RESPE$_{act}$ intelligent compensator to restrict residual earth fault current and voltage distortion in MV networks

Over recent years there has been a continuous escalation in expectations of electricity supply quality. The stringency applies particularly to industrial plant aiming at high productivity but is also relevant to domestic and general commercial situations. It relates to both the high quality of the supply and to its reliability, in that neither transient nor permanent faults should frequently occur. And yet suppliers are increasingly aware that the feedback effects on the grid from the users themselves are diminishing the quality of the supply to an extent that is actually endangering what used to be safe and predictable grid operation.

In this situation, medium voltage networks operated with a RESPE system (resonant earthing of the starpoint) that takes account of both commercial and technical aspects are proving their worth. With such a system it is not necessary to interrupt current supply immediately in the case of the most frequent network fault, a single-pole earth fault. It must, however, be said that this applies only if the residual earth fault current does not lead to illegal excessive touch potentials in the network. For 20 kV networks the implication is that the residual earth current $I_{RES,zul}$ should not exceed 60 A so that there is no danger to life and limb. The authors' investigations [1] have shown that breach of the limit for $I_{RES,zul}$ can already be expected in public MV supply networks if the detuning ν is ≤ 2 % and the attenuation d is ≤ 4 % because of the inevitable distortion to the supply voltage. The danger arises even in MV networks in which neither the limits for THDU nor for u_h as in [2] are exceeded. The harmonics component of the residual earth fault current is dominated by the fifth harmonic. This situation will probably not be relieved by the fact that modern televisions with a flat screen (whether displaying by means of LED, LCD or PDP) cause only a very tiny fifth harmonic current in the network current. This will doubtless be offset by the expected high use of energy-saving lamps in the 10 W to 20 W power range which promises to be another typical source of load on public electricity networks.

These factors will mean that in many networks it will be essential to have a system for reducing the harmonics element of the residual earth fault current by means of some sort of compensator.

In which distribution networks will restriction be necessary?

If the size of the residual earth fault current and especially the maximum level of the fifth harmonic is known for the supply voltage in the network, it will be possible in many cases to calculate in advance the harmonics element $I_{RES,OS}$ in the residual earth fault current at a sufficient degree of accuracy to support operational decisions. If the network structure is systematised as described in [1] and basic knowledge is obtained from analysing the harmonics ratios in public 20 kV MV networks (where $u_{h=5}$ will basically determine the THDU), it will be possible to calculate the harmonics residual current from equation (1):

$$I_{RES,OS} = \frac{200 \cdot \sqrt{3} \cdot u_{h=5}}{\sqrt{\left(3\,X_{L,ers,h=5} - X_{C,ers,h=5}\right)^2 + 3^2 R^2_{ers,h=5}}} \tag{1}$$

If typical parameters are then used as substitute values for the electrical equipment ($X_{L,ers,h}$ $X_{C,ers,h}$ $R_{ers,h}$) used in the network, such as transformers and cables, and if their frequency dependency is taken into account, equation (1) in numerical terms will provide a simply calculated figure for harmonics residual currents:

