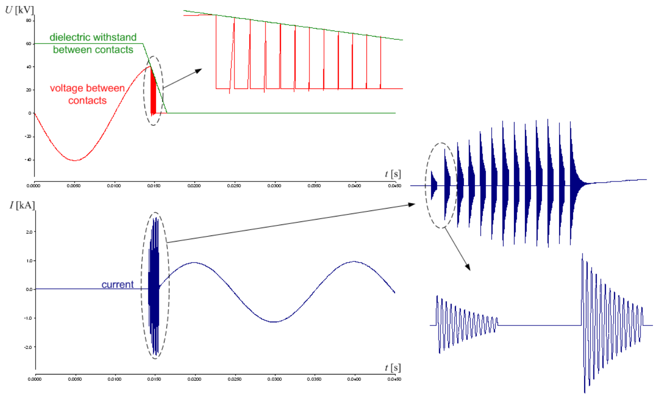

Fig. 2. Prestrikes during VCB closing.

B. *Transients during VCB opening*

Resulting overvoltages during opening of a VCB in Fig. 1 are much higher. Due to specific characteristics of vacuum, the interruption of magnetizing currents in no-load operation in a VCB is often accompanied with high-frequency current and voltage transients. When the current reaches the chopping current value I_{ch}, the arc in the VCB vacuum becomes unstable and extinguishes. Current sharply falls to zero and the voltage, being proportional to the derivative di/dt, suddenly rises, oscillating according to the oscillation frequency of the circuit, as depicted in Fig. 3.

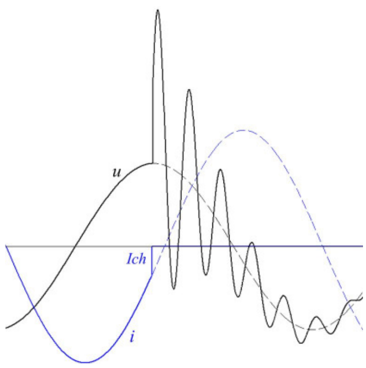

Fig. 3. Current chopping and the resulting overvoltage.

For the case of a MV arc furnace installation these transient voltages can be large in magnitude. At the moment when the VCB interrupts the current, the magnetic energy W_{mag} and the electric energy W_{el} in the disconnected part of the circuit are determined by the inductance L of the transformer windings, the chopping current I_{ch}, the capacitance C of the cables and the cable voltage. Since L and W_{mag} are much larger than C and W_{el}, overvoltages in Fig. 3 occur according to

$$W_{mag} = \frac{L \cdot I_{ch}}{2} = W_{el} = \frac{C \cdot U^2}{2} \rightarrow U = I_{ch} \cdot \sqrt{\frac{L}{C}}, \qquad (1)$$

where I_{ch} represents the chopping current and U the resulting overvoltage. I_{ch} can be obtained using the following equation [5]:

$$I_{ch} = (\omega \cdot i \cdot \alpha \cdot \beta)^q, \qquad (2)$$

where $\alpha = 6.2 \cdot 10^{-16}$, $\beta = 14.3$, $q = -0.07512$, ω is the network angular frequency and i the current amplitude. L and C determine the oscillation frequency.

Fig. 4 shows an example of an overvoltage occurring between phases L2 and L3. In this case the overvoltage reaches 5-times the nominal voltage amplitude.

