INTRODUCTION OF ADEQUATE NEUTRAL EARTHING SCHEMES IN EVO's DIFFERENT MEDIUM VOLTAGE NETWORKS TO MEET POWER QUALITY DEMAND

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SUMMARY

Energieversorgung Oberfranken AG (EVO) is a regional utility in southern Germany. In recent years an increasing number of cables have been installed to enhance the quality of power supply for customers and to reduce the maintenance costs for the utility. The networks were operated with arc suppression coils. In order to improve conditions from the point of view of power supply for customers and operation for the utility, adequate neutral earthing schemes for the different types of 20 kV distribution network were developed and put into operation.

INTRODUCTION

Energieversorgung Oberfranken AG (EVO) is a regional utility in southern Germany. It is part of the Bayernwerk Gruppe and based in Bayreuth. The area of supply is 8,800 km^2 and covers the whole region of Upper Franconia as well as parts of Central and Lower Franconia (Fig. 1). There are 703,000 customers in towns as well as in rural areas. The peak demand of 1,200 MW is fed to the extent of 2/3 from the overlaying 380 kV and 220 kV grids, and to 1/3 from the utility´s own Arzberg power station. The EVO network consists of 1,600 km of 110 kV lines and 7,060 km of 20 kV lines, of which 40 % are cables. There are also 14,000 km of low-voltage lines with 80 % cables.

Fig. 1 EVO's area of supply in Germany

In order to enhance the quality of power supply for customers and to reduce the maintenance costs for the utility, an increasing number of cables have been used in recent years to loop in new substations or to replace older overhead lines.

The medium-voltage networks were operated with arc suppression coils. Due to XLPE cables with a higher rate of insulation failures, permanent earth-faults developed into cross-country faults with major supply disturbances and interruptions. This behaviour was contrary to the aim of continuous power supply under earth-fault conditions.

In order to improve the conditions from the point of view of power supply for customers and operation for the utility, adequate neutral earthing schemes for the different types of 20 kV distribution network were developed and put into operation.

NEUTRAL EARTHING PRACTICE IN EVO's 20 kV NETWORKS

Under normal circumstances the method of neutral-point connection has no effect whatever on the transmission and distribution of power. On the other hand, however, it does have an effect on the operation of the network when earth faults occur; the latter are the most common kind of disturbance encountered. So, indirectly, there is an effect on the quality of the power supplied to customers.

In the past, the medium-voltage networks were almost entirely overhead power lines and were operated with arc suppression coils.

The advantage of using arc suppression coils is that arcing faults in air can extinguish automatically by means of the well tuned arc suppression coil. This means that single-pole flashovers resulting from pollution, atmospheric discharge, animals, vermin or similar causes can be eliminated without the need for any action on the part of the operating staff and without customers' supplies being interrupted.

The advantage in case of not self extinguishing earth-faults is the lower current loading at the site of the fault and the ability to continue supplying power to customers under earth-fault conditions.

The increasing amount of cabling being used in the networks now has caused the capacitive earth-fault current of the various subnetworks to increase substantially. Any earth faults that occur on cable runs are nearly always sustained earth faults which must be located and cleared. Past experience has shown that another earth fault often occurs in a different phase before the first fault can be cleared without interruption of supply. This situation leads to brief dips in

voltage, interruptions in power supplies to customers and to an excessive amount of work for the operating staff.
In 1990 EVO´s first venture into low-resistance neutral earthing was the two 20 kV cabled networks of the town of Kulmbach. Here, earth faults are detected as short-circuits to earth and cleared selectively. The operating staff implement measures for isolating the affected section immediately since, firstly, they know where the fault is and, secondly, there is no danger of the fault spreading as a result of continued operation with a neutral displacement voltage present.
Since then the cabled networks of the towns of Kronach and Lichtenfels have been similarly dealt with.
Following the positive experience with cabled networks, consideration began to be given as to how the advantages of arc-suppression coils and low-resistance neutral earthing could be utilized together in mixed cable and overhead-line networks containing a small proportion of overhead lines.
The diagram of the amount of cabling in the various subnetworks (Fig. 2) shows that, at the moment, three subnetworks have a proportion of overhead lines of between 20% and 40% referred to the total length of the conductors comprising the particular subnetwork.

