Overvoltages While Switching Off a HV-Transformer with Arc-Suppression Coil at No-Load

K. Teichmann, M. Kizilcay

Abstract--**This paper presents the results of the calculation of overvoltages that occur while switching off a 110/33-kV-transformer on the 33-kV-side with and without single phase-to-earth fault.**

The modelling of the components, the investigation and results for both existing and not existing single-phase-earth-fault in the 30-kV-network, assuming that the HV-side of the transformer is at no-load is presented. The transformer is modelled inclusive the winding-to-winding-capacitances and winding-to-earth-capacitances. Magnetic saturation of the core and the nonlinear behaviour of surge arrestors are also taken into account.

The system components are represented in detail using ATP-EMTP.

Aim of the investigation is to figure out the overvoltages in order to decide if the surge arresters are necessary to limit the overvoltages to permissible values.

Results show that the selection of cases investigated needs to be done with care to find the situations causing critical overvoltages.

***Keywords*--overvoltages, transformer, saturation, resonant earthed neutral system, surge arrester**

I. INTRODUCTION

Transformer is connected to the 30-kV-grid via a cable. Simulations are carried out to identify critical overvoltages that occur while switching off the feeder on the 33-kV-side.

The 30-kV-network has a resonant earthed neutral system, and the transformer compensates the earth fault current by means of an arc-suppression coil connected between star point of the transformer and earth [2].

To determine the location of a sustaining earth fault in a network with resonant earthed neutral system feeders are switched off sequentially until the faulty feeder is located. In this work the earth fault is assumed to be outside of the feeder comprising the cable and the transformer under investigation.

The modelling of the components, the investigation and results for both existing and not existing single-phase-earth-fault in the 30-kV-network, assuming that the HV-side of the transformer is at no-load is presented. This is only one of many possible scenarios studied. [3]

The transformer is modelled inclusive the winding-to-winding-capacitances C2 and winding-to-earth-capacitances C1 and C3. Magnetic saturation of the core is also taken into account. Furthermore the surge arrestors connected to the phases and the star point are considered.

The system components are represented in detail using ATP-EMTP [1].

II. REPRESENTATION OF THE SYSTEM IN ATP-EMTP

According to Fig. 1 a 3-phase voltage source provides an isolated voltage system by means of an ideal 1:1 transformer. 110% of the nominal voltage is assumed. "*Zgrid*" represents the short circuit impedance of the 30-kV-network and is set to (0.0766+j1.021)Ω. The capacitances "*CEo*" represent the phase-to-earth capacitances of the 30-kV-network. "*CEo*" is set to 5.2 µF causing together with the cable capacitance a capacitive earth fault current of about 106 A. This earth fault current is compensated by the arc-suppression coil "*Pet*" connected to the star point of the transformer T21. The impedance of "*Pet*" is set to (0.5+j201) Ω. The resulting earth fault current is about 15A.

The transformer "*T21*" has a rated power of 40 MVA and a short circuit voltage of $u_k = 0.118$ p.u. The saturation characteristic of the transformer is modelled by separate nonlinear inductances connected between the medium voltage side of transformer T21 and its star point. The capacitances *"C1"*, *"C2"* and *"C3"* are the winding-to-winding capacitances and the winding-to-ground capacitances of the transformer, respectively.

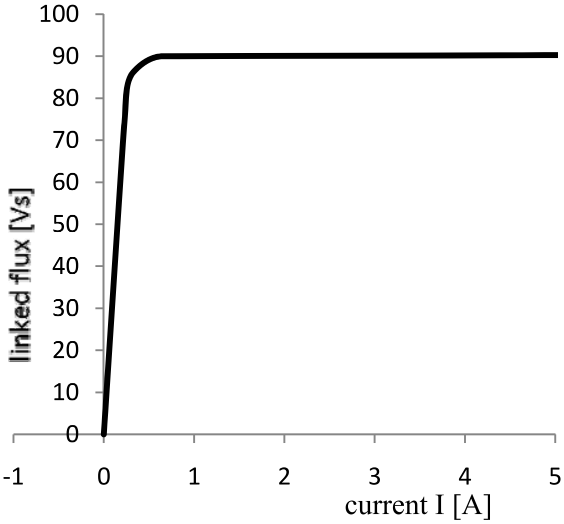

Fig. 2 Magnetization characteristic of T21, flux linkage in Weber-Turns versus magnetization current in A

