Flashovers at a 33-kV Filter Reactor during Energization

M. Kizilcay, K. Teichmann, A. Agdemir, G. Kaflowski

Abstract -- For an extrusion plant 33-kV filter circuits are installed to absorb harmonics of the 5th and 11th order in the electric power supply. During the system start-up of the filters flashovers occurred between the two coil parts of the reactor belonging to the filter for the 5th order harmonic in two of the three phases.

This paper shows how overvoltages can be produced during energization of the filter, which may cause flashovers at the filter reactor by means of digital simulations of switching transients. The system components including the filter circuit are represented in detail using ATP-EMTP. Both filters are fed by a relatively long 33-kV cable. The saturation characteristic of the filter reactors plays an important role in initiating repetitive high transient voltages. The neutral point of the filters is isolated, since the neutral of the feeding 33-kV system is not grounded.

The overvoltages across the reactor obtained by a statistical analysis of switching surges are far higher than the amplitude of the withstand test voltage performed at the factory. Severe overvoltage stress of the filter reactor may also happen, when the filter will be re-energized shortly after it has been switched off, so that the filter capacitors remain charged. In this case, the highest overvoltage of 83.9 kV is expected across the filter reactor.

Keywords: temporary overvoltages, flashover, magnetic saturation, temporary ferroresonance, energization, star point displacement, harmonic filter, reactor switching, EMTP

I. INTRODUCTION

FOR complex machinery two three-phase filter circuits were installed, intended to reduce harmonics of the 5th and 11th order in the electric power supply. The nominal voltage of the system is 33kV. During the system start-up only the filter for the 5th harmonic was energized resulting in flashovers between the two coils of the reactor (see Fig. 1) in two of the three phases.

This study investigates the origin of those flashovers by means of digital simulations of switching transients. According to the given information the situation during the initial start-up was characterised by:

- the 33kV system neutral is isolated
- filter circuit H11 for the 11th harmonic is disconnected
- filter circuit H5 was energized by the associated vacuum circuit breaker.

In the instant when the harmonic filter H5 for the 5[th] harmonic is energized the instantaneous voltage of the phase will appear at the terminals of the reactor of the filter, because the voltage of the unloaded capacitor C_{H5} of the filter remains nearly zero for the first moment. If the instant of switching is near to the amplitude of a line-to-neutral voltage, the expected voltage across the reactor will be

$$\hat{u}_{a-n} = \sqrt{2} \cdot 33kV / \sqrt{3} = 26.9kV \, . \qquad (1)$$

The reactor of the filter was tested at the factory with a 50 Hz sinusoidal test voltage of 28 kV (r.m.s. value) having an amplitude of

$$\hat{u}_{test} = \sqrt{2} \cdot 28kV = 39.6kV \qquad (2)$$

and duration of 1 min.

II. SYSTEM REPRESENTATION IN THE ATP-EMTP

The 33-kV system modelled in the ATP-EMTP consists of the components: 33-kV feeder, XPLE cables used to connect the harmonic filters H5 and H11 and the complete filter circuit of H5. The drawing of the modelled system created with the graphical pre-processor *ATPDraw* [2] is shown in Fig. 2.

A. 33-kV Feeder

The 33-kV feeder is represented by a Thevenin equivalent consisting of an ideal three-phase voltage source and positive-sequence short-circuit impedance. In order to provide an isolated neutral for the 33-kV source network an ideal transformer in delta-star connection is added.

The short-circuit (s.c.) data of the 33-kV feeder provided are:

Fig. 1. Filter reactor with two coils

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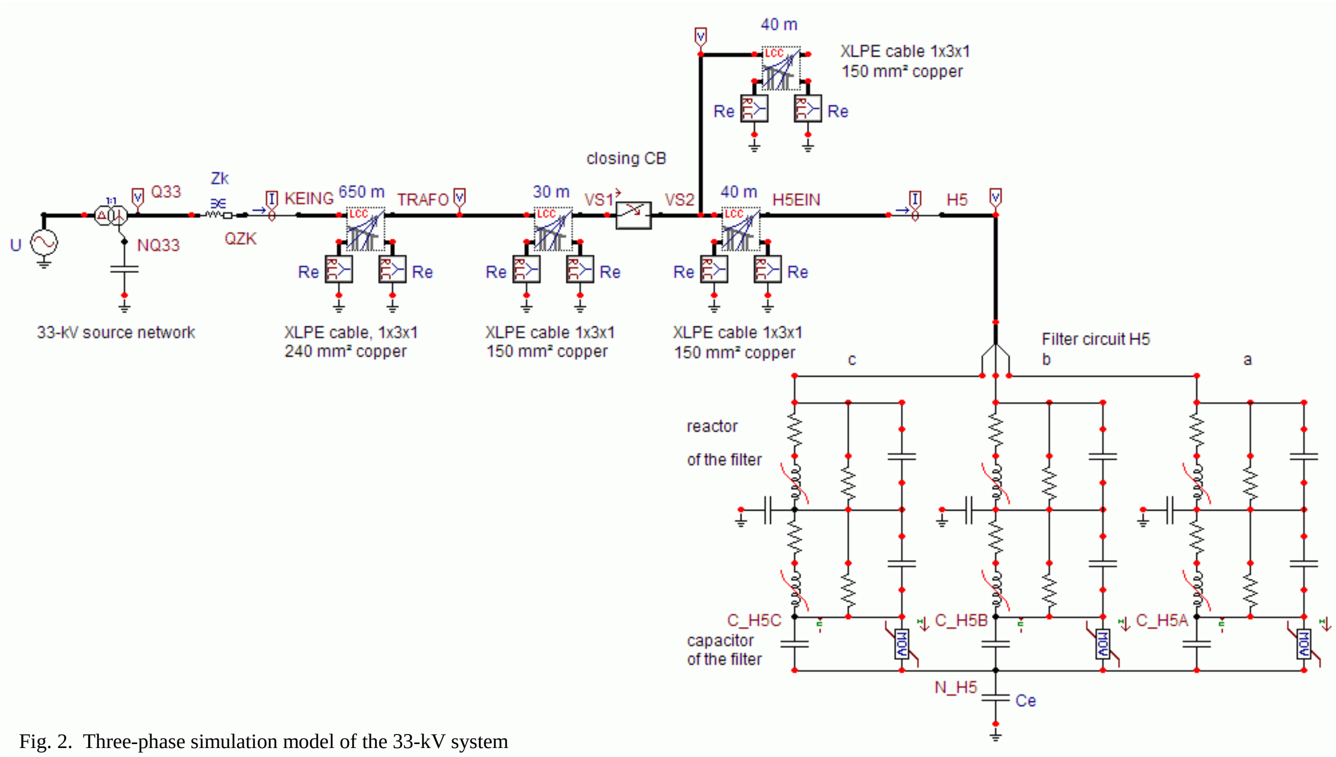

Fig. 2. Three-phase simulation model of the 33-kV system

– Nominal voltage, $U_n = 33kV$ (3)

– Minimum short circuit power, $S''_{k\,\min} = 375\,MVA$ (4)

– Ratio s.c. reactance to s.c. resistance, $X_{SC} / R_{sc} = 10$ (5)

With these values the positive sequence impedance results to $\underline{Z}_1 = (0.289 + j2.89)\Omega$ (6)

B. 33-kV Cables to Connect the Filters H5 and H11

For connecting the filters to the network XLPE-isolated cables are used.

Single-core, three-phase XLPE cables of size 240mm² and 150mm² are used as feeder cables between feeder and circuit breaker, and between circuit breaker and filter circuits.

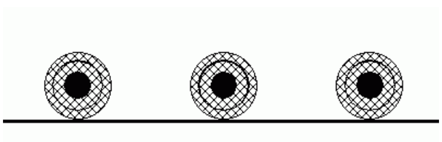

Fig. 3. Layout of the 1x3x1 XPLE single-core cable, 240 mm² copper

The cable will be laid in concrete trenches and basements. The cable sheath and armour will be earthed at both ends. The cable system (see Fig. 3) is represented using CABLE PARAMETERS supporting routine of ATP-EMTP [1] as *Constant-Parameter Distributed Line*. The sheaths are considered as non-earthed conductors and later earthed in the simulation model.

The ground resistivity is assumed as $\rho_e = 100\Omega \cdot m$. (7)

Following cable lengths were given:

– from feeder to switch 650 m (240 mm^2) plus 30 m (150 mm^2)

– from switch to filter 40 m (150mm^2)

C. Harmonic Filter H5

The filter H5 is built in three phases connected in star. The star-point of the filter is isolated to earth. It is assumed that there is a very small capacity between star-point and earth as shown in Fig. 2. In the simulation model this capacitance is estimated to be about 50 pF.