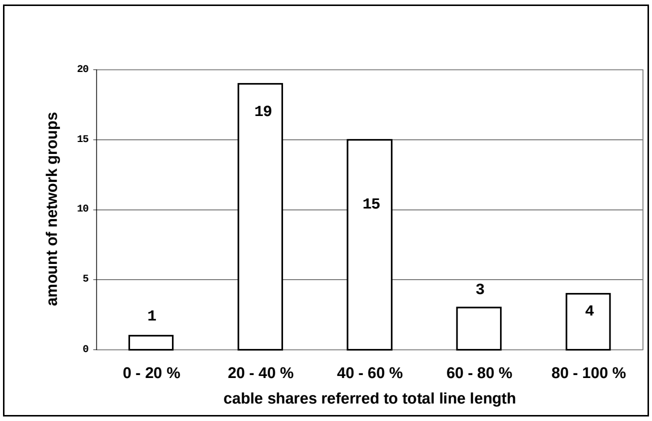

Fig. 2 Amount of cabling in subnetworks

In 1998 a system of short-time, low-resistance neutral earthing was installed and commissioned in Pegnitz as initial subnetwork.
Table 1 shows the methods of neutral earthing that are currently being used for the 42 subnetworks of EVO's 20 kV level.
The capacitive earth-fault current of the subnetworks with arc suppression coils is between 75 A and 500 A; the average value being 241 A. There are a total of 57 arc suppression coils installed.

Table 1

Number of subnetworks	Method of neutral earthing
1	Isolated neutral
35	Arc suppression coil
4	Low-resistance neutral earthing
2	Arc suppression coil and short-time low-resistance neutral earthing

THE KULMBACH NETWORKS

Kulmbach is fed from the 110 kV network through two substations sited on the edge of the town (Fig. 3). There are two separate 20 kV subnetworks each comprising 40 km of cabling. The peak load is around 20 MW for each subnetwork. The subnetworks are partly meshed and the type of selective protection employed is distance protection with overcurrent starting.

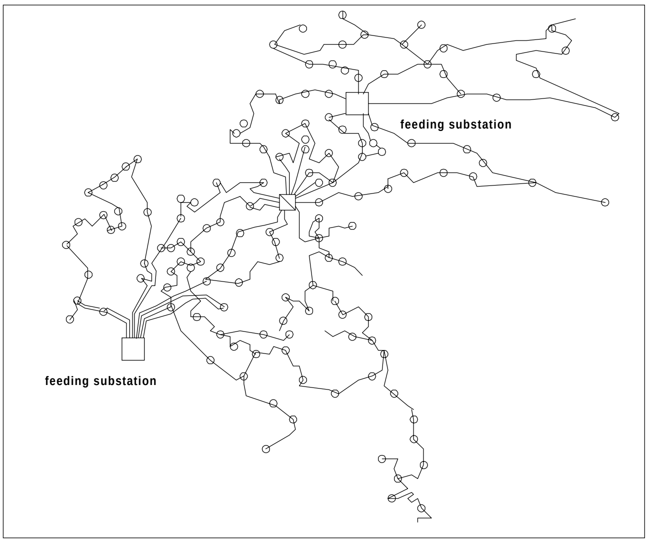

Fig. 3 The Kulmbach subnetworks

The first step in setting up a low-resistance neutral earthing system was to install earthing transformers with increased zero phase-sequence reactance so that the maximum earth fault current could be limited to 2000 A.
The arc suppression coils were removed and used in other subnetworks where there was a need. This course of action meant that, from the point of view of capital investment, the changeover cost little or nothing.
Operating experience so far has confirmed that the reduced amount of stress exerted on the insulation in the event of an earth fault compared with the arc-suppression coil system is a major advantage of low-resistance neutral earthing. Since the changeover of the method of neutral earthing there have been no more faults due to inadequate cable insulation, especially with the older types of XLPE cables.