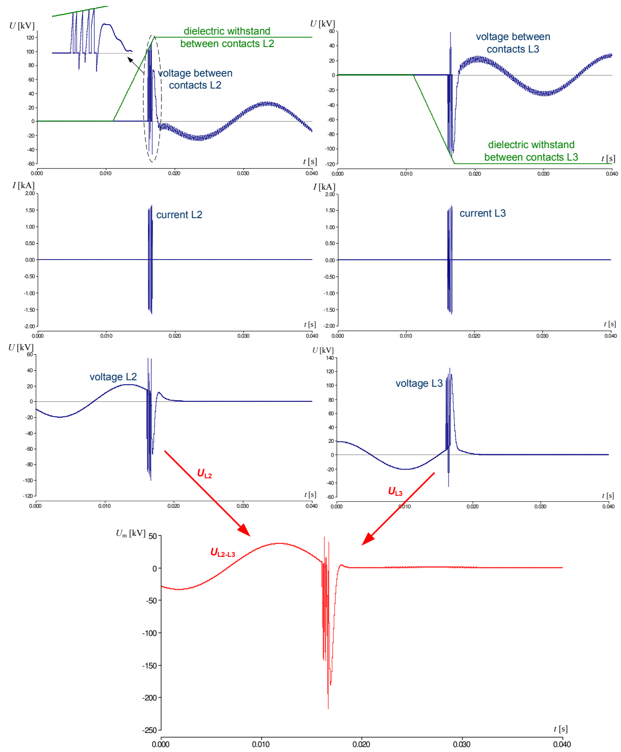

Fig. 4. Overvoltage during VCB opening.

Different current zero-crossings during the disconnection of three-phase breakers can lead to excessively high phase-to-phase overvoltages. These have a severe stress on the insulation of a transformer and require an installation of a suitable protective circuit.

III. Preparation of a Simulation Model

A. *Network under study*

A local MV arc furnace network shown in Fig. 5 is studied.

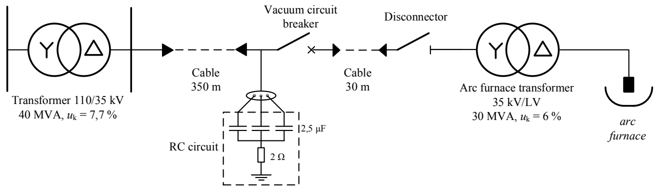

Fig. 5. Local network under study.

The network has no protective circuit installed near the arc furnace transformer. The existing *RC* circuit shown in Fig. 5 does not function as a surge suppressor. Before the start of every melting cycle the disconnector is switched on followed by the VCB. On the contrary, at the end of every melting cycle the VCB is first switched off followed by the disconnector.

B. VCB modelling

A suitable model of a VCB is required for the dynamic simulation of switching transients in the PSCAD simulation program. Characteristics of the breaker model used in the study were obtained based on a number of measurements [7]. The logic behind the VCB model incorporates current chopping, a linear change in dielectric withstand of contact gap during contact opening/closing and the high frequency current quenching capability. The model however does not include statistical variation of chopping current value and of other parameters [4]. Although this makes statistical results less accurate, this is not of particular importance. Only an approximate insight into the nature of overvoltages is required.

Measurements [7] show the dielectric withstand with fully open VCB contacts to be 100 kV. The contacts close in approximately 5 ms and the slope of the closing poles is 20 V/μs. The critical slope of the current quenching is set to 100 A/μs. Fig. 6 shows an example of all three phase voltages measured during opening of a VCB.

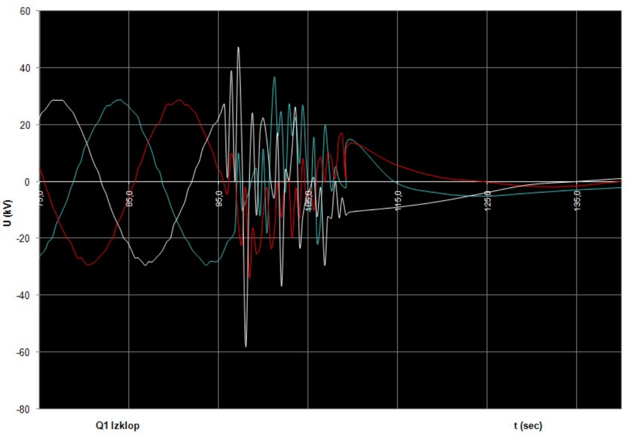

Fig. 6. Measured transients on the furnace side during VCB switching.

