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Smart Grids and Energy Markets

Evaluation of the operation of phase earthing with neutral compensated system

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Preface

This report has been done as a part of the research work of the Smart Grids and Energy Market (SGEM) research programme. The report relates to Task 2.2 “Development of Phase Earthing System” of the work package WP2 “Future Infrastructure of Power Systems 1”.

Considerable part of phase-to-earth faults can be extinguished without even short interruption to customers applying the modern phase earthing system developed before SGEM research programme cooperation with UTU Elec Oy, Fortum Distribution and Tampere University of Technology. This report presents the availability of the phase earthing with neutral compensated systems. Increasing of the line length of the underground cables leads to higher earth fault currents and hazard voltages. The distributed compensation of the earth fault current is a potential solution to reduce an earth fault current in order to fulfil the hazard voltage regulations. In many cases with distributed compensation the total compensation degree of the network remains relatively low because the medium voltage feeder is not allowed to be overcompensated. Overcompensation will lead the malfunctions of the feeder earth fault protection. The extinguishing conditions of the earth fault arc depend considerably on the compensation degree of the network. In many cases the centralized system for managing the earth fault current and hazard voltages is needed. The phase earthing provides one cost-effective solution for the centralized management of the earth fault current also with distributed compensation for reducing short interruptions to customers or electricity producers.

Contents

1. Introduction

During the past decades demands for the quality and reliability of supply have been rising constantly as society has become more and more dependent on continuous electricity supply. Also short outages have become more and more harmful especially for the industrial customers and power producers whose generators are connected to an MV distribution system. These short interruptions are the consequence of the fault clearing applying high-speed (HSAR) and delayed automatic reclosings (DAR) in order to avoid longer outages. Automatic reclosings (AR) are typically in use in overhead line MV networks.

Faults in MV networks cause a major part of the interruptions in power supply experienced by customers. In Finnish overhead line networks, about 90 % of faults have a temporary nature. According to long term statistics about 90 % of all faults in Finnish MV systems are cleared by ARs on feeders where they are applied and about 10 % of faults remain permanent leading to final tripping. Even short interruptions deteriorate the power quality which is not only significant to the customer but also to the distribution system operator (DSO). These short interruptions have been included in the regulation model [3]. Thus they have also direct economic value from the DSO’s point of view.

Major part of Finnish MV networks are overhead line networks or mixed networks which have isolated neutral points. Temporary faults are often one phase-to-earth faults. In neutral isolated or compensated network phase-to-earth fault does not technically prevent the continuation of the electricity distribution. Possible short interruption is caused by fault clearing applying ARs. The neutral point treatment has an essential significance for the extinguishing probability of the earth fault arc. The extinguishing conditions of the earth fault arc are significantly worse in neutral isolated network compared to neutral compensated systems. The conventional methods for reducing the number of short outages with earth faults are e.g. the changing of the MV network structure, cabling of overhead line feeders and applying Petersen coils for the earth fault current compensation. As consequence of the increased cabling, the capacitive earth fault current increases considerably. In many cases applying Petersen coils is needed in order to reduce touch voltages required by the hazard voltage regulations [1]. All these methods are relatively expensive.

Earlier main motive to compensate earth fault current was reducing earthing costs. Nowadays when the quality of supply is emphasized reducing the short interruptions has become the central basis for the investments. One drawback of earth fault current compensation is relatively high investment costs especially in networks where the compensated line length is high compared to customer density. When the fixed compensation units without automatic control are applied the compensation degree remains relatively low if the network is wanted to keep undercompensated in all cases. This clearly reduces the extinguishing probability of earth fault arc. In this case the phase earthing could be a worthy back up method to ensure the extinguishing of the earth fault arc. The temporary earth fault arc can be extinguished without interruption to customers by connecting the faulty phase temporarily to earth at a feeding primary substation (typically 110/20 kV).

Applying modern shunt circuit-breaker (SCB) equipped with novel control logic is cost-effective method for reducing the number of HSARS in MV networks with temporary earth faults and limiting the touch voltages. The faulty phase can be temporarily earthed at the feeding primary substation when the phase-to-earth fault appears. If the tripping delay of the earth fault protection can be set long enough taking into account the hazard voltage regulations the functioning of the SCB does not require any changes of normal feeder protection or settings. The SCB can be applied like a phase-to-earth reclosing before functioning of the proper feeder protection. Applying e.g. distributed earth fault current compensation the time available for the phase earthing can be increased. The essential requirements of the phase earthing system (PES) are the high-speed operation and reliable indication of faulty phase with an earth fault. Earlier phase earthing has been applied among others in France [2]. The method has also been tested in Finland in 1960 - 1970. At that time applying the PES in neutral isolated system was restricted the lack of reliable phase selection method. The complete phase selection was difficult to develop applying the relay technology of that time.

If an earth fault arc extinguishes during the PE any disturbances for DG units or customers does not appear. Normally the phase earthing has been applied with neutral isolated or via resistance earthed neutral systems. The line length of underground cables increases rapidly especially due to large distribution disturbances caused by storms during the last decade. This development leads to mixed networks including both overhead lines and underground cables and increases the need to compensate earth fault current in order to fulfil touch voltage regulations and the quality requirements of the supply.