THE PEGNITZ SUBNETWORK

The Pegnitz subnetwork comprises a 20 kV cabled network in the town itself of 32 km and overhead lines of about 22 km length for the regional supply (Fig. 4).

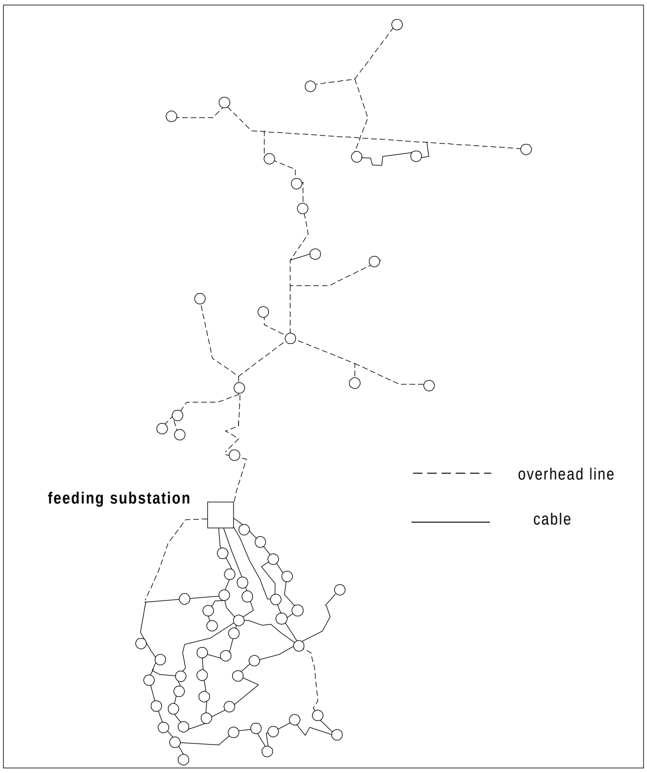

Fig. 4 The Pegnitz subnetwork

The peak load at present is around 12 MW.
The capacitive earth fault current of the subnetwork is approximately 140 A. In the Pegnitz substation, in the event of a sustained earth fault, a single-pole circuit-breaker connects a neutral-point resistor in parallel with the arc suppression coil after a delay of 2 seconds. The neutral-point resistor is rated to restrict the earth fault current to a maximum of 2000 A. The earth fault current is utilized to trip the faulted feeder.
From the standpoint of interference with telecommunications systems and the demands of protective earthing, the method of employing short-time, low-resistance neutral earthing is a special one.
The extinction limit above which a double fault is the governing factor for interference voltages affecting telecommunications equipment is raised because long-duration earth faults do not occur when earth-fault neutralization is being employed, so the probability of a double earth fault is greatly reduced (DIN VDE 0228).
Adherence to the maximum permitted touch voltages for earth fault current is only demanded for sites in which the neutral is earthed. The feeding substations where the neutral earthing is normally done have values of ground resistance that are usually already low because the equipment is designed for 110 kV earth faults. In the other parts of the system, such as ring main units, pole-mounted switchgear, etc., the relevant conditions are the same as for the use of arc suppression coils (DIN VDE 0141).

COMPARISON OF DIFFERENT CONCEPTS

Theoretical Considerations

The various methods of neutral-point connection employed differ in respect of voltage and current loadings at the location of the fault and in the network.
At the beginning and end of an earth-fault event, several things happen one after the other:

- Discharging of the faulted phase
- Recharging of the unfaulted phases
- Power-frequency earth fault or short-circuit to earth
- Recovery of the voltage

Discharging. The discharging of the faulted phase causes surges that, to all intents and purposes, are independent of the method of neutral-point connection being employed.