IV. SIMULATIONS OF VCB CLOSING AND OPENING

A. Simulations of VCB closing

Before the start of every melting cycle with the arc furnace transformer operating in a no-load state, a disconnector closes, followed by the VCB shown in Fig. 5. Simulation results of phase currents and voltages are shown in Fig. 7 and the results of phase-to-phase voltages and transformer winding currents are shown in Fig. 8 (U_1 and U_2 represent voltages on both sides of the breaker according to Fig. 1).

As the VCB contacts gradually close, voltage across the contacts shown in Fig. 7 surpasses the dielectric withstand between the contacts and according to chapter II, voltage and current transients occur. VCB closing is accompanied with relatively high current transients reaching a peak value of 600 A in L2 shown in Fig. 7. These currents have a return path mostly in the *RC* circuit shown in Fig. 8 and to a smaller extent through the cable capacitances. High winding inductance of both transformers acts as a strong resistance to high frequency current transients. Current transients thus do not affect main transformer as is also shown in Fig. 8. Immediately after the contacts fully close, high inrush magnetizing currents feed the arc furnace transformer. According to Fig. 8, during the VCB closing high frequency voltages between phases occur only on the secondary side of VCB and affect solely the arc furnace transformer.

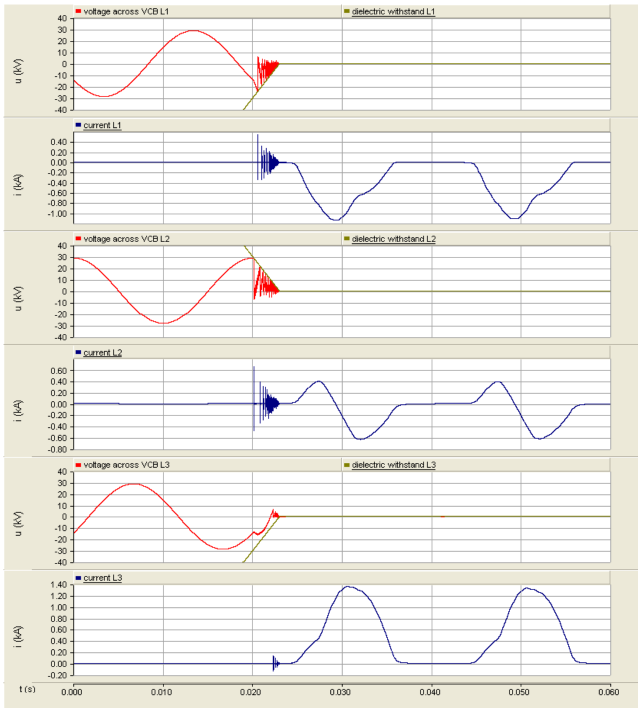

Fig. 7. Closing a VCB – circuit breaker voltages and phase currents.

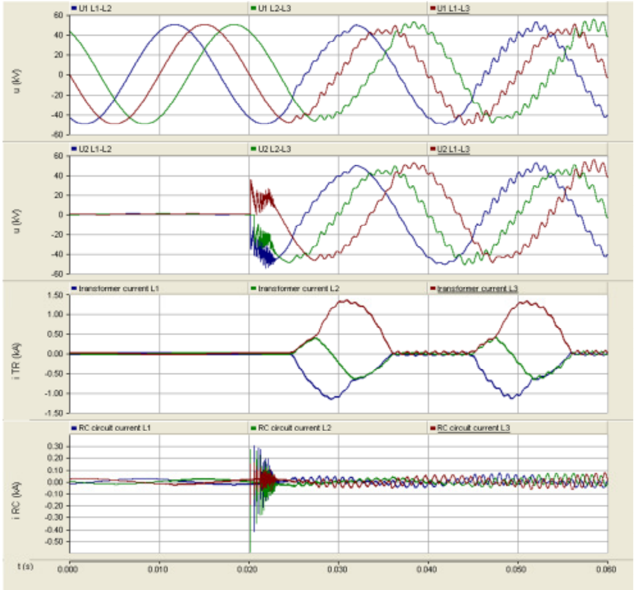

Fig. 8. Closing a VCB – phase-to-phase voltages and currents.