$$I_{RES,OS} = u_{h=5} \cdot a \tag{2}$$

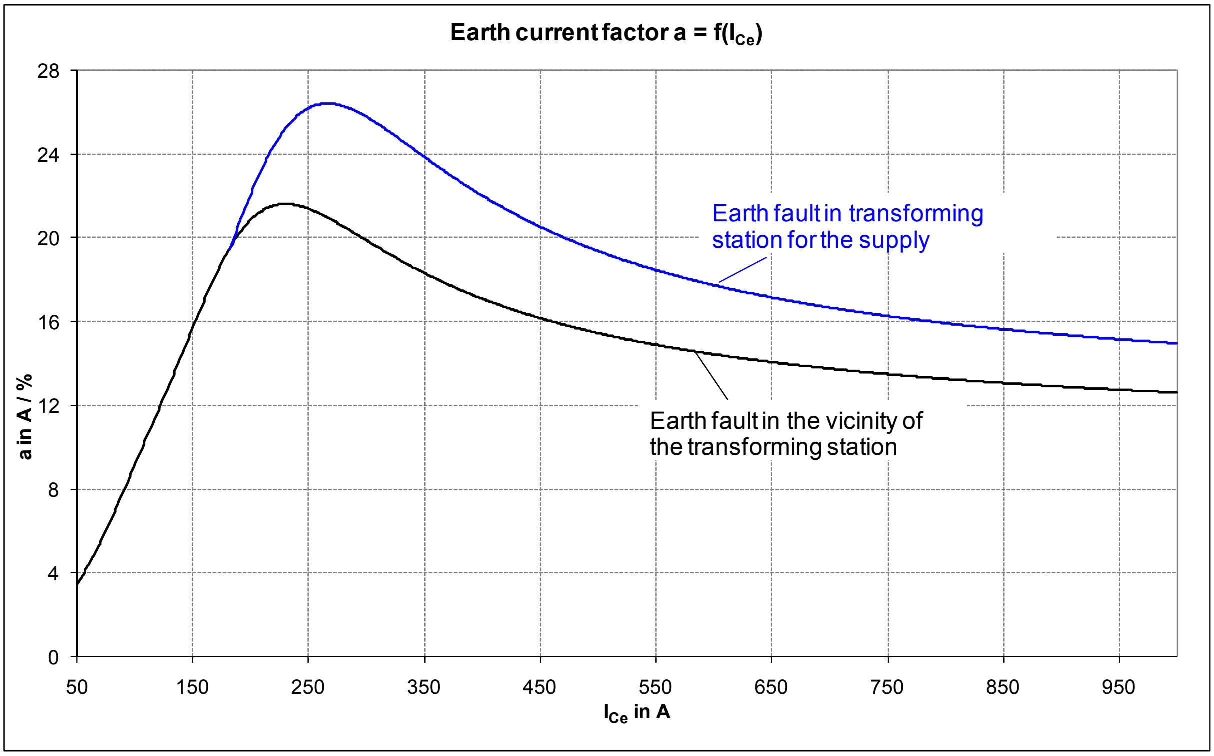

Fig. 1: Earth current factor a

The a in equation (2) for the earth fault factor is a function of the earth capacity and is shown in Fig. 1 for 20 kV supply networks in a typical arrangement [1] with an earth fault arising either in the switching station providing the supply or very near to it. If the supply voltage in the network has levels $u_{h=7}/u_{h=5} \leq 0.22$ and $u_{h=3}/u_{h=5} \leq 0.33$ (where $u_{h=3}$ is the value for both the positive and the negative sequences) it is sufficient to calculate the harmonics component of the residual earth current $I_{RES,OS}$ with the aid of equation (2) using only the maximum level at which the fifth harmonic (the 10-minute mean) which can possibly arise in the network. As is to be found in [1] in the range of I_{Ce} between about 150 and 250 A (i.e. in relatively “small” networks, the sort that may be created in what is known as “two-transformer” conditions), there may well be resonance phenomena in the case of the fifth harmonic in the residual earth fault current. In such situations it makes sense to calculate or actually to measure the eigenfrequency f_e of the network as this is what is crucial to the resonance if there is an earth fault.

As a fair approximation, the following formula will give the eigenfrequency of conductors not affected by the earth fault once the earth fault is present:

$$f_e = \frac{1}{2\pi} \sqrt{\frac{1}{3 L_{ers} C_e}} \qquad (3)$$

When the f_e is being mathematically calculated, the representative inductance L_{ers} can be taken to be the figure for the longitudinal inductance of the transformer supplying the medium-voltage network.

If it should be the case that $f_e \cong 250\,\mathrm{Hz}$, a high $I_{RES,OS}$ is to be expected, as the harmonics component in the residual earth fault current is, in effect, only limited by the $R_{ers,h=5}$. In a low-load situation for the network (when the 110/20 kV transformer is only operating at 10 % ... 15 % load) the a value for the earth fault factor may be as high as approx. 40 A/%. A low-load situation in the public 20 kV network, however, also means that the $u_{h=5}$ level will only lie in the range of about 1 % and there may be many cases where the critical residual earth fault currents (if ν is < 2 % and d ≤ 4 %) are not reached.

If the level of the fifth voltage harmonic in a 20 kV medium-voltage network is $I_{Ce} > 500$ A and the maximum level of the fifth harmonic in the supply voltage is

$$u_{h=5} > \frac{I_{Ce}}{200\,\mathrm{A}/\%} \qquad (4)$$

with $u_{h=5}$ in % and I_{Ce} in A, careful analysis of the network is indispensable. It is advisable and advantageous in this case to carry out the calculations for the harmonics component in the residual earth fault current using a calculation program such as Boses [3].