Current modern feeder terminals or other protection devices of the MV network cannot indicate faulty phase with phase-to-earth faults in neutral isolated or compensated systems. Indication method controlling the SCB must be capable to detect the faulty phase reliably during a phase-to-earth fault in order to connect faulty phase to an earth. The indication method must qualify high reliability demand because earthing of the healthy phase leads to more serious fault a cross-country fault. Hazard voltages caused by a cross-country fault can lead to damages in telecommunication systems.

Modern feeder terminals enable to develop and implement reliable and complete method for the detection of the faulty phase with phase-to-earth faults. Also high-speed close and open control are possible. The development of the vacuum circuit-breakers enables applying recloser type of circuit-breaker for SCB. Then temporary phase earthing can be arranged correspondingly as autoreclosing.

The extinguishing conditions of the earth fault arc are good in fully compensated system when the compensation degree is typically between 95 % - 105 %. In this case a significant benefit by applying phase earthing is difficult to achieve when the extinguishing conditions of the arc are thought. In that regard the phase earthing and centralized compensation with automatic tuning represent as parallel investments. Even in fully compensated systems including underground cables intermittent arc faults may exist. Applying phase earthing also intermittent faults can be extinguished. In the case of fully compensated system the phase earthing could be a backup protection function. Tripping delay of the feeder earth fault protection is allowed to be longer due to compensation. If the earth fault has not disappeared after a certain delay a temporary phase earthing can be done to ensure the extinguishing of the arc. Another aspect is that the mismatch of the compensation can temporarily be significant e.g. with some line switching operation. Then the phase earthing ensures the earth fault arc extinction. If the fault is permanent in some cases the phase earthing could be applied until the fault has been cleared. Thereby interruptions to customers could be avoided. In the case of partial compensation when the compensation degree is sufficiently low beneficial effects by applying phase earthing can be achieved. The partial compensation can be even centralized or distributed.

2. Phase earthing with a neutral compensated system

The earth fault arc can be extinguished by connecting the faulty phase temporarily to earth at a feeding primary substation. Then the major part of the fault current is transferred away from the fault location. The recovery voltage of the fault location after the arc current has tripped out is very advantageous for the extinction of the arc when the fault disappears during phase earthing. The residual fault current is also low. Both facts improve the probability that the temporary earth fault will be cleared without the operation of the feeder circuit-breaker. The method does not cause any interruption or voltage dip for the customers or generators of the electricity producers because it does not change phase-to-phase voltages of the MV system. Operation of the production unit connected to the feeder can technically continue normally during the phase earthing. The prevailing vector group of distribution transformers is Dyn11 in Finland. When the phase-to-phase voltages keep constant any voltage change cannot be detected at the low voltage side of the distribution transformer or block transformer of the DG unit.

The idea is that the PE could be done temporarily before the functioning of the normal feeder protection in the corresponding way as HSAR of the feeder circuit-breaker. It requires that the tripping delay of the earth fault protection (TDEF) is long enough. After the functioning of the SCB normal AR sequences can be done. In that case the PE does not affect the functioning of the normal feeder protection or the settings of the earth fault protection. The evaluation of the touch voltage at the fault location during the PE is also needed. Adopting the PE method requires installing one single pole controlled SCB and its control relaying in the 110/20 kV substation. A faulty phase is typically detected on the grounds of the phase-to-earth voltage analysis. If the faulty phase is kept earthed also with permanent earth faults for continuing the electricity distribution, a reliable method for determining the earthing voltage at the fault location is needed. In Finland, MV networks are not normally used during an earth fault. This solution offers high potentiality to reduce ARs because in typical Nordic MV networks 50-80 % of the faults are earth faults.

In the case of fully compensated system the phase earthing could be a backup protection function. Tripping delay of the feeder earth fault protection is allowed to be longer due to compensation. If the earth fault has not disappeared after a certain delay a temporary phase earthing can be done to ensure the extinguishing of the arc. Another aspect is that the mismatch of the compensation can temporarily be significant e.g. with some line switching operation. Then the phase earthing ensures the earth fault arc extinction. If the fault is permanent in some cases the phase earthing could be applied until the fault has been cleared. Thereby interruptions to customers could be avoided.

In the case of partial compensation when the compensation degree is sufficiently low beneficial effects by applying phase earthing can be achieved. The partial compensation can be even centralized or distributed. Due to increasing underground cabling the capacitive earth fault currents will considerably increase. This leads to need for distributed compensation. Without compensation large zero sequence currents cause considerable voltage drops. This can cause protection malfunctions and increase the mismatch of the distributed compensation. When applying distributed earth fault current compensation the compensation degree of the whole network remains normally sufficiently low. The reason for that is the fact that feeder earth fault protection must be based on the reactive component of the sum current. Without centralized compensation the adequate amount of the active fault current at the earth fault situation cannot be guaranteed. The low compensation degree of the system leads significantly worse self-extinction probability of the earth fault arc than with fully compensated system. The phase earthing provides one cost-effective way to manage centrally earth fault current and earthing voltage and improve the earth fault arc extinction.