Autors:
Dr.-Ing. Klaus Teichmann works at the University Of Siegen, Germany in the department Electrical Engineering and Information Technology on Electrical Power Systems.
(e-mail: Klaus.Teichmann@uni-siegen.de)

Prof. Dr.-Ing. Mustafa Kizilcay is Professor for Electrical Power Systems at the University Of Siegen, Germany in the department Electrical Engineering and Information Technology.
(e-mail: Kizilcay@uni-siegen.de)
(Mail: Universität Siegen, FB12 EEV, Hölderlinstr.3, D57076 Siegen)

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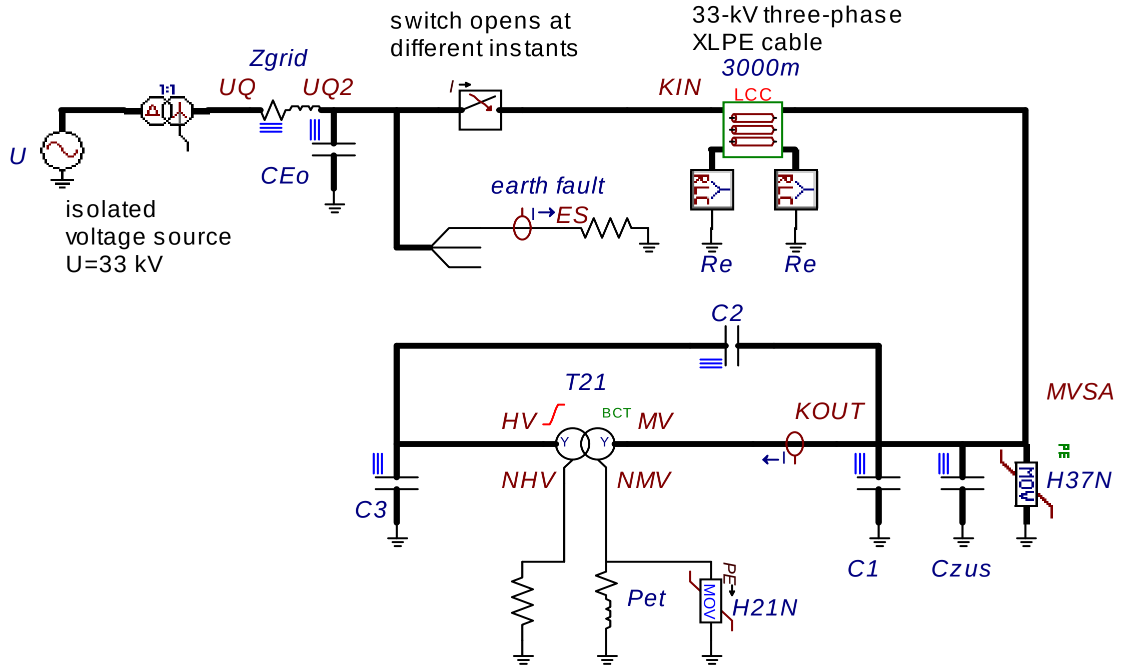

Fig. 1 Circuit under Investigation

The cable between the circuit breaker and the transformer consists of 3 phases, each being a N2XSY XLPE-isolated single phase cable with sheath having a square section of the conductor of 240 mm2 and a square section of the sheath of 25 mm2. The length of the cable is 3000m.

The sustaining single phase-to-earth fault is, if active, in phase *A*.

Surge arrestors can be considered that are connected between phase terminals and earth as well as between star point and earth of the MV-side. The surge arrestors are modelled as nonlinear resistors characteristic of which is given as point list according to table 1.

The arc in the circuit breaker between the nodes *UQ2* and *KIN* is assumed to extinguish at zero crossing of the current.

III. RESULTS OF SIMULATIONS

A. *Results without earth fault, Case S*

In this section the results are presented for the case when no earth fault occurs in the 30-kV network. The network is symmetrical and there is no star point displacement and no current through the arc-suppression coil occur in steady state. This case is called case S.

TABLE I
CHARACTERISTIC OF THE SURGE ARRESTORS

	H37N	H21N
i (A)	u (V)	u (V)
0.0001	52326	29698
0.01	65478	37193
1	73073	41508
10	78574	44632
100	84794	48165
1000	91300	51800
2000	95000	53900
3000	97200	55200

A load on the HV-side is not taken into account for the investigation presented here.

