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A PHYSICAL ARC MODEL FOR THE SIMULATION OF CURRENT ZERO BEHAVIOR OF HIGH-VOLTAGE CIRCUIT BREAKERS

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ABSTRACT

The interrupting capability of SF_6 circuit breakers has increased drastically during the last decade. After the development tests, high-voltage circuit breakers are tested in the High-Power Laboratory, where test conditions prescribed by standards and switching conditions in electrical transmission networks are simulated. It is important that the test circuits used in the laboratory give a correct representation of the current and voltage stress. In this paper the equations and parameters of a physical arc model are presented which can be used to compare test circuits with respect to the thermal and dielectric interrupting interval of SF_6 circuit breakers. An example calculation with the Alternative Transient Program (ATP) shows the interruption of a terminal fault with a 4-parameter TRV. The sensitivity of the arc model in the thermal interrupting interval is demonstrated by comparing artificial line circuits.

INTRODUCTION

Our paper cited in reference |1| discusses the background of circuit breaker modelling. It was demonstrated that the black-box model, which uses the Mayr equation to describe the variation in arc conductance of a switching arc in a high-voltage circuit breaker, is not suitable for simulating the thermal and dielectric interrupting interval. A physical arc model developed at KEMA's research department was introduced and comparison results of switching behavior of circuit breakers in a direct and two synthetic test circuits were presented. In this arc model, the arc conductivity before current zero is calculated from the energy balance using the modified Mayr equation with three free parameters before current zero only.

In the thermal and dielectric region after current zero the conductivity is calculated from the charged particle concentration and their drift velocity as a function of time in the afterglow. When the transient recovery voltage builds up across the breaker contacts, drifting of electrons and ions leads to a thermal post-arc current, or later in time, to ionization in the post-arc channel. This results in a thermal or dielectric failure of the breaker to interrupt the current.

The equations of the modified Mayr model, which are used to simulate the arc conductivity before current zero and the equations of the physical arc model which represent the arc conductivity in the thermal and dielectric interrupting interval after current zero, are given in this paper.

In practice, high-voltage circuit breakers must be able to interrupt a wide range of load and fault currents. The most severe test duty for testing the thermal interruption interval is the short-line fault test (SLF). A short-line fault occurs in an overhead line at a distance of a few hundred meters to a few kilometers from the terminals of the circuit breaker. Immediately after current interruption the still hot arc column is stressed by a very high initial rate of rise of the triangularly shaped recovery voltage.

In the High-Power Laboratory the interruption of a short-line fault is simulated by means of an artificial line |2|. The voltage wave shape generated by the line is very important. Especially SF_6-puffer circuit breakers are very sensitive to voltage stresses in the first few microseconds after current interruption, so a correct representation of the rate of rise of the recovery voltage can be decisive |3|. Three artificial lines are compared as case studies to demonstrate the arc-circuit interaction in the thermal interruption interval.

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The conductance of the arc model changes rapidly around current zero and in the computer calculations the step length must be very small to preserve accuracy |1|. Network-independent computer programs like the Electromagnetic Transient Program (EMTP) and the Alternative Transient Program (ATP) have a fixed time step and that makes these programs less suitable for implementation of an arc model. These transient programs, however, are widespread among utilities, research institutes and universities. For this reason the equations of KEMA's arc model for implementation in ATP are presented. The sensitivity studies, however, with the three artificial lines have been computed with ACSL (Advanced Continuous Simulation Language) using variable time step and Gear's integration routine.

ARC MODEL

During the current zero period the arc-resistance is of the same order of magnitude as the circuit impedance. This leads to strong arc-circuit interaction.

Before current zero the arc resistance is calculated with a Mayr-type differential equation for the arc conductance with a constant time parameter τ and a current-dependent cooling power $P(I) = p\,(P_o + C_I\,|I|)$ in which p represents gas pressure and I the arc current. The non-linear arc resistance

$$R_a = \frac{1}{G} = \frac{V}{I} \quad (1)$$

is calculated from

$$\frac{1}{G}\frac{dG}{dt} = \frac{1}{\tau}\left(\frac{I.V}{P(I)} - 1\right) \quad (2)$$

The three fitting parameters C_I, P_o and τ are derived from the measured arc resistance $R_a = 1/G$ and thus from arc voltage and current in the following way:

- C_I is derived from arc voltage at currents in excess of 1 kA.
- P_o is deduced from the slope in a plot of $\log(R_a(t_o))$ versus $\log(t_o)$ in which t_o is the time before current zero. This slope was found to be 1.2 - 1.3 for a rotating arc as well as a puffer-type SF_6 circuit breaker.
- τ can be derived from the $\log(R_a(t_o)) - \log(t_o)$ plot for $t_o < 5$ µsec. A high extinction peak or sharp increase in R_a for small t_o means a small time parameter τ. A time constant in the order of 1 µsec leads to a resistance $R_a(o)$ inbetween 100 Ω and 1000 Ω at current zero.

After current zero the number density of charged particles (electrons, positive and negative ions) was calculated in the decaying hot gas channel, starting from an initial electron number density in accordance with $R_a(o)$ at current zero, as calculated with the modified Mayr model. The afterglow channel is assumed to be uniform with length L and radius r. The conductivity of the channel changes due to changes in the electron number density N_e caused by diffusion (γ), electron-ion recombination (β_{e-i}), attachment (η) and ionization (α). Also, the ion number densities N_+ and N_- are changing with time; if charge neutrality is assumed then:

$$\frac{dN_e}{dt} = -\gamma N_e - \beta_{e-i} N_e N_+ + \alpha_{eff} |V_{dr}| N_e \quad (3)$$

$$\frac{dN_-}{dt} = -\alpha_{eff}^{\min} |V_{dr}| N_e - \beta_{i-i} N_- N_+ \quad (4)$$

$$N_+ = N_e + N_- \quad (5)$$

When a voltage is applied to this channel, the charged particles drift in an electric field $E = V/L$. Conductivity can be expressed as (see reference |4|):

$$G = C_e N_e \frac{T}{p}\frac{r^2}{L} + C_i\,(N_+ + N_-)\,\frac{T}{p}\frac{r^2}{L} \quad (6)$$

in which T is the neutral gas temperature, p gas pressure and C_e and C_i constants depending on the gas (composition). Parameters like $\alpha_{eff.} = \alpha - \eta$, V_{dr}, β_{e-i} and β_{i-i}, $N \sim p/T$, T and r are all time-dependent and some are E-field or temperature dependent and will now be discussed in more detail.

The drift velocity V_{dr} of electrons and ions in an electric field depends on the reduced electric field E/N, in which N represents gas density. Linear dependence on E/N is assumed. The proportionality constant is fitted to data from the literature in the region where $\alpha = \eta$.

The attachment coefficient in this region is only mildly dependent on E/N and therefore taken constant. The ionization coefficient, however, increases strongly with E/N. Therefore, the effective ionization coefficient $\alpha_{eff} = \alpha - \eta$ is defined as:

$$\alpha_{eff} = \max\left(\alpha_{eff}^{\min},\ C_\alpha \left|\frac{V}{L}\right| - \frac{p}{T}\,(E/N)_{crit}\right) \quad (7)$$

and shown in the diagram in Fig. 1. For decomposed hot SF_6-gas the numerical value for η is only about 1% of the value for cold SF_6-gas, because attachment is mainly to F atoms and in hot air it is about 0.1% of the value for cold SF_6-gas.

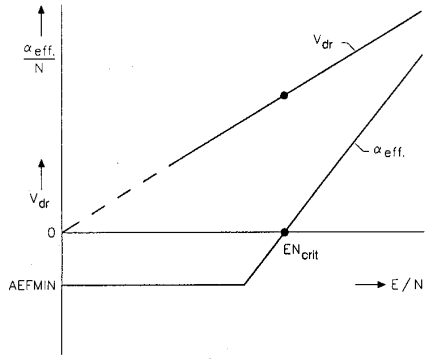

Fig. 1

Ionization coefficient and drift velocity as a function of E/N.

Recombination coefficients for molecular gases at room temperature are in the order of $10^{-14} m^3/s$ for electron-ion processes and $10^{-13} m^3/s$ for ion-ion processes. In hot decomposed gases the temperature dependence has been taken into account by a factor proportional to $T^{-3/2}$; also numerical values were taken from measurements in air and SF_6 in a hot afterglow of a rotating arc experiment and have been normalized at 3000 Kelvin. The time dependence of the gas temperature T is modeled as a double exponential decay, starting at 8000 Kelvin with time constants τ_1 (10 µsec) and τ_2 (200 µsec) of the arc core and arc boundary layer. Finally, the arc radius r is assumed to decay exponentially with a time constant τ_r (500 µsec).