3. Feasibility of applying the shunt circuit-breaker in neutral compensated MV networks

3.1 Coordination of feeder protection and phase earthing

The longest TDEF in neutral isolated or compensated system is determined by touch voltage regulations [1]. In neutral compensated system the tripping delay may be set longer than in corresponding neutral isolated system because the earth fault current and earthing voltage due to it are normally considerably smaller. The TDEF is typically between 0.2 – 1.0 s. In resonance controlled compensated system even longer TDEF would be possible according to touch voltage regulations in many cases [1]. When the PE is applied as a complementary function as part of the normal E/F protection, the temporary PE should be made during the TDEF if the settings of the E/F protection are not wanted or allowed to change due to touch voltage regulations [1]. If the fault does not disappear during the PE the normal feeder E/F protection operates the same way as without PE. In some cases it is necessary to prolong the TDEF in order to give the PE enough time to extinguish the earth fault. Then the fulfilling of the touch voltage regulations must be checked [1].

3.2 Implementing the phase earthing system

Phase-to-earth fault can be indicated according to neutral-to-earth voltage. Applying the PES also requires the indication of the faulty phase. With low-ohmic faults the faulty phase can be detected applying the analysis of the phase-to-earth voltages. On the grounds of the criteria based on the analysis of neutral voltage and phase-to-earth voltages the faulty phase can be earthed temporarily at the feeding primary substation. The SCB short-circuits the original phase-to-earth fault and major part of the fault current moves from the fault location to flow via the SCB due to considerably lower earthing resistance of the primary substation. In addition, the phase-to-earth voltage at the fault location becomes smaller when the original fault is short-circuited. This improves the extinction of the earth fault arc and reduces the earthing voltage. Figure 1 presents the typical operation sequence of the E/F protection when the PE is included with neutral compensated system. I_E is the earth fault current at the fault location. The combined operating time of the relay and circuit-breaker is supposed to be approximately 100 ms and the duration of the PE is here 300 ms. The tripping delay setting of the relay is denoted t. Applying the preceding settings requires that at least 500 ms fault current-flow duration is acceptable considering the touch voltage regulations [1]. Really the residual fault current decreases considerably due to the PE but the touch voltages are desirable to be on the safe side evaluated according to the original fault current (without PE). Small residual current at the fault location can be detected during PE depending on the ratio of earthing resistance at the primary substation to fault resistance at the fault location and loading rate of the feeder. The preceding protection sequence is illustrated in Figure 1.

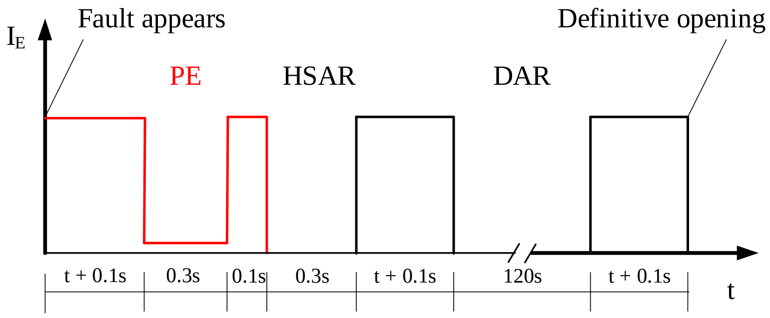

Figure 1. Operation sequence of PE and E/F protection with neutral compensated system.

In this study, the PE was considered as an alternative or supplementary function with normal AR functions. Temporary earth fault that can be extinguished by the PE typically includes an arc between the live part of the system and the protective earthing or earth. Thus temporary earth faults have relatively low fault impedance. High impedance earth faults are not so relevant when considering the PE because they rarely have a temporary nature.

3.3 Influences of phase earthing on touch voltages

Touch voltage limits due to earth faults are given in Figure 2 [1]. The curve represents the value of voltage (U_{TP}) that may appear across the human body, bare hands to bare feet. No additional resistances have been considered in the calculations.

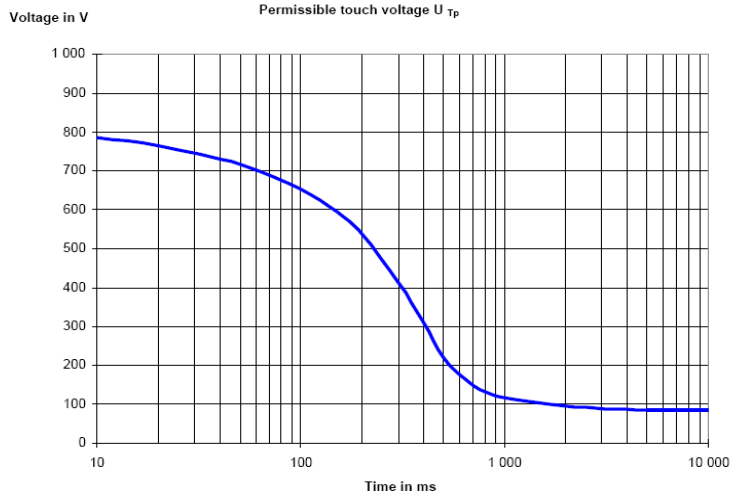

Figure 2. Permissible touch voltages U_{TP} for limited current-flow duration [1].