RESPE$_{act}$ compensator on basis of power convertors fulfils the restriction requirements

What has been said above shows that there is, with ever-increasing frequency, the possibility that prescribed residual currents in case of earth fault may be exceeded if these earth faults occur in public medium voltage networks with resonance star-point earthing. The reason is that distortion in the supply voltage cannot be influenced by the network operator without the presence of compensation devices. Because the harmonics element in the residual earth fault current, as shown in [1], is, effectively, a bisymmetric load on the network and the point where the fault arises will not be certain in advance, an active filter as compensatory mechanism is advantageous. This can only be put into practice via the three-phase system, whether the current is flowing in one direction or the other. The compensator must, therefore, be a three-phase compensator based on a 6-pulse power converter in the three-phase system. If the right algorithms are applied to the regulation and control of the converter, it will, of course, also serve where necessary, even when there are no earth faults, as a compensator reducing any distortion in the supply voltage to the levels desired or prescribed: [2] shows the permissible limits.

Coupling the three-phase compensation power converter via a regulated two-pulse inverter connected to the AC in parallel to the earth current choke coil is the optimal means of making it possible to set the 50-Hz active and reactive power of the residual earth fault current to "desirable" levels.

Making this connection in the zero-phase system of the network can also find a use in the measurement of the frequency-dependent zero admittance, for example, and in locating earth faults (Fig. 2).

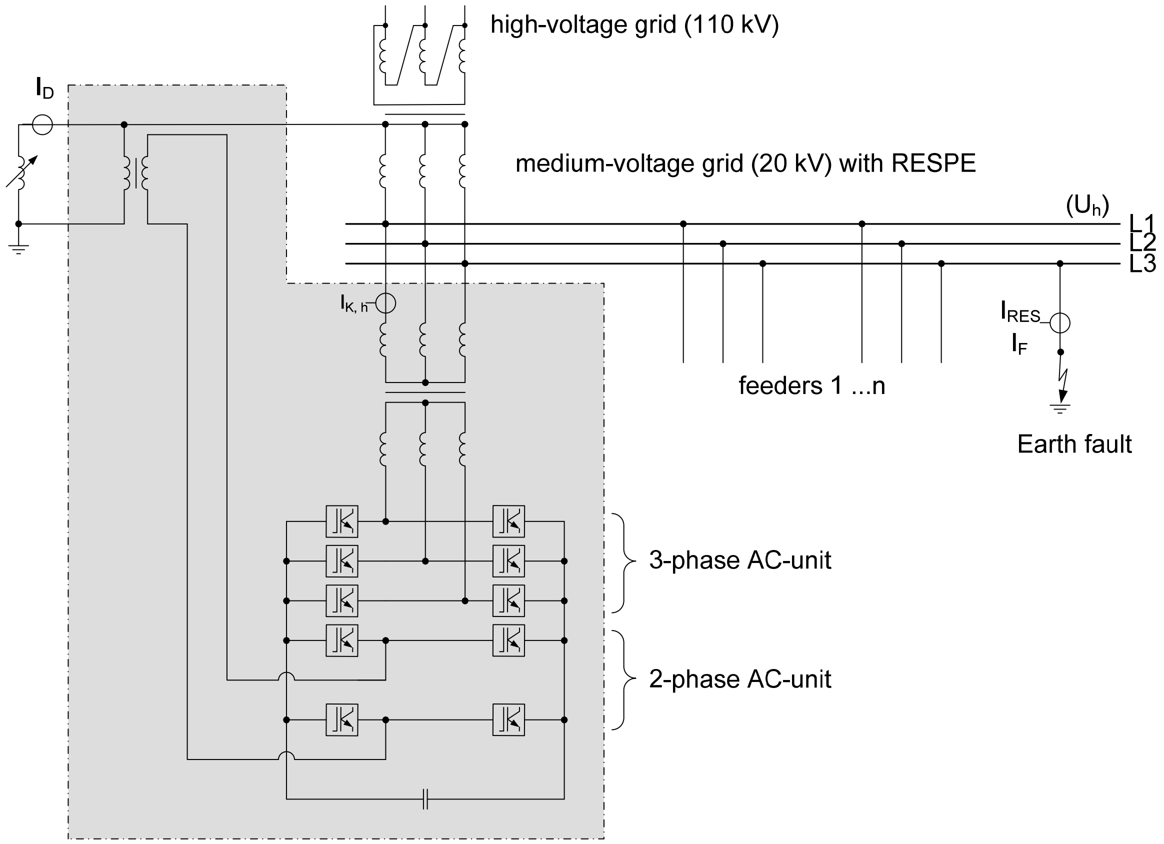

Fig. 2: Five-phase RESPEact active compensator connected to the power input point of the medium-voltage network.

The whole power-converter switching, the requirements applying to the control algorithms and the necessary equipment for its integration and testing within the network are described in full in [4]. A functioning prototype of the five-phase active filter constructed in this way was tested over a period of several months in a medium voltage distribution network.