According to the known setup of the reactor, it is modelled as two parts being connected in series for each of the three phases of the filter. Each part of the reactor is represented by four lumped elements as shown in Fig. 4: L is saturable inductance in series with the ohmic resistance R_{Cu} of the winding. The two parts of the coil are magnetically coupled, since they have only one magnetic core, comparable to an autotransformer. The parallel resistance R_{Fe} represents the magnetisation losses in the iron core. Parallel to these three elements the 4th element is the winding capacitance C_W of one coil. Following values are provided for one coil of the reactor:

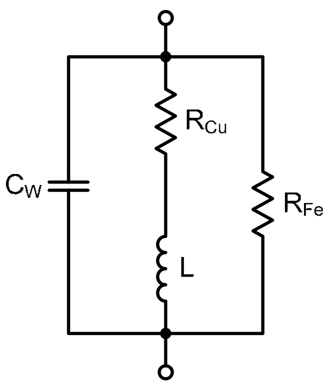

Fig. 4. Representation of one coil of the reactor

$$L = 31.46 mH;\ R_{Cu} = 33 m\Omega$$
$$R_{Fe} = 2.21 k\Omega;\ C_W = 0.828 nF \quad (8)$$

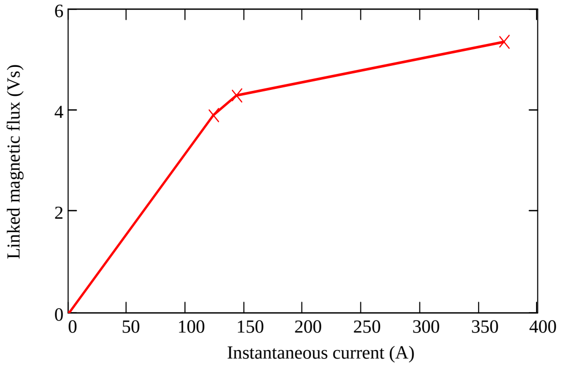

Fig. 5. Saturation characteristics of the filter reactor

The magnetisation curve of the saturable inductance is constructed according to the measurements, as shown in Fig. 5 for a complete reactor of one phase. For one coil of the reactor the linked flux needs to be halved.

The capacitor of the filter H5 is assumed to be an ideal capacitor with a capacitance of C_{H5} = 13.98 µF. (9)

D. Surge Arrester Protecting the Capacitor of the Filter H5

The surge arresters connected parallel to the capacitors C_{H5} of the filter are modelled by nonlinear resistors. The voltage/current characteristic of the surge arrester 3EL2 is shown in Fig. 6.

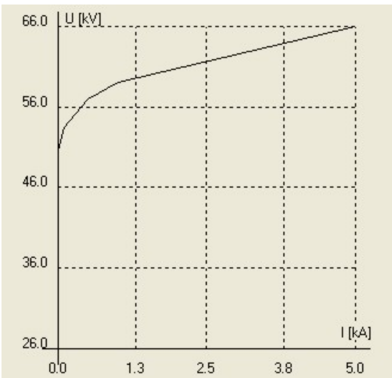

Fig. 6. Surge Arrester Protecting the Capacitor of the Filter H5

III. Computation of Switching Surges and Discussion of the Results

With the system representation according to section II several computations of transient voltages and currents were performed. Since the closing times of the circuit breaker poles can vary randomly, a statistical analysis of the overvoltages is appropriate.

A. Simultaneous Switching of all Three Poles at Voltage Maximum

For the first calculation all three poles of the circuit breaker are assumed to close at the same instant, when the voltage of phase *a* of the feeding network is maximum. The voltages across the three reactors are plotted in figure 7.

There are relatively high overvoltages in all three phases. In this case the maximal voltage appears in phase c (blue curve) about 0.2 ms after the switching-instant with nearly 40 kV.