The highest permissible earthing voltage is double compared to the voltage U_{TP} or quadruple if the touch voltage U_{TP} is proved by measurements to remain below the values of the curve (Figure 2).

According to the operation sequence presented in Figure 1, current-carrying time from the appearing of the fault to the HSAR is at least 500 ms. If the duration of the PE increases the corresponding current-carrying time increases respectively. The original earth fault affects about 200 ms and the faulty phase is earthed during 300 ms. In some circumstances longer PE is reasonable to use. Normally the residual earth fault current is significantly lower during the PE compared to the original fault but it is difficult to prove in advance covering all possible fault and loading situations. Among others the loading rate during the PE affects the residual current. Applying present touch voltage regulations [1] the duration of current flow is the sum of the operational delays of the relay and circuit-breaker and the duration of the PE. Then the longest tripping delay of the feeder relay including the PE is determined according to maximum fault current (R_F = 0 Ω, without PE) and the highest earthing impedance. Thereby the partial distributed or centralized compensation of the earth fault current would provide more time for the PE which would improve the self-extinguishing probability of the fault.

The novel PES has been tested in due course arranging the field experiments in the real network when the prototype SCB was installed and ready for service in the primary substation (110/20kV). Artificial earth faults were made along the 20 kV feeder. The PES operated well and predictably with the field experiments. Figure 3 presents the fault current measured at the fault location. It can be noticed how the fault current and thus also earthing voltage decreases during the 400 ms phase earthing.

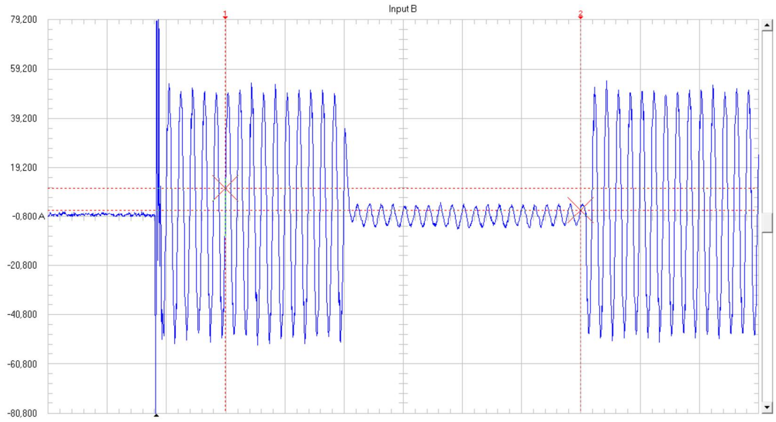

Figure 3. Fault current at the fault location with the phase earthing system.

3.5 Two phase-to-earth faults

The functioning of the shunt circuit-breaker must be prevented reliably when two phase-to-earth fault exists in the network. Phase-to-phase-to-earth faults are normally more or less similar to two phase short-circuits. The fault impedance between phases is normally clearly smaller than the fault impedance between phases and the earth. The short-circuit component of the fault current is dominant and the neutral voltage remains clearly lower than with low-ohmic phase-to-earth fault. Thus the functioning of the SCB can be prevented using suitable setting of the neutral voltage in the most cases. The programmable logic controller (PLC) of the SCB prevents the simultaneous closure of the two phase-to-earth circuit-breakers. The cross country fault can be problematic when it happens during the operation delay of the SCB. The SCB must be dimensioned taking into consideration that it must be capable to disconnect the fault current of the cross country fault which may be in the worst case in order of magnitude of phase-to-phase fault current. When applying the phase earthing system a reliable and fast method for the indication of the cross country faults should be developed in order to prevent the functioning of the SCB in these situations.

4. Influence of neutral treatment and phase earthing on self-extinguishing of earth fault arc

The extinction of the earth fault arc is primarily dependent on the following factors and their coincidence: system earthing practice (neutral isolated, partially compensated, fully compensated, resistance earthed), size of galvanically interconnected network (uncompensated earth fault current), damping of the system, operating voltage of the system, deionization speed of arc channel, weather conditions (speed and direction of wind, moisture, rain), no-load current of distribution transformers and tripping time of the E/F protection.

When the arc extends in the protective spark gap or in some other electrode gap, it becomes unstable and extincts at the zero of the fault current. If the recovery voltage rises rapidly enough, it causes an increase in the current through the arc thereby increasing its conductivity. Thus, the arc does not extinct ultimately but continues burning intermittently. The deionization speed of the arc channel is of crucial significance because after a deionization the recovery voltage cannot ignite the arc again. The insulation level of the spark gap depends on the ionization velocity of the exhaust and is the higher the longer time has elapsed after the interruption of the current. The rising speed of the recovery voltage immediately after arc extinction is of absolutely crucial significance considering the re-ignition probability. The magnitude of the residual fault current and arcing time also affects the extinction because they affect the degree of ionization. Wide deviation of arcing times is very typical. It is due to the nature of the arcing phenomenon burning in the free air.