Recharging. The recharging of the capacitance of the unfaulted phases to the phase-to-phase voltage is effected through the inductance of the infeed. When an earth fault occurs in the vicinity of a natural voltage zero, the recharging gives rise to a voltage in the unfaulted phases that can reach (1+√3) times the peak value of the phase-to-earth voltage.

The frequency of oscillation can be calculated from the short circuit power S_k and the charging power S_c of the network.

$$f = f_n \sqrt{\frac{S_k}{3 \cdot S_c}}$$

For 20 kV networks with a short circuit power of 500 MVA and a charging power of between 2 MVAr and 4 MVAr, the frequencies are between 450 Hz and 320 Hz.

Power-frequency state. When there is a sustained earth fault, the zero-sequence voltage in a network with arc suppression coils is 20/√3 kV, causing the unfaulted phases to be increased to 20 kV.
In a network with low-resistance neutral earthing, the earth fault current causes a drop in voltage in the positive phase-sequence system and the negative phase-sequence system. Consequently, the zero-sequence voltage is less than 20/√3 kV, the phase voltages do not reach 20 kV and the actual voltages of the unfaulted phases are different.

Fault clearing. After the fault has been cleared, the waveform of the recovery voltage is determined by the characteristics of the zero phase-sequence system and, hence, by the method of neutral-point connection.
In a network with arc suppression coils the transient characteristics of the zero phase-sequence system are only weakly attenuated. The frequency of the transient charac-

teristics is determined by the capacitive earth fault current of the network and the set value of coil current.

$$f = f_n \sqrt{\frac{I_{Coil}}{I_{CE}}}$$

Depending on the chosen tuning of the coil, the frequency in practice is very closely above or below 50 Hz.

Due to the transient characteristics deviating from 50 Hz, the voltage of the faulted phase increases only slowly and beating of the unfaulted phases occurs.

In a network with low-resistance neutral earthing through a reactance, the breaker extinguishes the earth fault current as the current passes through zero. Since the zero-sequence voltage is at a maximum at this instant, transient oscillations occur in the zero phase-sequence system.

$$f = \frac{1}{2\pi\sqrt{L_{0\,Reactance} C_{0\,Network}}}$$

For a 20 kV network with a capacitive earth fault current of 150 A and a maximum limited earth fault current of 2 kA the figure is approximately 160 Hz. This oscillation is superimposed on the phase voltage so overvoltages can occur.

In a network with resistance earthing the earth fault current is also extinguished at the current zero crossing. Since the zero-sequence voltage does not suffer any phase displacement and the zero phase-sequence system, as an RC circuit, is not capable of oscillation, the healthy three-phase system is available immediately.

Earth Fault Trials

Kulmbach Reactance Earthing. The results of the earth fault test recorded in the feeding substation are shown in Figs. 5 to 9. The earth fault was applied by means of a single-pole fault initiating switch at the end of a 1 km long cable run.