Fig. 3 shows the currents through the switch that are symmetrical before the opening of the switch at t = 20 ms. Shortly after opening of the switch contacts, at t = 20.3 ms, the first current in phase *A* is interrupted. By this action the circuit becomes unsymmetrical, what causes the current in the arc-suppression coil to increase. After the interruption of the second and third phase current, i_C and i_B, the current of the arc-suppression coil needs to flow through capacitances causing oscillations in the zero sequence system.

The very fast decay of the phase *B* current i_B short before its interruption results from a peak in magnetization current due to the magnetic saturation of phase *A* as can be seen in Fig.5.

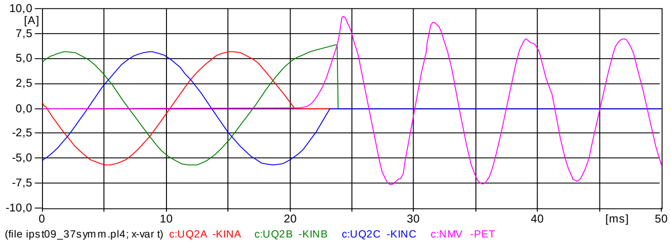

Fig. 3. Phase currents of the circuit breaker and current of the arc-suppression coil, topen=20ms, Case S

Fig. 4 shows the phase-to-earth voltages at the MV-terminals of transformer T21. After the interruption of current i_A the voltage of phase *A* decays slowly. This results in a large voltage-time-area, what is a linked flux, causing the saturation of the core *A* at t = 23.8 ms, compare Fig. 5.

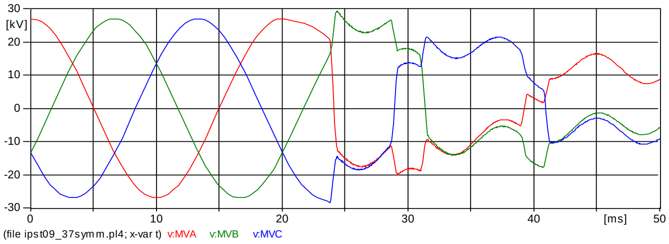

Fig. 4 Phase-to-earth voltages at the MV-terminals of transformer T21, Case S

This saturation is linked with a high magnetizing current. The magnetizing currents through the external nonlinear inductances are shown in Fig. 5. All three phases show current peaks due to saturation. Furthermore Fig. 5 shows the voltage from terminal A of the transformer to its star point.

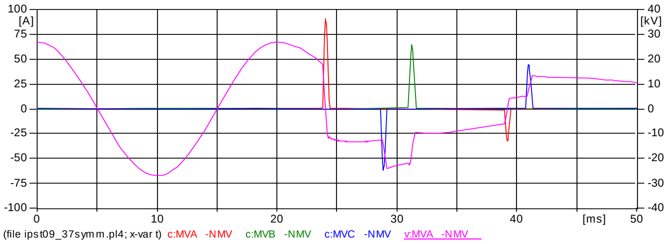

Fig. 5 Magnetization currents (scaled on the left axis) and voltage at the MV-terminal of phase *A* to star point *NMV* (scaled on the right axis), Case S

These current peaks through the external nonlinear inductances do not flow through the arc-suppression coil or the surge arrestor connected to the star point, but flow back through the other phases of the transformer towards the 30-kV cable, as is shown in Fig. 6. There the phase current towards the complete transformer, comprising T21 and the external nonlinear inductances, is drawn.

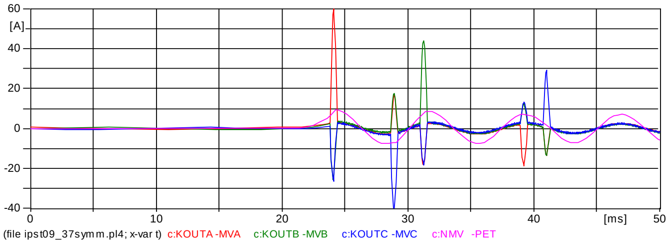

Fig. 6. Line currents from the 30-kV cable to the transformer T21 and current of the arc-suppression coil, Case S

In comparison to Fig. 5, where the currents through the external nonlinear inductors are shown, the currents flowing from the 30-kV cable towards the transformer show that each current peak in one external nonlinear inductor is associated to two opposite peaks of half the size in the other two phases, as shown in Fig. 6.