Simulation results in Fig. 7 and Fig. 8 show that VCB closing is accompanied with steep rising voltages during prestrikes. These can stress the arc furnace transformer insulation, yet the amplitudes of such voltage transients are insignificant.

B. *Simulations of VCB current interruption*

To study the severity of overvoltages occurring during interruptions i.e. opening of the breaker, the simulation model was again put in use. As the magnetizing current flowing through the VCB terminals corresponds to approximately 20 A, the chopping current according to (2) amounts to approximately 6 A.

An example simulation with severe overvoltages occurring during VCB opening is presented in Fig. 9 and Fig. 10. Fig. 9 shows phase currents and circuit breaker voltages in three phases. Phase-to-phase voltages are shown in Fig. 10. As the contacts of the beaker slowly separate, the current at one point falls below the chopping value and the arc extinguishes. Consequently, the voltage sharply rises. When the recovery voltage exceeds the dielectric withstand of the vacuum gap between the separating poles, a conducting path ignites a high frequency current. When the current quenches, the voltage rapidly rises and the process is repeated.

Voltages between circuit breaker contacts reach a maximum amplitude of 70 kV in phases L1 and L2 in Fig. 9. With the dielectric withstand reaching 100 kV at fully open contacts, the VCB is able to effectively resist these overvoltages. Currents in Fig. 9 reach the maximum amplitude of 1.3 kA in phases L1 and L2. Oscillating current, similarly to VCB closing, has a return path in the *RC* circuit shown in Fig. 5 and does not reach arc furnace transformer windings.

The resulting phase-to-phase overvoltages shown in Fig. 10 experience an exceptionally large amplitude during the swing after the initial oscillation. Phase L1 to phase L2 overvoltage experiences a 145 kV amplitude, more than three times the amplitude in normal operation. Phase-to-phase overvoltages are thus much larger than phase voltages. Only the arc furnace transformer is affected by such overvoltages.

Such overvoltages pose a much more serious problem to transformer insulation than transients experienced during VCB closing.

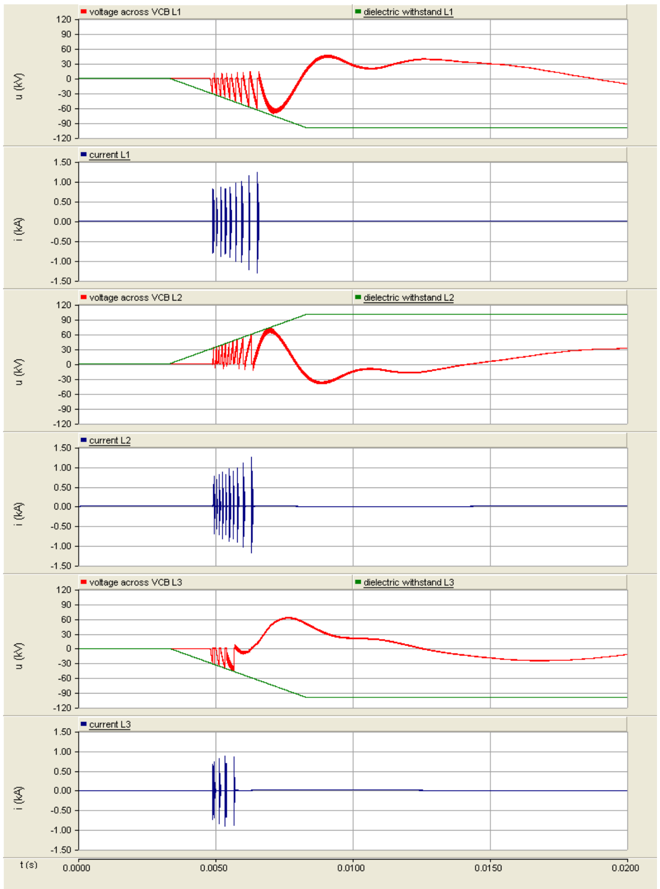

Fig. 9. Opening a VCB – circuit breaker voltages and phase currents without *RC* suppressor.