Arc conductivity and arc current can now be calculated in the afterglow as a function of the transient recovery voltage (TRV) generated by the electrical network. A dielectric reignition in the hot channel is possible if the ionization coefficient α exceeds the attachment coefficient to cause an increase in electron number density N_e, outnumbering the e-i recombination and attachment. This happens when the TRV generates a reduced electric field E/N exceeding E/N_{crit}. The increase in conductivity results in a high post arc current and finally a voltage collapse. The computation returns in this case to the Mayr model to calculate the fast and slow transients in the network properly. If electron number density decay just after current zero is not fast enough (insufficient attachment and recombination), the post arc current will become high and so will the power input in the post arc channel. If this power input exceeds P(o) by a certain factor (1.5), then the computation also returns to the Mayr model and the reignition is called thermal.

IMPLEMENTATION OF THE ARC MODEL IN ATP

The behavior of an electric arc in a circuit breaker is described by means of variable conductance. In reference |5| Kizilcay demonstrated that it was possible to implement circuit breakers in EMTP by means of a TACS-controlled resistance. However, in EMTP version M39 this device was not yet present. In later ATP versions of this transient program a special TACS-controlled resistance type 91 was available. In reference |5| a single arc equation was used to describe the arc behavior before and after current zero. As demonstrated in our paper cited in reference |1| such a black-box model is not suitable for simulating the thermal and dielectric interrupting interval.

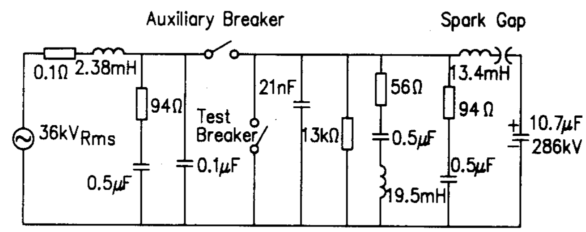

Fig. 2

Parallel current injection circuit for a 245 kV - 40 kA - 60 Hz circuit breaker. First-pole-to-clear factor 1.3.

Generally speaking, when modeling a circuit breaker in ATP a number of steps can be distinguished:

1. The current flowing in the arc of the breaker is transferred to TACS.
2. In TACS the arc equations are solved and arc conductance is calculated.
3. This conductance value is transferred to ATP.
4. The node equations are solved in ATP.

Step 2 will now be described more in detail. Before current zero arc conductance is calculated with equation (2) and after current zero with equation (6). In TACS both equations are solved for each time step.

Equation (2) is easily solved with a controlled integrator type 58 but for the solution of equations (3, 4, 5, 6, 7) a number of Fortran expressions have to be used to calculate the change of the electron densities N_e in the afterglow as well as the ion density N_+ and N_-. The next step in TACS is to determine if the current passed through zero and the appropriate conductance value was chosen. In TACS the reignitions are also detected. A reignition can either be thermal due to the insufficient cooling or dielectric due to ionization in the hot gas channel.

As an example a bolted terminal fault of a SF_6 puffer breaker with a nominal rated breaking current of 40 kA in a parallel current injection test circuit, with a four parameter transient recovery voltage, was calculated (Fig. 2). In these simulations the following parameters were applied before current zero:

$$P_0 = 1000 \text{ W/bar}$$
$$C_I = 100 \text{ W/A/bar}$$
$$\tau = 0.7 \ \mu s$$

and after current zero:

$$E/N_{crit} = 5.0 \text{ E5}$$

$$AEFMIN = -0.01$$

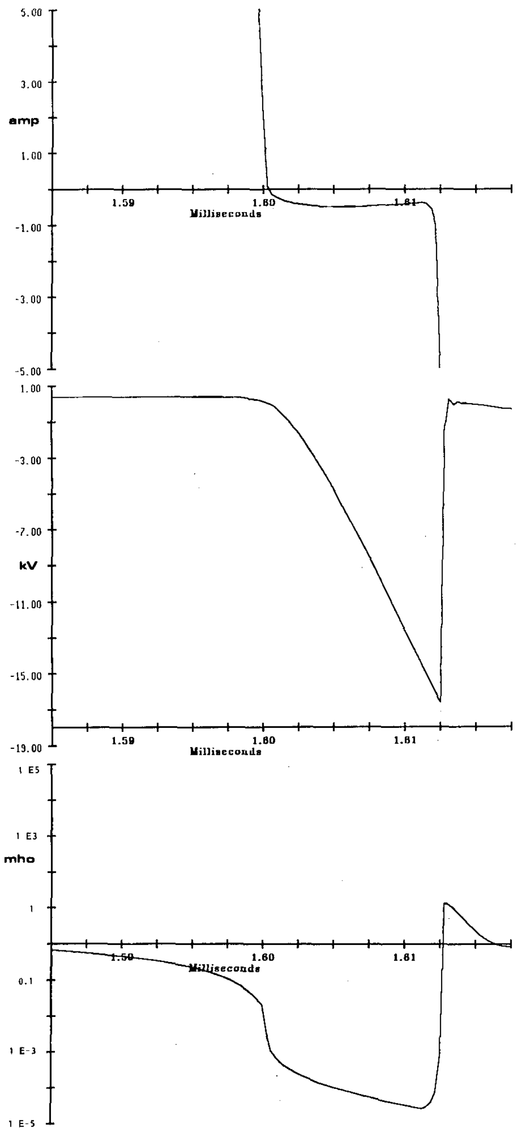

Fig. 3

Current, recovery voltage and arc conductance for the circuit of Fig. 2. SF_6 pressure 3.95 bar.

In the breaker model the SF_6 pressure was varied to find the critical pressure below which reignition occurs. At a gas pressure of 4.0 bar the breaker model was just able to clear the short-circuit current without thermal reignition.

The post-arc current, the recovery voltage and the arc conductance are shown in Figure 3. The value of the post-arc current just before breakdown is about 0.5 Amps. The arc resistance changed from 200 Ω to 100 kΩ (conductance from 5E-3 mho to 1E-5 mho) within 11 µs. These results are in agreement with calculations with ACSL and experimental experience.

There is, however, a drawback when using EMTP or ATP for circuit breaker studies. For a correct calculation the time step must be small compared with the smallest time constant in the network. In this case it is the time constant of the arc model (0.7 µs) so a time step of 0.1 µs was used. Such a small time step is necessary, because the conductance of the arc changes very rapidly around current zero.

This results in 25 min. computation time on an APOLLO 3000 computer for 2 milliseconds circuit calculation. About half this time was used to simulate the arc before current zero. However, in this interval the arc conductance changes only one decade which means that a greater time step could have been used. Therefore, it can readily be concluded that when detailed parameter studies have to be performed, for instance during circuit breaker development it is very inconvenient to use ATP. A more sophisticated and faster approach is to use a set of first-order differential equations and solve them with ACSL as described in our paper cited in reference [1]. This has been done to conduct the sensitivity studies with artificial lines.

SENSITIVITY STUDIES WITH ARTIFICIAL LINES

In the past several types of artificial lines have been designed and built based on series connection of LC-parallel networks (the Todoriki line) or pi networks. The disadvantage of these designs is that in theory the number of sections must be infinite in order to obtain an ideal triangularly shaped wave form. In practice, however, at least 6 sections are required for a line built with pi sections and for a line built with series LC-networks at least three sections are required (Fig. 4) to generate a triangularly shaped wave form. A line built with a limited number of pi sections always has an inherent time delay caused by the capacitor seen from the terminals of the line. For the pi section line this time delay is:

$$t_d = C_1 * Z_L$$

Z_L is the surge impedance of the line.

For the line with three LC-series networks the inherent time delay is:

$$t_d = {}^{1}/_{3}\ C * Z_L$$

An artificial line that has theoretically no inherent time delay, viz. the KEMA line, has been described in reference |2|. The inherent transient recovery voltages of the three different artificial lines for the first few microseconds after current zero are shown in Fig. 6.

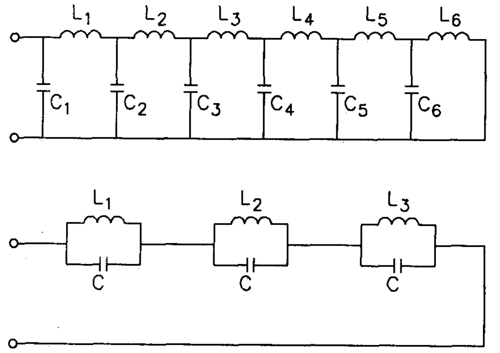

Fig. 4

Pi section line (top) and Todoriki line.