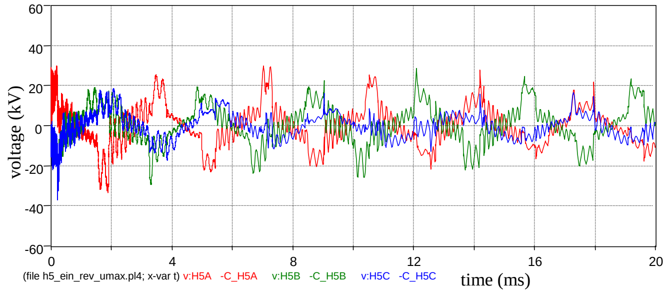

Fig. 7. Reactor-voltages for simultaneous switching at voltage maximum of phase *a*

Even after several milliseconds sudden rises of the voltages across the reactors can be seen, that are caused by the saturation of the magnetic cores of the reactors of other phases. This saturation appears like additional switching actions, where the inductance varies nearly instantaneously between linear and saturation region. This saturation makes the symmetrical three-phase system to change to an unsymmetrical three-phase system causing displacement of the star-point voltage what also influences the reactor-voltages.

Oscillations of different frequencies are caused during switching transients, having different origins. The low-frequency oscillation has a frequency range of 250 Hz… 300 Hz caused by the circuit elements, i.e. short-circuit inductance of the feeding network, the reactor and capacitor of the filter H5.

As it can be seen in Fig. 7 a high-frequency oscillation of 7 kHz is superposed on the voltage waveforms, which results from the interaction of the filter circuit and the total capacitance of the feeder cables. Additionally, due to travelling waves along the cables very high frequency oscillations can be seen within the first millisecond after energizing the circuit.

B. Case with the Maximal Overvoltages across the Reactors

The pole span which is a characteristic of the circuit breaker is the time difference between the first and the last pole to close. Even a small deviation from ideal simultaneous closing can lead to a noticeable increase in the overvoltage magnitudes. Here, rather a pessimistic value of 5 milliseconds is used for pole span. ATP-EMTP has a feature that allows varying systematically or randomly the instant of circuit-breaker pole switching in a given time-interval. Using this feature a statistical analysis of overvoltages is possible (See section III.*C*).

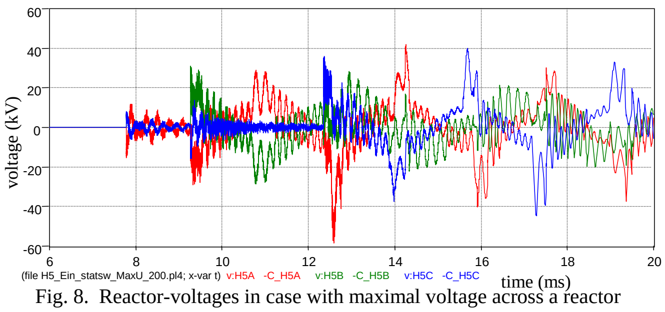

Fig. 8. Reactor-voltages in case with maximal voltage across a reactor

As a result of these statistical investigations one case with the maximal overvoltage is found and discussed in more detail in the following. The reactor-voltages for the worst case with the highest overvoltage are shown in Fig. 8.

The maximal overvoltage across an reactor found appears in this case in phase *a* (red curve) at about $t = 12.7$ ms and has a value of $\left|\hat{u}_{\max}\right| = 58.55kV = 1.48 \cdot \hat{u}_{test}$. (10)

The reactor-voltage in phase *c* also exceeds the maximal test voltage of $\hat{u}_{test} = 39.6kV$. (2)

Fig. 9 shows the voltages between the terminals of the filter and ground for the case of maximal overvoltage.

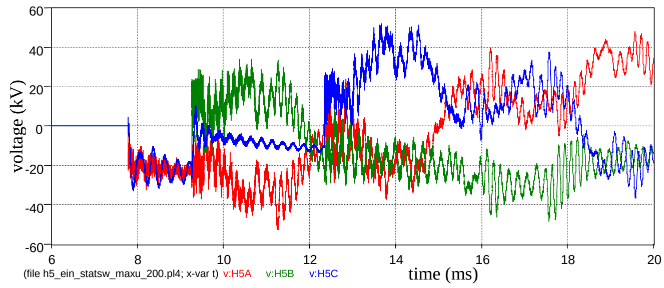

Fig. 9. Voltages between the terminals of the filter and ground for the case with maximal reactor-voltage

The voltages between the terminals of the filter and ground often exceed 40kV for all phases. This is the result of the displacement of the star-point of the filter (voltage of star point is shown in Fig. 10) caused by the unsymmetrical impedance due to saturation.