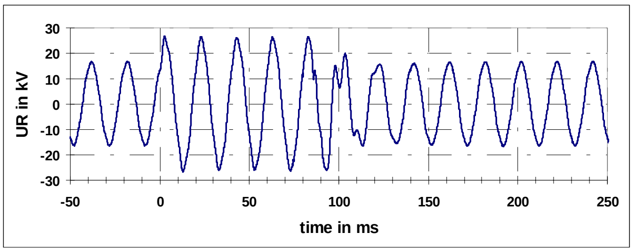

Fig. 5 Voltage U_R

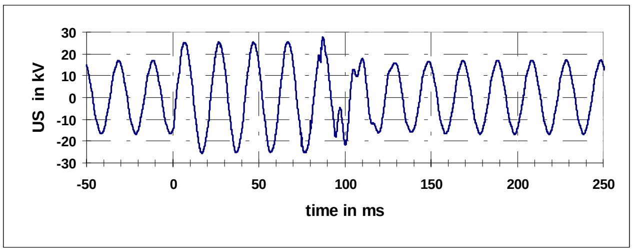

Fig. 6 Voltage U_S

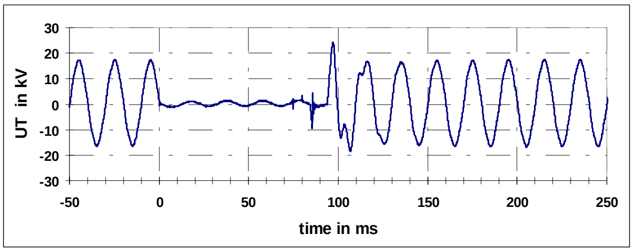

Fig. 7 Voltage U_T

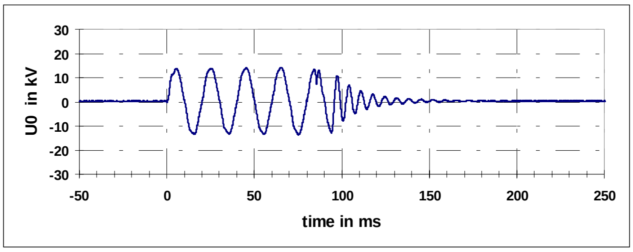

Fig. 8 Voltage U_0

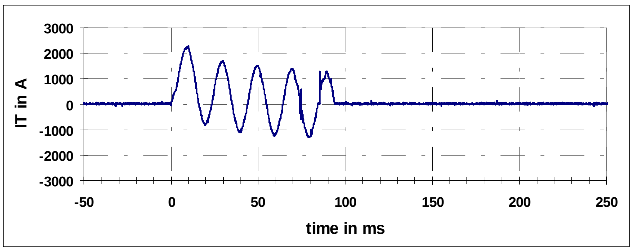

Fig. 9 Fault current I_T

Since the earth fault begins at the voltage zero crossing, no recharging oscillation occurs. The voltage of the unfaulted phases increases to 18 kV rms. Due to the fault beginning at the voltage zero crossing the fault current is displaced to the start. When the fault is cleared the fault current is not interrupted successfully at the first current zero crossing. After clearing of the fault current the transient zero-sequence voltage superimposes itself on the phase voltages.

Fig. 10 shows the waveform of the phase-to-neutral low voltage in the substation. A voltage dip of up to approximately 10% can be seen during the earth fault. The dip in the phase-to-phase voltages showed a maximum of 15%.

The voltages measured in this substation are also applicable to all the other substations in the subnetwork with the exception of those along the outgoing circuit leading to the site of the fault.

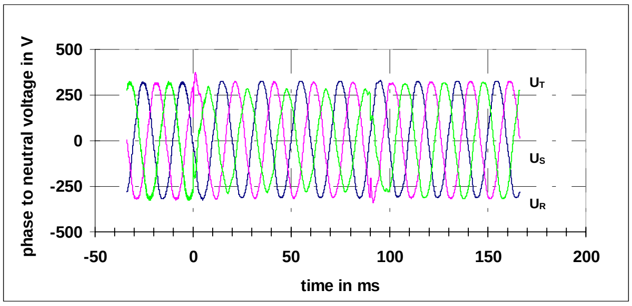

Fig. 10 Low voltage system

Pegnitz Earth Fault Trial. The results of the earth fault trial recorded in the feeding substation are shown in Figs. 11 to 15.