The current of the arc-suppression coil is sinusoidal after the interruption of all three phase currents, in spite of current peaks due to saturation. With this it can be understood, that a current peak in the external nonlinear reactor in one phase can influence voltages and currents in other phases. This is the reason why the current of phase *B* in Fig. 3 can decrease so rapidly before its interruption. Furthermore it can be explained why all three phase voltages are affected by the current peaks due to saturation. In the further it is favoured to show the currents through the external inductances over showing the currents towards the transformer since less current peaks occur.

B. *Results with sustaining earth fault in phase A*

This section shows the result for three different cases. The sustaining earth fault makes the circuit unsymmetrical. Depending on the instant of mechanical opening of the contacts of the switch the currents in different phases are the first to be interrupted, so three cases are possible.

1) *Current in phase A is interrupted first, Case A*

Fig. 7 shows the currents of the circuit breaker between nodes *UQ2* and *KIN*.

Before opening of contacts of the switch the three phase currents nearly form a zero sequence system, since the amplitudes are quite equal and the phase shifts between the currents are small. This behaviour is as expected for the arc-suppression coil, since it is intended to increase the impedance of the zero-sequence-system by setting up a parallel resonance.

The instant of opening of the contacts of the switch is set to 19.5 ms. In this case the current in phase *A* is interrupted first. So this case is further on called case A.

The current in phase *B* is interrupted 0.5 ms later. Only the current in phase *C* continues to flow some more milliseconds, showing a negative peak with nearly 100A shortly before it is interrupted. This peak is caused by the magnetic saturation of phase *A* as can be seen in Fig. 9.

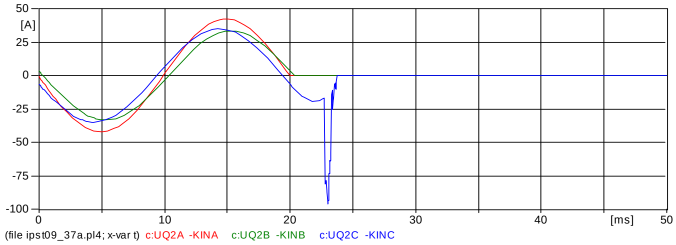

Fig. 7. Phase current of the circuit breaker, topen=19,5ms, Current in Phase *A* is interrupted first, Case A

Fig. 8 shows the phase-to-earth voltages at the MV-terminals of *T21*. At the instant when the core of phase *A* goes into saturation and the current peak in phase *C* of the circuit breaker occurs, the voltage of phase *B* reaches a value of nearly 80kV. It is limited by the phase-to-earth surge arrestor.

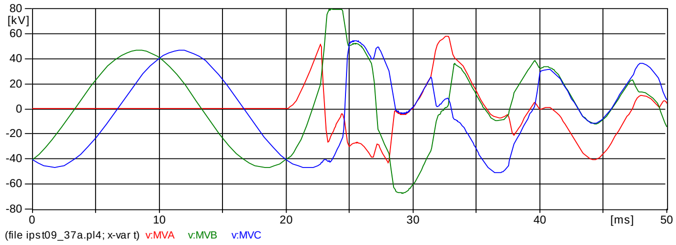

Fig. 8 Phase-to-earth voltages at the MV terminals of transformer T21, Case A

Fig. 9 shows the magnetizing currents from the MV-terminals to the MV-star point. Taking the magnetization characteristic of the core according to Fig. 1 into account, it is clear that the cores are heavily saturated, since the maximum value of the current in phase *A* is nearly 250A. The reason for this saturation is the increase of the voltage from MV-terminal *A* to MV-star point that is also displayed in Fig. 9.

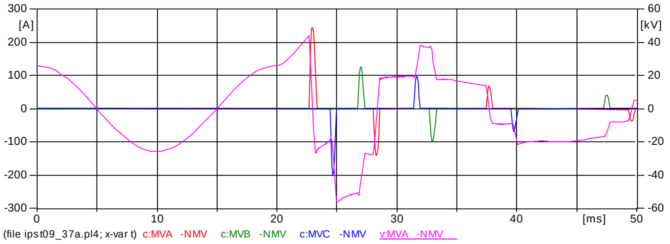

Fig. 9 Magnetization currents (scaled on the left axis) and voltage from MV-terminal of phase *A* to star point *NMV* (scaled on the right axis), Case A

After the interruption of the phase currents i_A and i_B at about t = 20 ms this voltage increases beyond the steady state amplitude instead of decreasing. This results in a large voltage-time-area, what is a linked flux, causing the saturation of the core A at t = 23 ms.