Figures 4, 5 and 6 present the recovery voltage and the behaviour of the neutral voltage after the fault current has been interrupted at the zero crossing point in neutral isolated system, neutral compensated network and when phase earthing is applied with neutral isolated system. It can be seen from Figure 4 how steep the recovery voltage is in neutral isolated system. Together with the magnitude of the earth fault current the high rising speed of the recovery voltage is the main reason for poor self-extinguishing probability of the earth fault arc in neutral isolated systems.

Figure 5 presents the typical waveform of the recovery voltage in fully compensated system. When the compensation degree is sufficiently low the rising speed of the recovery voltage is significantly higher. If the additional resistor is connected parallel with the coil when a fault current is interrupted the attenuation is stronger and more rapid.

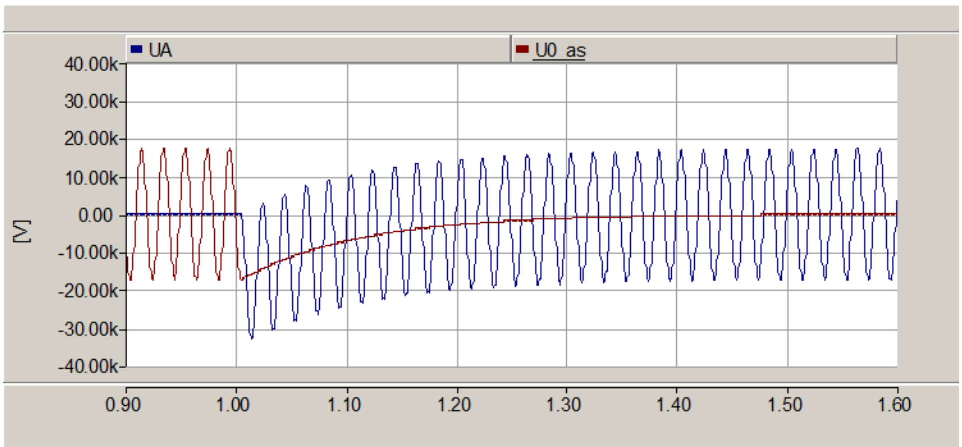

Figure 4. Recovery voltage (U_A) and neutral voltage (U_0) after earth fault arc extinction in neutral isolated network.

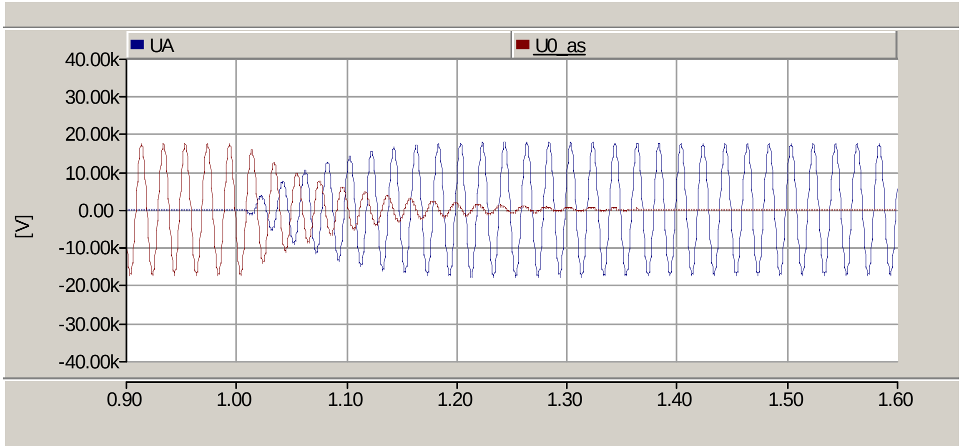

Figure 5. Recovery voltage (U_A) and neutral voltage (U_0) after earth fault arc extinction in neutral compensated network.

When the phase earthing is applied (Figure 6) the residual fault current and thereby the phase-to-earth voltage of the faulty phase at the fault location is very small. Essential matter is that any significant recovery voltage does not exist when the residual fault current has been interrupted. This leads to very advantageous self-extinguishing conditions of the earth fault arc and reduces the number of rapid autoreclosings with temporary earth faults. When the SCB is opened after the phase earthing cycle the behaviour of the neutral voltage and the recovery voltage depends on the operational earthing of the system. In Figure 6 the network has an isolated neutral point and thereby the recovery voltage after the SCB has been opened is similar as in Figure 4.

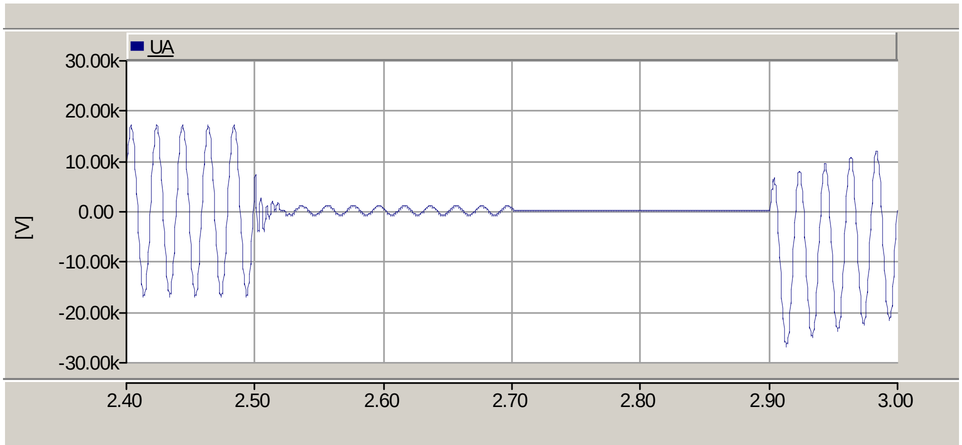

Figure 6. Recovery voltage (U_A) after earth fault arc extinction when phase earthing is applied with neutral isolated network.