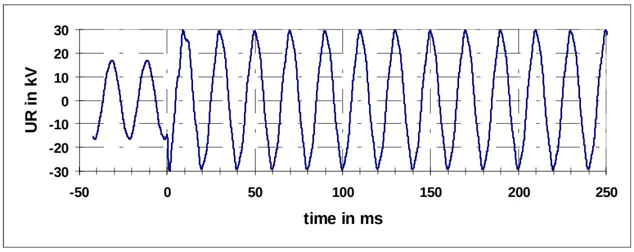

Fig. 11 Voltage U_R

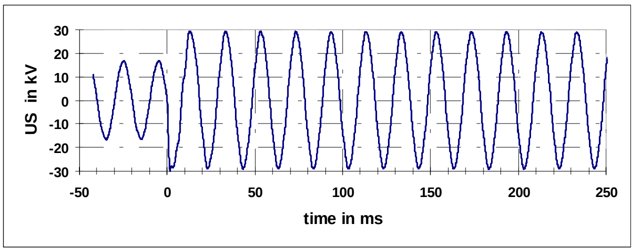

Fig. 12 Voltage U_S

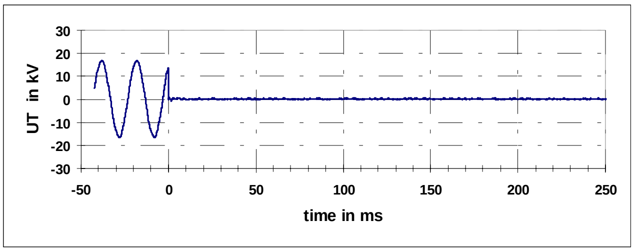

Fig. 13 Voltage U_T

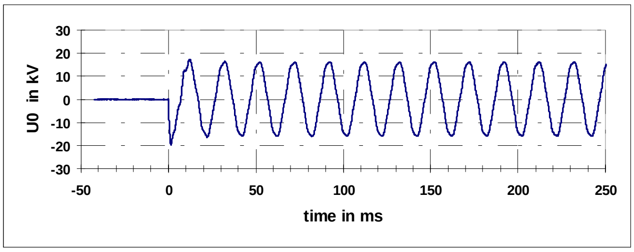

Fig. 14 Voltage U_0

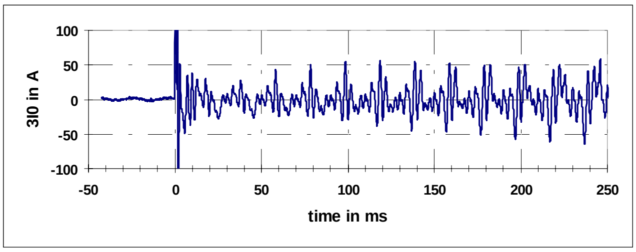

Fig. 15 Fault current $3I_0$

The fault was applied by means of a single-pole fault initiating switch at the end of a 3 km long cable run. The earth fault begins close to the voltage maximum. In the zero-sequence voltage and in the healthy phases it is possible to see the waveform of the recharging oscillation. No transient earth fault overvoltages of significant magnitude occurred in this case.

In the earth fault current the peak of the discharge can be seen at the instant the earth fault starts. The earth fault current is badly distorted by harmonics. The proportion of the fifth harmonic is 100% of the fundamental wave.

The traces of the voltages after the earth fault had been cleared show that the recovering voltage of the faulted phase rises slowly. It attaines the 20 kV level after 60 ms. The beating influence of the zero-sequence voltage lasts for a longer period. Thus the zero-sequence voltage falls to 20% after 500 ms.

Pegnitz Short-Term Earthing via Resistor. The results of the short-term earthing trial recorded in the feeding substaion are shown in Figs. 16 to 20.

Initially, the earth fault was applied by means of a single-pole fault initiating switch at the end of a 3 km long cable run. The transition to a short-circuit to earth occurred after 165 ms. This short delay period was taken for test purpose only.

Due to the use of a neutral-point resistor the transition occurs without any transient phenomena. The phase voltages fall from 21 kV rms to 18 kV rms. After the fault has been cleared the transition to a healthy three-phase system takes place instantaneously without any further transient phenomena.

The trace of voltage in the low-voltage network during the earth fault and short-circuit to earth shows a dip in the phase-to-earth voltage of one phase of 10% and in the phase-to-phase voltage of 6% while the short-circuit to earth was in progress.