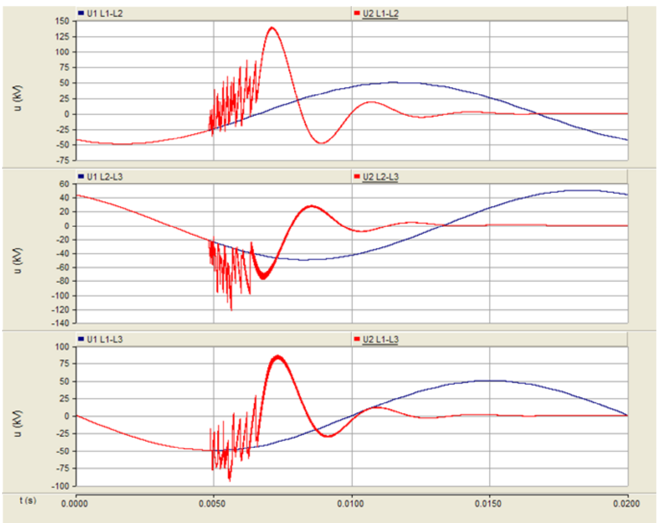

Fig. 10. Opening a VCB – phase-to-phase voltages on both sides of a VCB without *RC* suppressor.

V. The Role of a Protective RC Circuit

A. Operation without the surge suppressor

The arc furnace transformer shown in Fig. 5 was operating without the *RC* surge suppressor and without the surge arresters for a long period of time. During this time the transformer suffered several malfunctions. Subsequent analysis of the transformer clearly showed a severely degraded insulation, presumably a consequence of arising overvoltages.

Simulated example of arising overvoltages shown in Fig. 10 is an extreme example, but nonetheless one that is likely to occur considering frequent VCB interruptions in such facility. The severity of such overvoltages depends on several factors e.g. the moment of interruption, the state of the vacuum between contacts etc. As such, the interruptions are mostly random in nature. Fig. 11 shows the cumulative amplitude-frequency characteristic of phase-to-phase overvoltages. The probability curve corresponds to different moments of interruption covering the whole cycle.

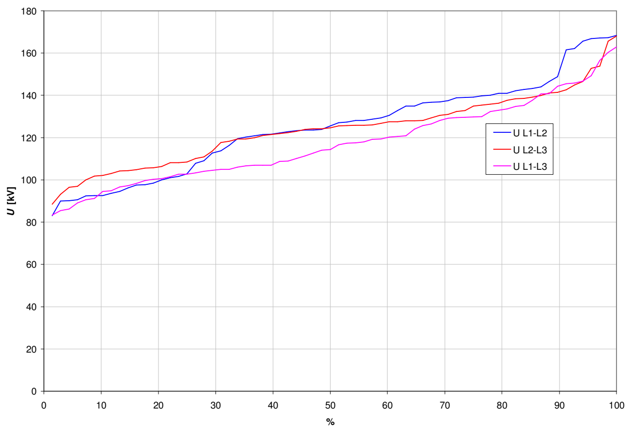

Fig. 11. Cumulative probability characteristic of phase-to-phase overvoltages without the use of surge suppressor.

In a narrow frequency range in Fig. 11 the overvoltages reach a peak amplitude of 170 kV which is more than 3-times the normal phase-to-phase voltage amplitude of 50 kV (in the 35 kV network).

B. Operation with the surge suppressor

The severity of such overvoltages requires the use of *RC* surge suppressors [1]-[3]. The suppressor should be installed near the arc furnace transformer as is shown in Fig. 12.

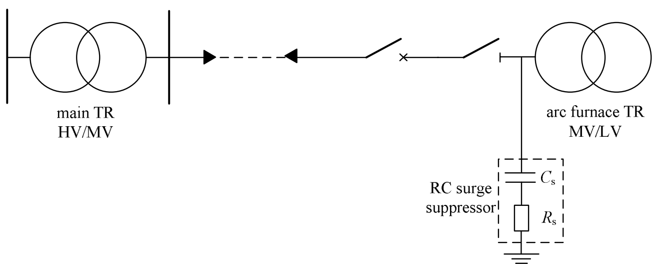

Fig. 12. *RC* surge suppressor in the network.