The first current peak results in an increase of the voltage from phase *B* to earth to nearly 80 kV.

After the interruption of the phase current i_C at t = 23.7 ms several current peaks of the magnetization currents occur also in the other phases. Since the circuit breaker is open these current peaks discharge and charge the capacitors in the MV-feeder. As long as the magnetization currents are close to zero, these capacitor voltages contain an offset voltage superposed to the oscillation in the zero sequence system, where the inductances of the transformer and the arc-suppression coil oscillate with the capacitances that mainly consists of the cable capacitance. This can be seen in Fig. 8 for instance in the range 40 ms < t < 47 ms. The linked magnetic flux as integral of the voltage goes into saturation causing magnetization currents that modify the capacitor charges.

In order to demonstrate the influence of the surge arrestors Fig.10 shows the results if the surge arrestors are inactive. A maximum voltage of nearly100 kV is reached.

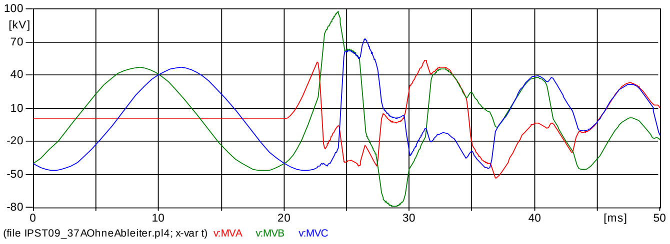

Fig. 10 Phase-to-earth voltages at the MV terminals of transformer T21, Case A, without surge arrestors

2) *Current in phase B is interrupted first, Case B*

By setting the instant of opening to t = 20 ms the current in phase *B* is the first to be interrupted. This case is called case B. Figures 10 to 12 show the plots comparable to case A. In comparison to case A the results are quite similar: Current i_B is interrupted, while currents i_A and i_C continue flowing for some milliseconds. Again a large negative current peak appears when the core gets saturated.

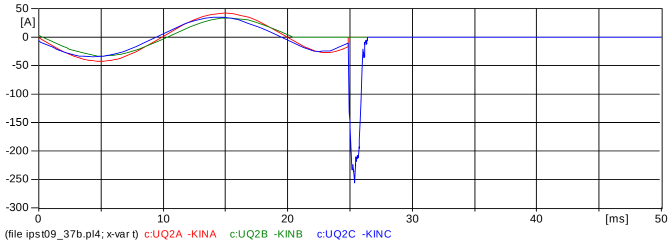

Fig. 10 Phase current of the circuit breaker, topen=20,0ms, Current in Phase *B* is interrupted first, Case B

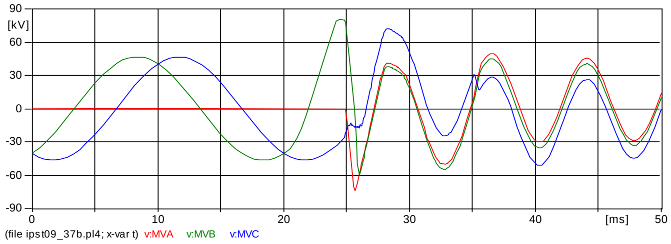

Fig. 11 Phase-to-earth voltages from the MV terminals of transformer, Case B

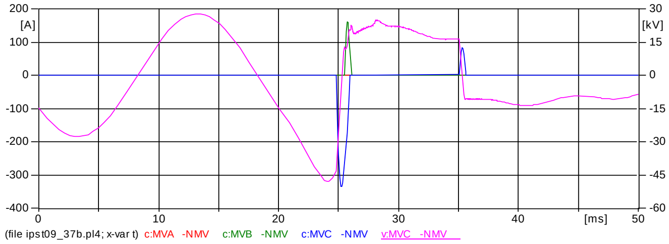

Fig. 12 Magnetization currents (scaled on the left axis) and voltage from MV-terminal of phase *C* to star point *NMV* (scaled on the right axis), Case B

The maximum voltage that appears in case B is slightly higher than in case A. The DC-components superposed to the oscillations in the zero sequence system are less than in case A and lead consequently to less current peaks due to saturation of the core. The maximum voltage occurs in phase *B* with about 80.5 kV. It is limited by the surge arrestors.