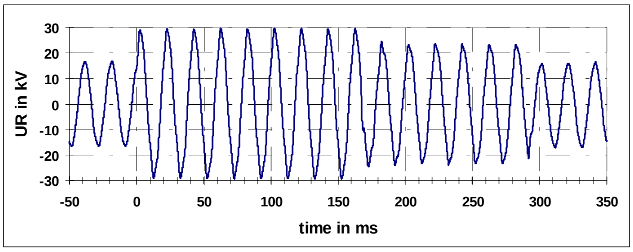

Fig. 16 Voltage U_R

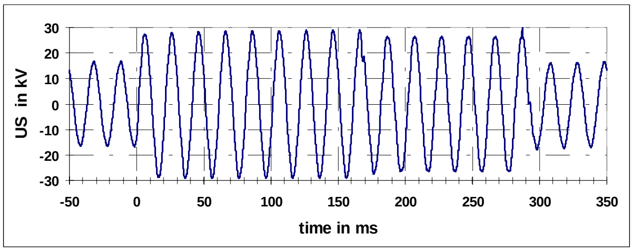

Fig. 17 Voltage U_S

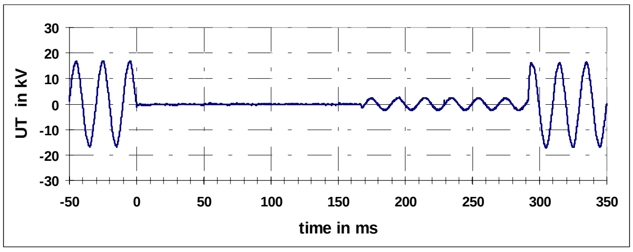

Fig. 18 Voltage U_T

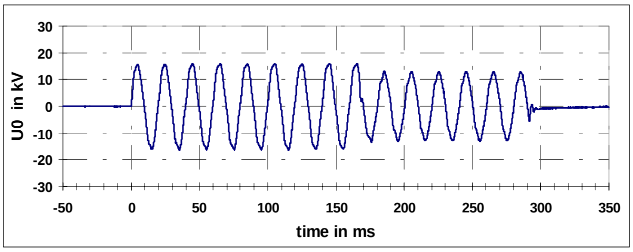

Fig. 19 Voltage U_0

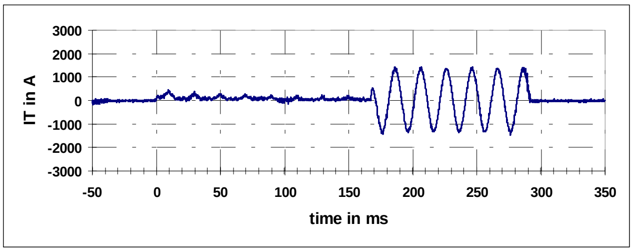

Fig. 20 Fault current I_T

CONCLUSIONS

EVO has accumulated experience with various methods of neutral earthing in its many 20 kV subnetworks.
In an overhead-line network, arc suppression coils are the most suitable method of neutral-point connection because transient faults can extinguish automatically. For dealing with multipole short-circuits on overhead power lines due to atmospheric discharges, however, autoreclosing has proved effective. The successful location and clearing of sustained earth faults without interruption of supply requires extra devices in the protective relaying. A simple network configuration facilitates operational management of the system.
In cabled networks low-resistance neutral earthing has proved itself in both technical and economic terms. Not having to continue operating under conditions of sustained earth fault, which places extra stress on the insulation, is regarded as a special advantage. The trials have shown that the pertubation of the low voltage system from the short-circuit to earth which appears as voltage dip for supplied loads is minimal. The supply failures and voltage dips that have been the consequence of double earth faults in the past are avoided.
In mixed cable and overhead-line networks with a predominant amount of cabling, short-term earthing with fault clearing has proved an optimum solution for EVO. The extra cost of plant and equipment is more than offset by the economic advantages that arise from the reduced stressing of the insulation and hence the longer service life.
The use of a neutral-point resistor instead of a neutral-point reactor means higher capital cost initially but the attenuation in the zero-sequence system provided by the neutral-point resistor is a major benefit.