The basic idea behind its use is in discharging the stored magnetic energy of the transformer core. In choosing the capacitance C_s one has to consider that only 35 % of this energy stored in the core can be retrieved [1], [3]. An approximate formula for the calculation of C_s is according to [3]:

$$C_s = \frac{89.1 \cdot S_n \cdot I_{mag}}{U_n^2 \cdot f} \quad (\mu F), \tag{3}$$

where S_n represents the rated power of the transformer in (MVA), I_{mag} the magnetizing current in (%) of nominal current, U_0 the nominal voltage of the network in (kV) and f = 50 Hz.

C_s is normally in the order of 0.1 – 0.3 µF and primarily limits the slope of the rising voltage which could lead to development of an arc. The surge capacitors are unable to control the severity of overvoltages during trips. The amplitude of the overvoltage is attenuated with the use of a series resistor R_s calculated according to [3]:

$$R_s \geq 2 \cdot \sqrt{\frac{L_C}{C}}, \tag{4}$$

where L_c represents the sum of all inductances and C the sum of cable and surge capacitances in the switched part of the network. R_s is normally in the range of several tens of ohms.

Additionally, lightning arresters should be connected phase-to-phase on the arc furnace transformer primary terminals.

Opening of VCB with the use of surge suppressor with C_s and R_s calculated according to (3) and (4) was simulated and the results are shown in Fig. 13 and Fig. 14. Fig. 13 shows phase currents and circuit breaker voltages in all three phases. Phase-to-phase voltages are shown in Fig. 14. The breaker voltage across the contacts does not exceed the dielectric withstand and as such no current transients occur in Fig. 13 after the current is chopped. *RC* suppressor thus effectively limits the slope of arising voltage.

Phase-to-phase overvoltages in Fig. 14 are of normal amplitudes. Overall, the transients are less intense compared to the operation without the *RC* suppressor. Yet as the energy transferred from the arc transformer core is similar to the case without *RC* suppressor operation, this means that the transients are longer in duration.

The cumulative probability curve in Fig. 15 proves that the circuit experiences no severe overvoltages with the *RC* suppressor. The largest overvoltages are 1.6-times the nominal voltage in the 35 kV network and thus much smaller than the case from Fig. 11.

The effect of virtual current chopping should also be investigated when considering protective measures from overvoltages. In this case during the switching maneuver the high-frequency current in one phase reaches two other phases through the capacitance of cable connections. This current is added to the network frequency current and can at one point force the cumulative current to zero value (virtual current chopping). As with VCB opening, voltage transients occur and can lead to high phase-to-phase overvoltages. In this case additional surge arresters in all three phases and between three phases of the main transformer are required. Ref. [8] should be considered when specifying the lightning withstand voltage and the protective level of the surge arresters. The combination of surge suppressors and surge arresters greatly improves the protection of such installations from overvoltages.