A $\text{RESPE}_{\text{act}}$ compensator provided with intelligent software and based on know-how respecting the demands of the network operation was created in the context of a product family. This can be universally installed in all resonance star point earthed medium voltage networks, including those in industry. There now follows a report of some of the early experience of operating a network with this functioning $\text{RESPE}_{\text{act}}$ prototype, together with its electrical performance both in a network free of earth faults and in one suffering from these.

Intelligent software in the compensator regulates the limiting processes

The $\text{RESPE}_{\text{act}}$ compensator limits the distortion in supply voltage to settable levels for the non-earthing network. If it has recognised a single-pole earth fault in the network which it is controlling, it will be able, in co-operation with the three-phase unit (Fig. 2), once the compensation processes have been completed that are associated with the occurrence of the fault, to restrict the 3rd, 5th and 7th harmonics in the residual earth fault current to the level decreed by health and safety regulations (this is $I_{RES} < 60$ A in 20-kV networks). The effect will be that the power output subject to the fault will not have to be switched off as soon as the fault occurs. The example shown in Fig. 3 is the procedure for limiting the fifth harmonic in a 20-kV network. In the case here described, the mean value for $\overline{I}_{RES,h=5}$ of 5.5 A was calculated in the network with the earth faults and thus it can be assumed (from previous experience with this network) that in the time interval (from t = 10 s to t = 50 s) this mean value is also that of a mean potential residual earth fault current $\overline{I}_{RES,h=5\,prospektiv}$ with approx. the same dimensions if there were no current restriction on the part of $RESPE_{act}$.