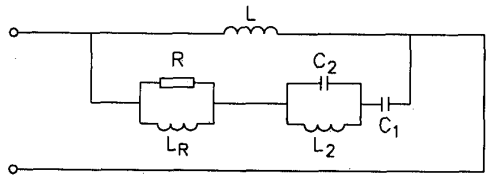

Fig. 5

KEMA line.

A comparison of the wave shape quality of several artificial line circuits showed that the KEMA line has the best performance with a minimum of components (Fig. 5). The wave form of this artificial line matches the wave shape of a real transmission line best. The line circuits have been used to prove the sensitivity of the arc model and to investigate the effect of arc-circuit interaction when using different types of artificial lines. It was not the aim of the calculations with the KEMA arc model to compare the three different artificial line circuits with each other, because the practical and theoretical performance of the artificial line circuits has already been demonstrated |2, 3|.

The circuit that was used for the computer calculations and the different line circuits is shown in Fig. 7.

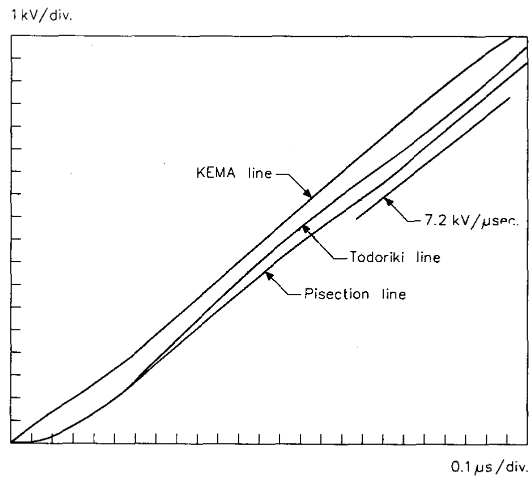

Fig. 6

Inherent recovery voltage for the KEMA line, the Todoriki line and the pi section line. SLF 90%, 245 kV - 40 kA - 50 Hz.

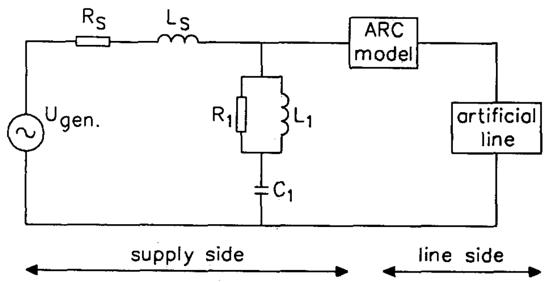

Fig. 7

Circuit used for the computer calculations.

245 kV - 40 kA - 50 Hz

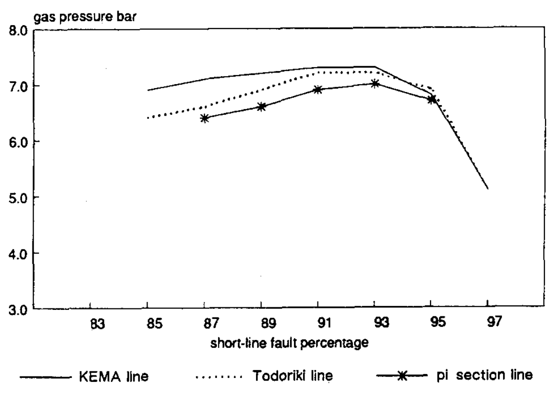

Fig. 8

Minimum required gas pressure (bar abs) as a function of the short-line fault percentage for three artificial lines.

The circuit parameters of the line circuits were calculated for short-circuit factors of 85%, 87%, 89%, 91%, 93%, 95% and 97%.

Gas pressure was used as a variable parameter in the arc model. It influences the performance of circuit breakers in practice and it does so in the KEMA model as well. In the three different line circuits the gas pressure parameter of the arc model was varied until the value was found at which the arc-models were just able to clear the short-line fault current without thermal reignition.