5. Clearing intermittent earth faults

Intermittent earth faults are a problem encountered especially in compensated underground cable networks where the fault current is compensated at a low level. The initial reason for the fault is a spot of damaged insulation in the cable. When the insulation has been damaged, there are normally two possible consequences. The breakdown may lead to a permanent fault immediately or it may first lead to an intermittent earth fault. The damaged spot in the cable has an impaired insulation capability. It will break down again after the voltage of the faulty phase has risen to a sufficiently high level. The outcome of this is a series of breakdowns called an intermittent earth fault. Conventional protection schemes have been designed for permanent faults and may therefore show poor performance with intermittent ones [4].

In neutral isolated networks the intermittent earth faults may also occur when the fault current is very low (< 10 A). The earth fault extincts rapidly due to low arc current, but reignites almost immediately due to steep and high recovery voltage.

The repetitive reignition of the arc cause high overvoltages to healthy phases of the system. The self-extinguishing mechanism functions well in neutral compensated system when the insulation medium is air or some other gas. Instead, in solid insulation material, like cable insulation, the breakdown mechanism and its damage are permanent. The intermittent fault easily causes a secondary fault (short-circuit or cross country fault) causing damage to the network itself (underground cables, cable terminals, overvoltage arresters) and possibly to wired telecommunication systems.

The mechanism of overvoltages concerning the successive current interruptions and restrikings is considered. In unearthed system, the capacitive fault current leads the neutral voltage by approximately 90°. When the current is interrupted at the zero crossing, the neutral voltage is close to its maximum, i.e. 1 per unit. This voltage is charged to earth capacitances and will subside only slowly due to the high shunt resistances of the zero sequence system. After a half-cycle (50 Hz), the voltage between a faulty phase and the earth is almost twice compared to the normal peak value (Figure 4). If a restriking occurs at this moment, a high frequency transient is initiated and if this current is interrupted at the next zero crossing the neutral voltage charged to earth capacitances will be close to -3 per unit. This process of restriking could theoretically continue but in real systems the generated overvoltage would soon cause a breakdown of insulation leading to a permanent fault.

Main factor which cause the repetitive restikings is the recovery voltage at the fault location. The rising speed of the recovery voltage depends considerably on neutral treatment practice. This type of restriking phase-to-earth faults can be extinguished effectively applying phase earthing system. When the faulty phase is earthed the residual phase-to-earth voltage at the fault location is very low. When the residual fault current interrupts any significant recovery voltage cannot be detected until the SCB is opened (Figure 6). After opening of the SCB the neutral voltage and recovery voltage behave according to the neutral earthing practice of the network.

6. Testing the phase earthing with neutral compensated systems applying PSCAD simulations

Functioning of the phase earthing system was tested applying PSCAD simulations. The network model used here was modified utilizing the model presented in Deliverable 2.2.1. Network model consisted of the models of feeding 110 kV network, main transformer, real 20 kV feeder and background network. Because the neutral compensated system was observed the overhead lines of the studied feeder were replaced underground cables (AHXAMK-W 120) in order to increase capacitive earth fault current. The earth fault current compensation was modelled both centrally and distributed. The functionality of the feeder protection with real protection settings was also modelled and thereby the protection responded respectively as in the case of real network. The logic controlling the shunt circuit-breaker was also included in the model. This logic was based on new indication method of faulty phase (D2.2.1). Normally there is some capacitive unbalance in the real 20 kV network. This fact was taken into consideration in the model connecting one 0.2 μF capacitance between one phase and earth at the primary substation. The capacitive earth fault current produced by the network without compensation was 116 A and capacitive sum current produced by the studied feeder was 67.5 A. The total loading of the appropriate MV feeder was 1.15 MVA.

Four separate cases were studied:

- Case 1: Phase earthing without compensation
- Case 2: Phase earthing with distributed compensation (3x15 A)
- Case 3: Phase earthing with distributed compensation (3x20 A)
- Case 4: Phase earthing with distributed (3x15 A) and centralized compensation (compensation degree 95 % of residual fault current)

In all cases the feeder protection was based on $I_0 \sin\varphi$ characteristics. The distributed compensation was dimensioned so that the 20 kV feeder was undercompensated. If the feeder would be overcompensated the feeder E/F protection will function if an earth fault happens in the background network. In this case feeder E/F protection should be based on $I_0 \cos\varphi$ characteristics. The additional active fault current component is normally produced centrally connecting an additional loading resistance between the neutral point and earth at the feeding primary substation. The tripping delay of the feeder E/F protection was set to 0.6 s. In these cases functioning of the shunt circuit-breaker lengthens the total tripping time because the start signal goes down due to low sum current of the feeder during phase earthing. The duration of the phase earthing was 0.4 s and faulty phase was A.