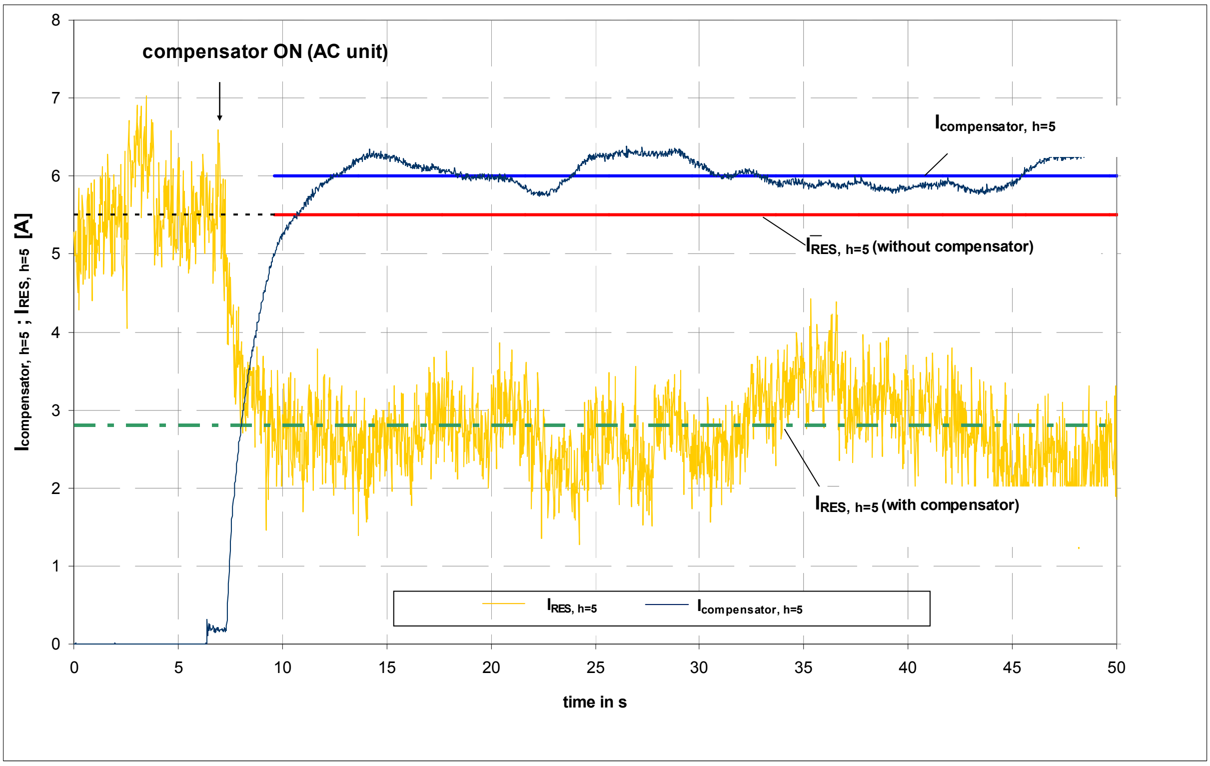

Fig. 3: Limiting the residual earth fault current for h = 5

In the network which had been suffering from earth faults the compensator was switched on manually at approx. t = 6 s in the context of the test programme. With a mean compensation current $\overline{I}_{K,h=5}$ of 6 A, the task of keeping the mean value lower than 3 A is safely achieved; the value in this case was 2.7 A. This “overcompensation” $\overline{I}_{K,h=5} > \overline{I}_{RES,h=5\,prospektiv}$ comes naturally because the asymmetric compensator current (with its active and reactive components) at the point where the ($RESPE_{act}$) compensator is connected to the bus-bar of the substation is shared between the earth fault point, the 20 kV branches and the high-voltage-to-medium-voltage transformer in accordance with CDR, the current divider rule.

The three-phase unit in the $\text{RESPE}_{\text{act}}$ compensator can be used when there is no earth fault for the purpose of keeping down the voltage distortion due to the 3rd, 5th and 7th harmonics within the limits set in EN 50160 [2] or to a different prescribed level. An example of the restricting process for the fifth harmonic is shown in Fig. 4.

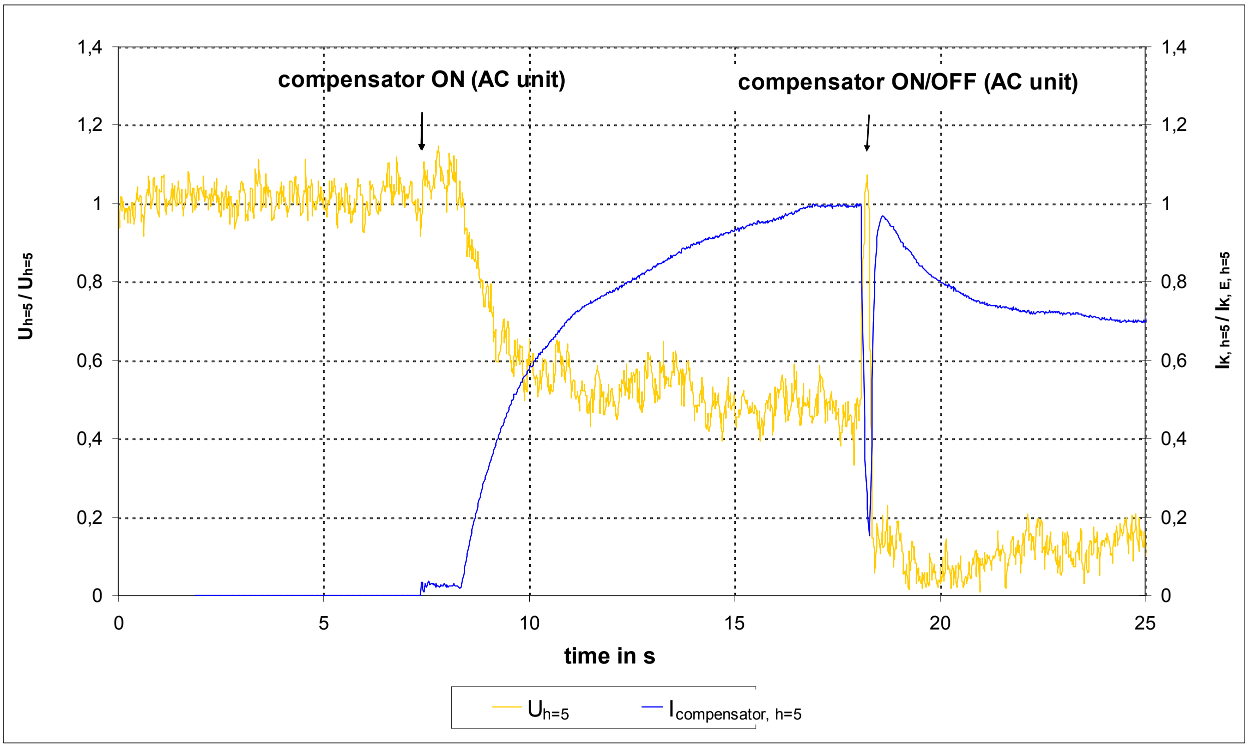

Fig. 4: Restricting distortion in supply voltage in 20-kV network without earth fault (shown for h = 5)

At the point in time t = 7 s, the “THD control” of the three-phase unit of the compensator is activated: one second later, approximately, the limitation kicks in. Within two or three seconds, the 5th harmonic has been brought down to about 0.5 power units (50 %). The compensator current, $I_{K,h=5}$, reaches the final value set for it: $I_{K,E,h=5}$. The compensator is switched off briefly (for about 0.1 ... 0.2 s) after about 10 s (i.e. when t = 18 s) and this procedure serves to determine the phase position of the interference currents which are causing the distortion in the network voltage, so that when the compensator is switched on again and the phase compensation using compensator current of approx. 0.7 power units has taken place, the targeted compensation ($U_{h=5}/\overline{U}_{h=5}$ < 0.2 power units) will be reached. As it can be assumed that both the phase position and the size of the “interference currents” vary over time, the on-off-switching procedure described is repeated at regular intervals.