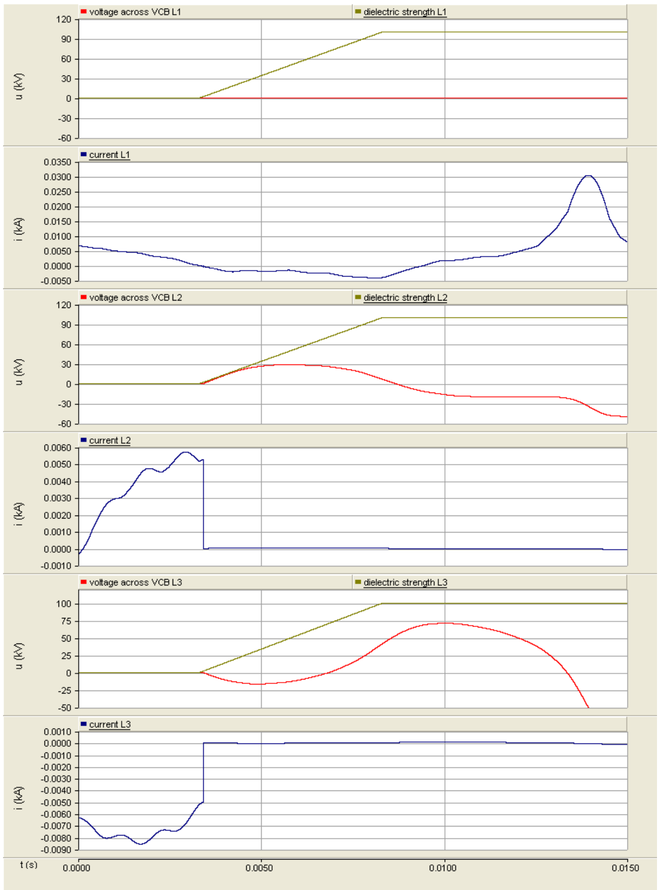

Fig. 13. Overvoltage during VCB opening with *RC* surge suppressor.

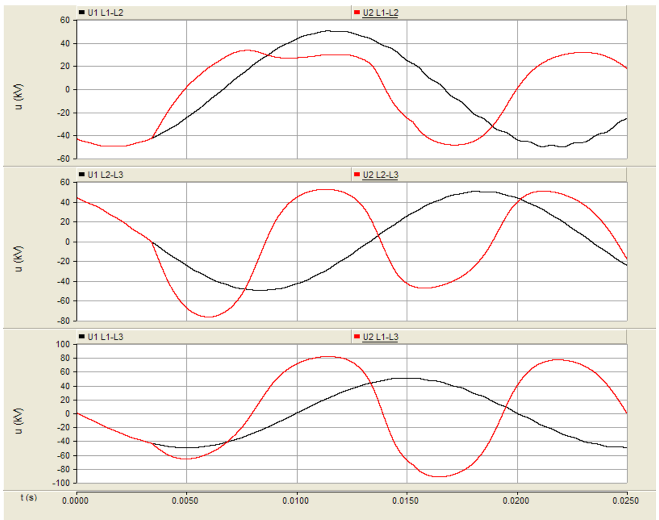

Fig. 14. Phase-to-phase overvoltages during VCB opening with *RC* suppressor.

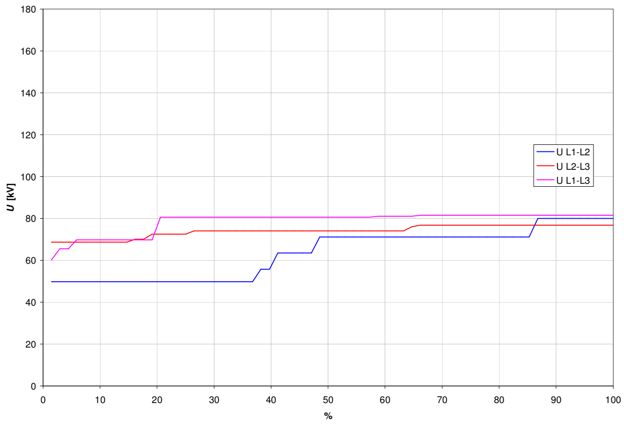

Fig. 15. Cumulative probability characteristic of phase-to-phase overvoltages with the use of surge suppressor.

VI. Conclusions

Digital simulation proved that a severely degraded arc furnace transformer insulation in a local steelmaking installation was the result of overvoltages arising from voltage circuit breaker opening. A complete solution to damping of the overvoltages and to protection from the effect of virtual current chopping can be sought with the use of a protective *RC* surge suppressor unit installed near the arc furnace transformer together with surge arresters installed on the main transformer secondary and arc furnace transformer primary terminals. With the abovementioned solutions taken in place we can expect less interruptions of the production at the arc furnace plant.

VII. References

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