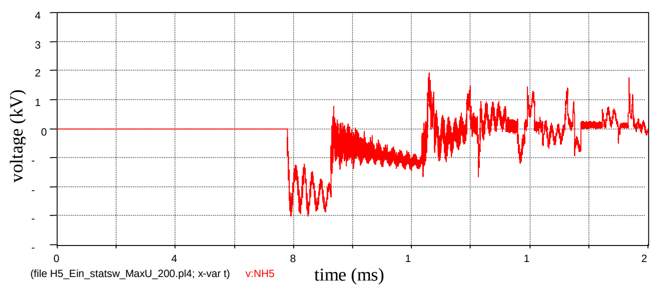

Fig. 10. Voltage of the star point of the filter to ground

This voltage is not critical, because the system is isolated against the ground and linked only by parasitic capacitors.

Important are the voltages across the capacitors C_{H5} of the filter H5 that are shown in Fig. 11. These voltage waveforms show d.c. components due to the switching and superposed oscillations with a frequency approximately equal to the natural frequency of the filter.

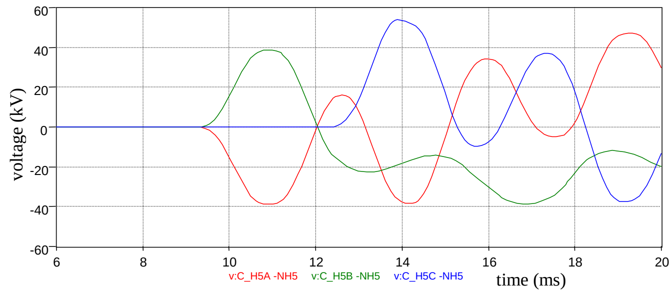

Fig. 11. Voltages across the filter-capacitors C5 for the case with maximal reactor-voltage

The maximal voltage across the filter-capacitor in phase *c* (blue curve) is about 55 kV. These voltages are high and may be dangerous for the capacitors. In fact the surge arrestors connected parallel to the capacitors C_{H5} have operated. The currents of the surge arrestors are shown in Fig. 12. Comparison of Fig. 11 and Fig. 12 shows that the surge arrester of phase *c* (blue curve) has operated at voltage maximum around $t = 14$ ms. In Fig. 12 the current of the surge arrestor in phase *c* (blue curve) refers to the left scale and the currents of the phases *a* (red line) and *b* (green line, value almost zero) refer to the right scale.

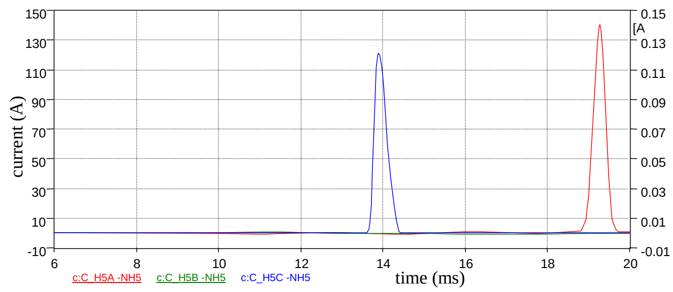

Fig. 12. Currents through the surge arrestors parallel to CH5 for the case with maximal reactor-voltage

The limiting effect of the current through the surge arrestor in phase *c* on the capacitor voltage can be seen in Fig. 11, at about $t = 14$ ms. Near to the maximum there is a small deviation from the sinusoidal curve form. Finally, for this case the currents flowing into the filter are displayed in Fig. 13.

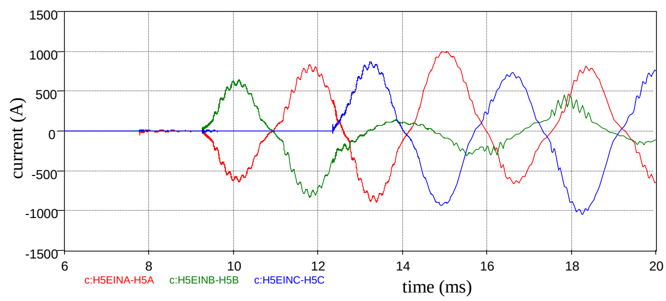

Fig. 13. Currents through the filter for the case with maximal reactor-voltage

The different instances for the switching of the three phases can be seen clearly in this figure. The switch in phase *a* (red line) is taken as a reference and is supposed to close first at about $t = 7.8$ ms. The switch in phase *b* (green line) is delayed for about $\Delta t = 1.5$ ms and the switch in phase *c* (blue line) is delayed for about further $\Delta t = 3$ ms. In the time interval 7.8 ms < t < 9.3 ms the current in phase *a* is very small since this current may only flow through parasitic capacitors. In fact this already causes noticeable voltages as shown in Fig. 8 and 9.