The fact that the RESPE$_{act}$ compensator is a five-phase instrument with a variable-frequency AC unit has other benefits, including reduction of the 50-Hz reactive power element in the residual earth fault current, as Figure 5 makes clear.

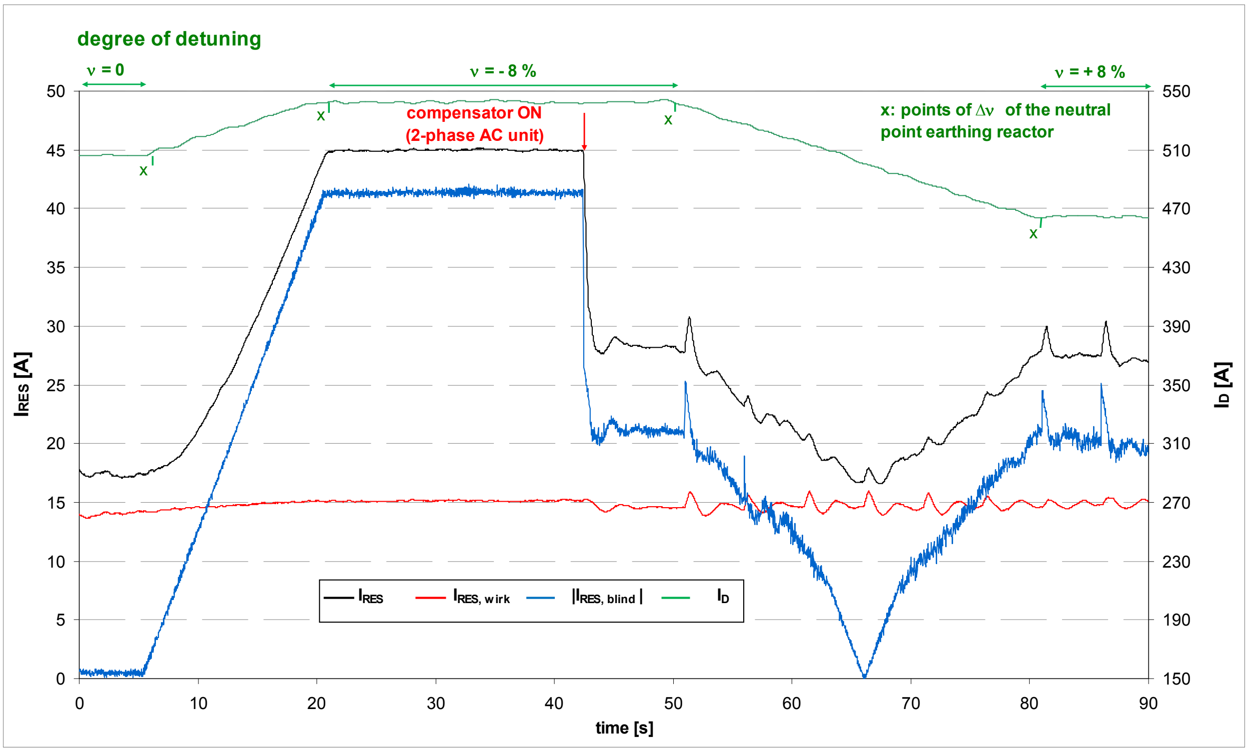

Fig. 5: Compensator restricts residual earth fault current (50-Hz reactive component)

To enable the electrical behaviour of the RESPE$_{act}$ compensator to be evaluated when the de-tuning ν alters because of a single-pole earth fault, the detuning was changed from 0 % to -8 % and then to +8 % while there was a steady-state earth fault in the network. In the time interval shown, the effective active residual current $I_{RES,wirk}$ remains practically constant and the figure for the effective reactive residual current $I_{RES,blind}$ follows the current I_D from the choke for the earth fault as it changes over time, up to the approximate point t = 42 s (Fig. 5), at which the AC unit of the compensator is activated for the task of compensation, i.e. reduction of the inductive reactive residual current (50 Hz value) to a prescribed value, 20 A. The AC unit thus regulates the current to a capacitive compensated current of 20 A (50 Hz value). After a further interval, at t ≈ 65 s, where the detuning ν is assuming the value zero, the reactive residual current $I_{RES,blind}$ also becomes zero in order eventually to match the capacitive compensated current of 20 A (50 Hz component) with positive detuning of +8 %.