Fig. 8 shows the minimum gas pressure as a function of the short-line fault percentage for a 245 kV/40 kA, 50 Hz circuit breaker in a test circuit with a pi section, the Todoriki and the KEMA artificial lines.

It shows clearly that the KEMA line which has no inherent time delay and the correct surge impedance as required by the IEC standards, is severer on a circuit breaker than the Todoriki line or the pi section line, when the effect of arc circuit interaction taking into account. This is in accordance with the conclusions of earlier publications (see reference |2| and |3|) and it proves the sensitivity of the KEMA arc model in the thermal interruption interval of a circuit breaker.

To demonstrate the influence of the circuit breaker rating, calculations have been done with the KEMA line for a 170 kV, 245 kV, 420 kV and 525 kV voltage rating and a nominal short-circuit current of 40 kA at 50 Hz. Minimum gas pressure as a function of the short-line fault percentage is shown in Fig. 9.

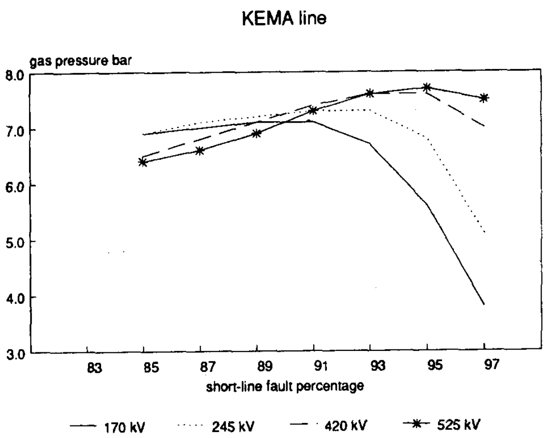

Fig. 9

Minimum required gas pressure (bar abs) as a function of the short-line fault percentage for four breaker voltage ratings. The artificial line is the KEMA line.

CONCLUSIONS

The calculation of current and voltage transients in test circuits for high-voltage circuit breakers requires a good model for the rapidly changing conductance in the switching arc. The conductivity around current zero is modeled with a modified Mayr equation before current zero and the thermal and dielectric interval after current zero with a recombination model. The KEMA arc model leads to thermal and dielectric reignitions under too severe electrical stress after current interruption of bolted terminal faults as has been demonstrated in our earlier publication see reference |1|.

The arc model is easy to implement in transient programs such as EMTP and ATP; however, a small time step in the calculation leads to relatively long computation times.

The KEMA arc model is also very sensitive in the first few microseconds immediately after current interruption, as is demonstrated by the comparison of three artificial line circuits.

REFERENCES

|1| L. van der Sluis and W.R. Rutgers, "Comparison of test circuits for High-Voltage Circuit-Breakers by numerical calculations with arc models", paper presented at the 1990 IEEE-PES International Power Meeting, New Delhi, India, 28 Oct. - 1 Nov. 1990. Paper 90 IEC 568-6 PWRD.

|2| L. van der Sluis and W.A. van der Linden "A new artificial line for testing High-Voltage Circuit-Breakers". IEEE transactions on Power Apparatus and Systems, Vol. PAD-102, No. 4, April 1983, p. 797-803.

|3| Guy St-Jean and Michel Landry, "Comparison of wave shape quality of Artificial Lines used for Short Line Fault Breaking tests on HV Circuit-Breakers. IEEE transactions on Power Delivery, Volume 4, No. 4, October 1989, p. 2109-2113.

|4| W.R. Rutgers, "A new model for the calculation of switching arc phenomena", Proceedings IX International Conference on Gas Discharges and their applications, Venice 1988, p. 103-106.

|5| M. Kizilcay, "Dynamic Arc modelling in EMTP/TACS", 10th European EMTP users Group meeting, May 5/6, 1986, Copenhagen, Denmark.

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His work involved the measurement of pre-breakdown currents in the neighbourhood of spacers in SF_6 insulation. In 1980 he joined KEMA as a researcher in the Electrical Research Department. His work involved ageing of polyethylene cables and surge arresters as well as the measurement of transient phenomena in high-voltage networks. Presently he is employed by the Dutch Electricity Generating Board, where his work concerns the protection of the Dutch 400 kV network. Mr. Koreman is a member of CIGRE WG 33-03, "High-Voltage Testing and Measuring Techniques".