The filter capacitors C_{H5} do not show noticeable voltages (see Fig. 11), since the transported charge is still very small.

In the time interval 9.3 ms < t < 12.3 ms only currents in phases *a* and *b* flow and are already so big, that the reactors of these phases are saturated, what can be seen if one takes into consideration the magnetisation curve in Fig. 5, where the limit of the linear part is at about 150 A. The currents through the resistor representing the iron losses R_{Fe} and through the winding capacity C_W may be neglected for this consideration. At the instant $t = 12.3$ ms, when the switch in phase *c* closes both reactors of the phases *a* and *b* tend to leave the region of saturation. A short period of time, $\Delta t = 0.5$ ms, after the closing of switch *c*, the current in phase *c* reaches the value of 150 A, indicating that the reactor of phase *c* is going to be saturated. Exactly at this instant, $t = 12.8$ ms, the maximal voltage across the reactor appears in phase *a*, as shown in Fig. 8 with $\hat{u}_{\max} = -58.55kV$. (11)

C. Statistical Tabulation of Reactor Overvoltages

ATP-EMTP has a feature that allows varying randomly the instant of circuit-breaker pole switching time specified by a mean switching time and standard deviation, here called “statistical switch”. Thereby either Gaussian or uniform distribution can be used to determine the switch closing times randomly. This part presents the results of such a statistical study about the influence of the pole span on the overvoltage across the reactors of the filter.

One simulation case based on this “statistical switch” proceeds for this investigation in three steps:

1. The instant t_a of closing for the first pole (phase *a*) is determined in an interval from 0 ms < t_a < 10 ms in order to represent all phase angles within half a period as starting point. For this a uniformly distributed random number is used.
2. The closing instants for the remaining poles t_b and t_c for the phases *b* and *c* are now determined in an interval of $0 < \Delta t < 5$ ms after the instant t_a according to uniform distribution.
3. With these closing instants the energization of the filter is performed and one maximal value of the voltage across the filter reactors found for this single energization case.

To perform a statistical investigation these three steps should be repeated for a sufficient number of cases. This statistical study is based on 200 simulation cases. The 200 values of the maximal voltages over the reactors need to be processed by statistical means. The calculated overvoltages of all 200 cases are classified using classes with a class width of 5% of the amplitude of the voltage of the feeder network:

$$class\,width = 0.05 \cdot \sqrt{2} \cdot 33kV / \sqrt{3} = 0.05 \cdot 26.9kV = 1347V \quad (12)$$

The cumulative distribution of overvoltages of 200 energization cases is shown in Fig. 14. To give a better orientation the red line indicates the amplitude of the withstand test voltage performed at the factory,

$$\hat{u}_{test} = 39.6kV \ . \quad (2)$$

Fig. 14 shows that 26.5 % of the 200 calculated energizations result in maximal reactor-voltages that are higher than the amplitude of the withstand test voltage.

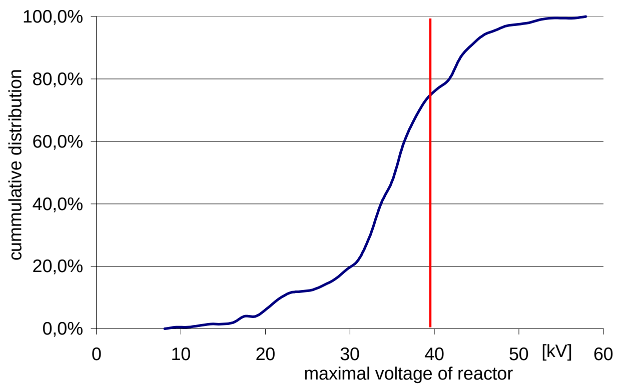

Fig. 14. Cumulative distribution of maximal voltages across the inductors obtained from 200 energization cases.

D. Re-energization of the Filter after Switching-Off

Another severe case of overvoltages across filter reactor can be expected, when the filter H5 will be disconnected and re-energized after a short while, keeping the capacitors of the filter charged. Disconnection of the filter with isolated neutral point results in charged capacitors whose voltage will decay slowly. Energization of the filter with a source voltage of opposite polarity can cause high voltage drop across the reactor of the filter. Simulation results of a re-energization of the filter are shown in figures 15 and 16.