If switching procedures to localise an earth fault in a medium-voltage network are used, the 50-Hz reactive current component in the residual earth fault current will change with every switching episode, on or off, at a particular power output point. This, by its very nature, can only be compensated for with considerable time delay by regulating the choke coil. The compensator will recognise a modification to the 50-Hz residual earth fault current associated with the switching procedure and will employ its AC unit to adapt the first harmonic reactive component in the residual earth fault current so that the compensatory current of 20 to 30 A required in such cases is reduced or raised as necessary and without delay (Fig. 6).

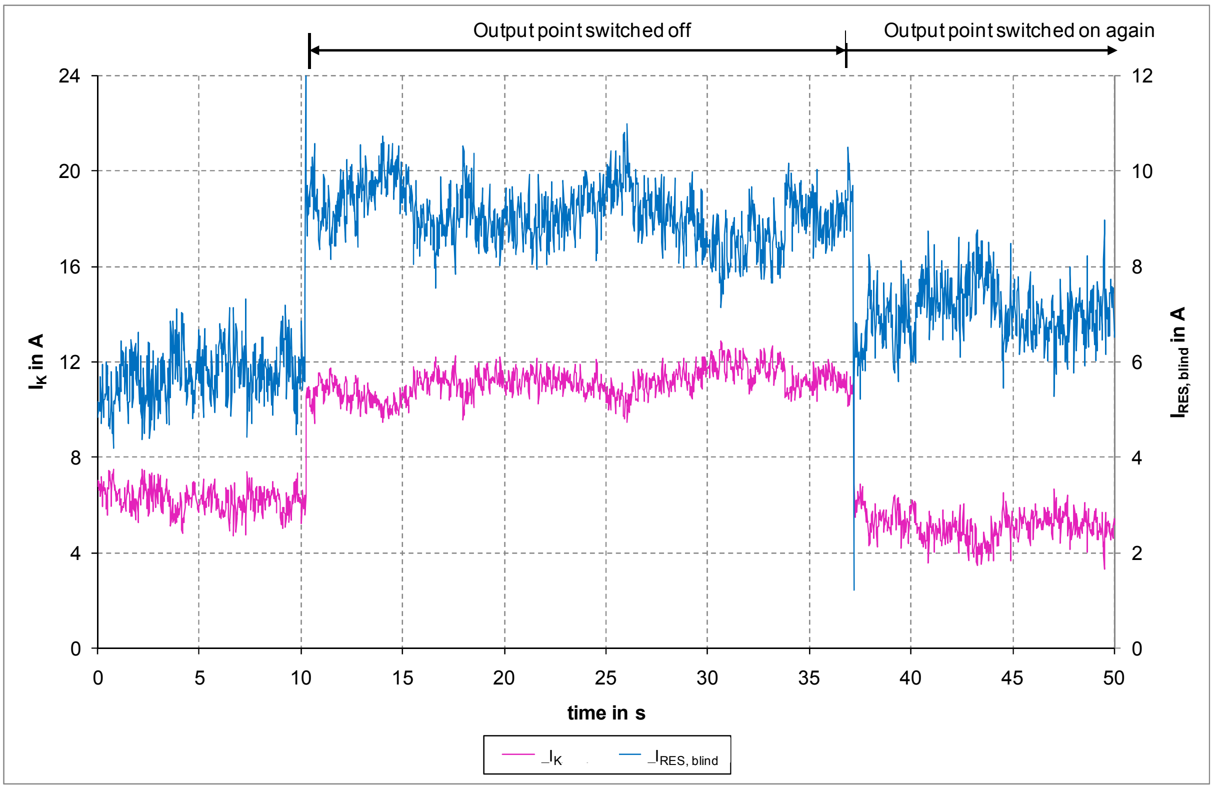

Fig. 6: Compensator (AC unit) restricts the reactive residual earth fault current ($I_{RES, blind}$) to $I_{RES, blind} \approx 10$ A while an output point is switched off (for fault localisation). Without restriction the $I_{RES, blind}$ would be approx. 17 A.