Figure 7 presents the functioning of the earth fault protection including automatic faulty phase selection and control logic for the shunt circuit-breaker applying previously described PSCAD model. The fault resistances studied was 1 Ω and 500 Ω. The uppermost curve of Figure 7 (U_0) is the neutral voltage. Signal Trip A is the control signal for Phase A of the shunt circuit-breaker. Signal I_PhEA is the current of Phase A of the shunt-circuit breaker. Signal IeF2_rms means the effective value of the earth fault current from Phase A to earth at the fault location. Signal UE2 represents the earthing voltage calculated according to earth fault current at the fault location. The maximum tripping time is defined according to maximum earthing voltage defined by the touch voltage regulations [1]. The worst protective earthing of the feeder (highest earthing resistance) and the maximum fault current determine the highest earthing voltage. Permissible touch voltages U_{TP} for limited current-flow duration are presented in Figure 2 [1]. The curve of Figure 2 defines the highest permitted touch voltage and tripping time. With these simulations the earthing resistance 10 Ω was used for determining the earthing voltage and the highest permissible touch voltage. Signal UTP2 represents the highest permissible touch voltage which determines the longest tripping delay of the feeder E/F protection. When the tripping time is set 0.6 s and the maximum earthing resistance is 10 Ω the maximum touch voltage is about 175 V. The earthing voltage permitted is then 350 V. Red horizontal lines represent the limits for the maximum earthing and touch voltage with the settings applied in the simulations. Signals F1_Start and F1_Trip represent Start and Trip signals of feeder E/F protection.

When the functioning of the phase earthing system was simulated the fault resistances 1 Ω and 500 Ω were applied. In the touch voltage regulations [1] the earthing voltage is calculated applying the maximum fault current and earthing resistance of the protective earthing. Typically the maximum fault current is calculated corresponding to the fault resistance 0 Ω although it is a theoretical value. In these simulations the fault resistance 1 Ω was applied in order to avoid fast transient phenomena corresponding to the fault resistance 0 Ω. In practice 1 Ω fault resistance has no influence on the magnitude of the fault current compared to the value 0 Ω.

6.1 Case 1: Phase earthing with isolated neutral point

First the neutral isolated system was studied. In spite of 116 A fault current the touch voltage regulations [1] could be fulfilled corresponding to the tripping time 0.6 s when the faulty phase is earthed. In this case the total tripping time should consist of only the time the faulty phase is earthed. If the phase earthing would not be available in this case the primary action would be shortening the tripping time of the feeder E/F protection. Thereby the touch voltage limit could be raised. In all studied cases the starting signal of the feeder relay went down during phase earthing and thereby the calculation of the set tripping delay 0.6 s begins not until the shunt circuit-breaker has been opened. With 500 Ω fault resistance the residual fault current and earthing voltage at the fault location during phase earthing are almost zero due to the fault resistance ratios between the feeding substation and the fault location. With 500 Ω fault resistance the load current of the faulty phase between the primary substation and the fault location flows in practice completely via the phase conductor. The load current flowing via earth is very low in this case.

It can be seen that applying the shunt circuit-breaker the earthing voltage and the highest permissible touch voltage remain below the permissible limits during the phase earthing

(Figure 7). In practice the tripping delay of the feeder E/F protection should be shortened because the starting of the relay is stopped due to the earthing of the faulty phase. When applying the phase earthing the tripping delay of the E/F protection could be shortened to a very low value e.g. 0.1 s because temporary earth faults extinct probably during the phase earthing. Thereby the hazard voltage regulations could be fulfilled with the help of phase earthing in this case.