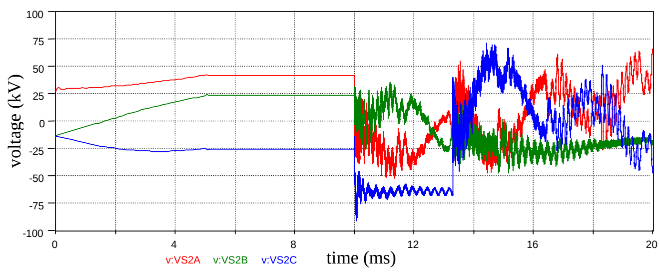

Fig. 15. Voltages at the terminals of the circuit breaker at the filter side

First the circuit breaker is opened resulting in trapped charges in capacitors (d.c. voltages in Fig. 15) and subsequently the circuit breaker poles are closed with the closing instants:

$$t_a = t_b = 10ms; \quad t_c = 13.3ms \tag{13}$$

As shown in Fig. 16 the overvoltage across the filter reactor reaches 83.9 kV.

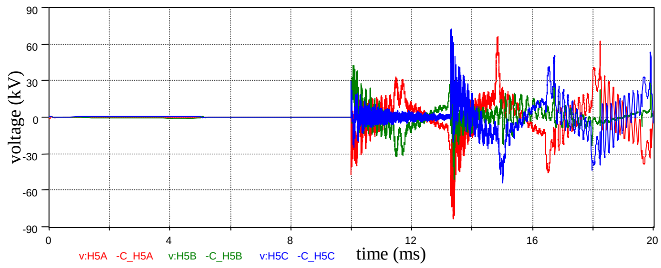

Fig. 16. Voltages across the reactors of the filter H5 due to re-energization

IV. Conclusion

The combination of several reasons leads to the overvoltages across the coils of the harmonic filter during energization. These reasons are:

- Saturation of the magnetic core of the inductors. This saturation acts like a switching action, where the inductance changes nearly instantaneously from the unsaturated inductance to the saturated value. This transition is associated with a voltage collapse across the inductor being saturated, causing voltages across other inductors to rise.
- The saturation, comparable to a switching action, causes transient reactions of the system since there are several inductors and capacitors involved, leading to additional voltage rise. Furthermore travelling waves on the cables cause impulse-like overvoltages superimposed to remaining transient voltages.
- The saturation of the reactors of only one or two phases makes the filter unbalanced resulting in the displacement of the star point of the filter.

Since the inductors are saturated on both sides of the magnetisation curve repetitively, this behaviour is comparable to ferroresonance. These effects decay and disappear after a while and could so be called temporary ferroresonance.

Another severe case of overvoltages across filter reactor can be expected, when the filter will be disconnected and re-energized after a short while, keeping the capacitors of the filter charged.

Most important point of the calculated overvoltages during energization is the use of the statistical switch in order to consider the effect of numerous switching instants. Compared to the case where all poles switch at the same instant with $\hat{u}_{\max} < 40kV$, the statistical maximal voltage is much higher with $|\hat{u}_{\max}| = 58.55kV$.

V. References

[1] Canadian/American EMTP User Group, *ATP Rule Book*, last revision 2003 (information: http://www.emtp.org).

[2] H. K. Hoidalen, "Multi-Phase Circuits in ATPDraw," European EMTP-ATP Meeting 2006 Proceedings, Dresden, September 2006.

VI. Biographies

Mustafa Kizilcay (M'94) was born in Bursa, Turkey in 1955. He received the B.Sc. degree from Middle East Technical University of Ankara in 1979, Dipl.-Ing. degree and Ph.D. degree from University of Hanover, Germany in 1985 and 1991. From 1991 until 1994, he was as System Analyst with Lahmeyer International in Frankfurt, Germany. 1994-2004 he has been professor for Power Systems at Osnabrueck University of Applied Sciences, Germany. Since 2004 he is with the University of Siegen, Germany, holding the chair for electrical power systems as full professor. Dr. Kizilcay is winner of the literature prize of Power Engineering Society of German Electro-engineers Association (ETG-VDE) in 1994. His research fields are power system analysis, digital simulation of power system transients and dynamics, insulation-coordination and protection. He is a member of IEEE, CIGRE, VDE and VDI in Germany.

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