3) *Current in phase C is interrupted first, Case C*

Finally the case C is represented where the current in phase *C* is the first to be interrupted. This is the most probable case since all instants of opening of the switches within half a period in the time span 10.3 ms < t < 19.4 ms will produce this case, while only instants of opening in the time span 19.4 ms < t < 20.3 ms will produce cases A or B, so that these cases will occur relatively seldom.

Figures 13 to 15 show the results. The voltages occurring at the terminals of transformer *T21* are much less than in cases A and B and do not exceed the steady state amplitude during earth fault.

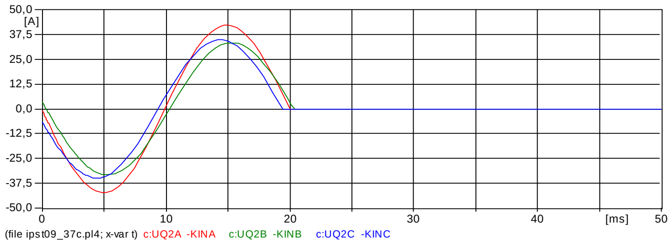

Fig. 13 Phase current of the circuit breaker, topen=19,0ms, Current in Phase *C* is interrupted first, Case C

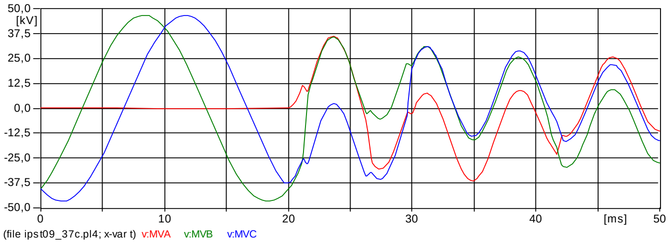

Fig. 14 Phase-to-earth voltages at the MV terminals of transformer T21, Case C

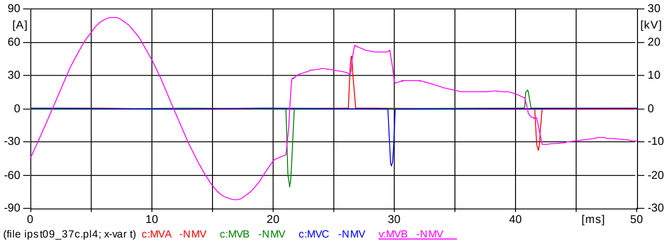

Fig. 15 Magnetization currents (scaled on the left axis) and voltage from MV-terminal of phase *B* to star point *NMV* (scaled on the right axis), Case C

In this case all three currents are interrupted within a short time span of less than 1 ms. There is no current peak in the currents of the switch as it occurs in the cases A and B. So the capacitors are not charged additionally and no overvoltages occur in this case. As a result of the little difference in the instants of interruption of the currents through the switch a relatively small DC component is found in the voltages. Again magnetic saturation causes current peaks in the magnetization currents of the external nonlinear inductances of smaller amplitude; that as a consequence does not have so important influence on the voltages.

IV. CONCLUSION

The aim of this overvoltage study is to identify the conditions that cause overvoltages and to compute their magnitudes in case of switching-off an MV-transformer feeder with arc-suppression coil connected to the star point of the transformer windings. The overvoltages are linked to the current of the arc-suppression coil and the magnetization currents that are very much influenced by the saturation characteristic, so nonlinear circuits need to be investigated.

In most cases there are no critical overvoltages found. Only in certain cases, that do not occur very frequently, important overvoltages are observed. This makes clear that the selection of the investigated cases needs to be done with care to find the relevant situations.

The investigations prove, in combination with further investigations [3], the need for the installation of surge arrestors phase-to-earth and starpoint-to-earth in those systems.

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V. BIOGRAPHIES

Klaus Teichmann (Dr.-Ing) was born in Welschen-Ennest in Germany, in 1958. He graduated from the University of Siegen in 1983. His doctoral thesis from 1989 dealt with test of protection devices by means of real time transient network analyzer.
Now he is assistant professor at the University of Siegen, Dept. of Electrical and Computer Eng., Institute of Electrical Power Systems.

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.