Operation of prototype RESPE$_{act}$ in a network proves its practicability and sound functioning

A prototype operated over several months within the 20-kV distribution network of a particular public electricity supplier using resonant earthing of the star point has confirmed that both the hardware and the software compnents of the RESPE$_{act}$ compensator are eminently serviceable. It was successfully shown that particular voltage harmonics (the 3rd, 5th and 7th) were safely kept within pre-set limits for the supply voltage when there was no earth fault in the network, and that when there was a single-pole earth fault the level of the current (3rd, 5th and 7th) harmonics in the residual earth fault current was well compensated: there was unfailing fulfilment of the standard conditions for maintaining personal safety, namely that the level I_{RES} = 60 A never be exceeded in 20-kV networks which are subject to the possibility of earth faults arising.

An assumption made in the overall design of the $RESPE_{act}$ has proved itself particularly useful: this is to ignore transient earth faults but treat intermittent earth faults like steady-state faults for purposes of residual current limitation. The compensator is not primarily or necessarily set up to pursue the goal of improving earth fault clearance. To what extent the conditions for extinguishing a short-circuit arc are modified or improved by the restriction of residual current undertaken by the compensator has not yet been closely investigated. The operation of the functioning prototype in a network and the earlier experiments using it in a 400 V network have led to the firm conclusion that neither the location of the earth fault, the resistance of the earth fault nor the type – whether metallic connection to earth, short circuit arc (steady-state or intermittent) – impair the correct functioning of the $RESPE_{act}$. Likewise, there is no impairment from the detuning ν in the network or from the switching that goes on during normal network operation or from any primary or secondary technology present in the network. It has also been shown to be advantageous, effective and practically useful to have continuous monitoring by the $RESPE_{act}$ compensator of the network allocated to it but no active compensation for any fault arising until after the lapse of a certain interval set by the network operator. This leaves it open to the conventional safety and regulating mechanisms present in the substation responsible for the supply to react "in the normal manner" applicable to its normal running.

It was also proved, on the other hand, that the compensator is suitable for use in medium voltage distribution networks with supply voltages between 6 and 24 kV and that no restriction was required in the usual operating modes of these networks. The modular construction means it can be supplied in an economical form exactly adapted to the particular network requirements. Parallel operation of more than one compensator within a single network is possible.

Summary

Employing the $RESPE_{act}$ compensator in a medium voltage network of the public electricity supply will

- guarantee the necessary voltage quality of medium voltage networks in normal operating conditions,
- limit the steady-state residual earth fault current to the values permitted in personal safety terms, enabling the network to continue to be operated if necessary even if there is an earth fault,
- not require a costly adaptation of the network (as would be the case with low-resistance star point earthing),
- reduce interruptions to supply necessitated by possible changeover from low-resistance star point earthing to resonance star point earthing and
- not cause any restrictions to the existing means of network operation, whether in respect of general operability, protection, switching activity or location of faults.

Being modular in construction, it permits optimum adaptation to the particular network requirements and is patented both within Germany and the rest of Europe.

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Symbols

a	earth fault factor
C_e	earth capacity
d	attenuation (50 Hz value)
f_e	eigenfrquency
f_h	frequency of the harmonic h
h	harmonic index (for the frequency relation $h = f_h/50$ Hz)
L_{ers}	representative inductance
I	current (effective value)
I_{Ce}	capacitive earth fault current (effective value)
I_D	current in choke coil (effective value)
I_F	fault current (effective value)
I_h	current of the harmonic (effective value)
I_K	current in compensator (effective value)
$I_{K,h}$	current in compensator of the harmonic h (effective value)
$\overline{I}_{K,h}$	mean value of $I_{K,h}$ over 10 min
$I_{K,E,h}$	final current in compensator of the harmonic h
I_{RES}	residual earth fault current (effective value)
$I_{RES,blind}$	reactive power component of I_{RES} (effective value)
$I_{RES,wirk}$	active power component of I_{RES} (effective value)
$I_{RES,zul}$	permitted residual earth fault current (effective value)
$I_{RES,h}$	residual earth fault current of the harmonic h (effective value)
$\overline{I}_{RES,h}$	mean value of $I_{RES,h}$ over 10 min
$\overline{I}_{RES,h,prospektiv}$	targeted mean value of $I_{RES,h}$ over 10 min
$I_{RES,OS}$	harmonic share of the residual earth fault current (effective value)
ν	detuning
$R_{ers,h}$	representative resistance at frequency h
t	time
THDU	Total harmonic distortion in voltage (as a %age)
U_h	voltage of the harmonic h (effective value)
$\overline{U}_h$	mean value of U_h over 10 min
u_h	voltage of the harmonic h (power unit value, percentage value)
$X_{L,ers,h}$	representative resistance (inductive) at frequency h
$X_{C,ers,h}$	representative resistance (capacitive) at frequency h