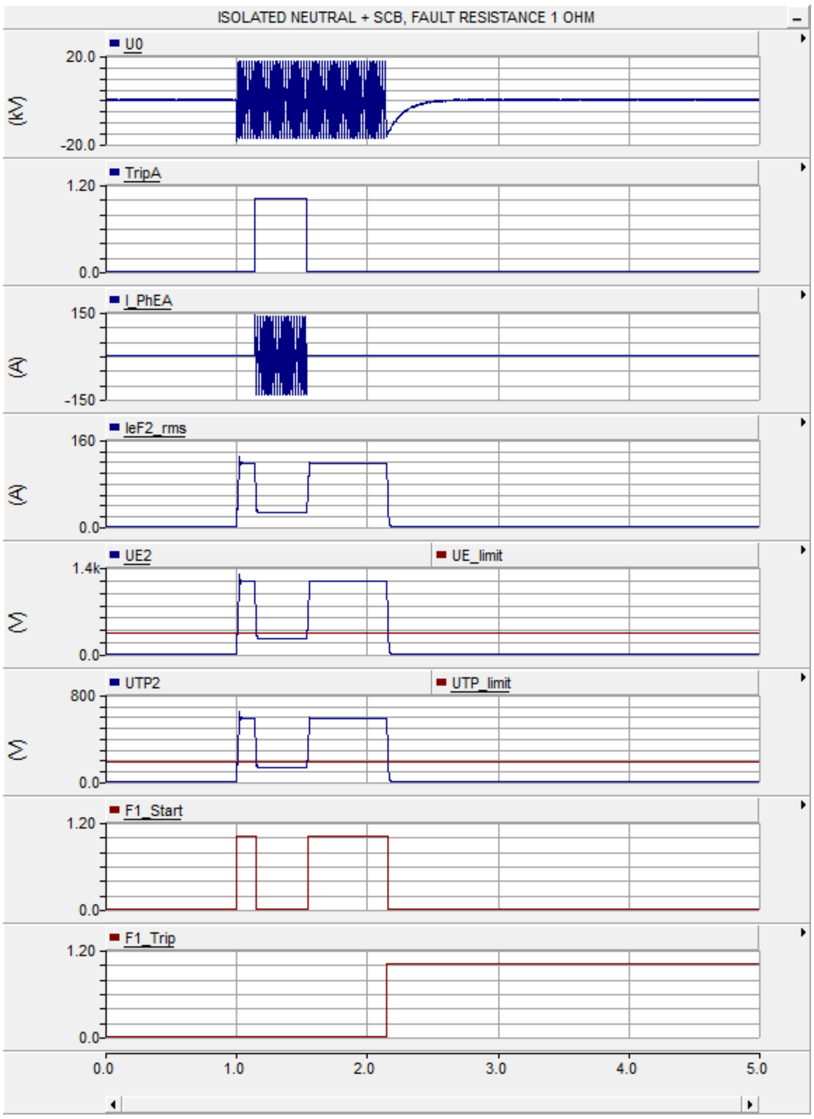

Figure 7. Applying SCB with neutral isolated system when fault resistance was 1 Ω.

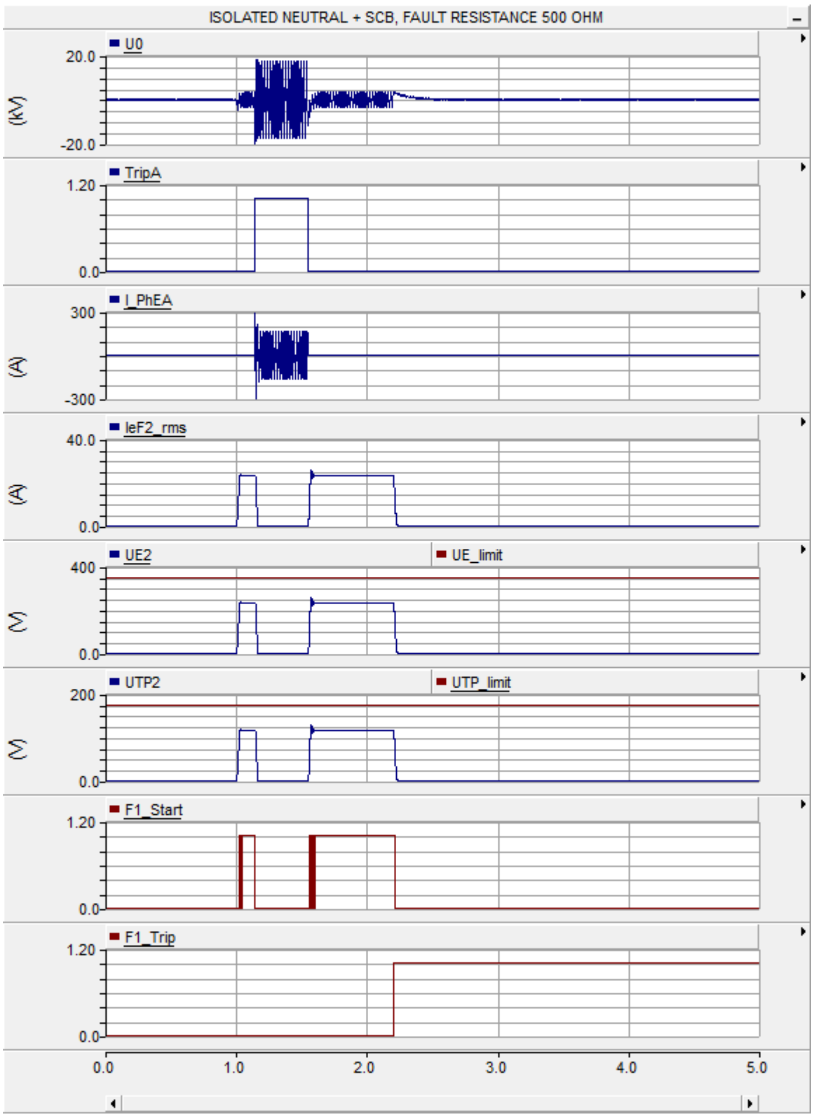

Figure 8. Applying SCB with neutral isolated system when fault resistance was 500 Ω.

6.2 Case 2: Phase earthing with distributed compensation (3x15 A)

In this case the phase earthing was studied when only distributed compensation was connected along the appropriate feeder. The compensation degree of the whole network was approximately 39 %. This means that the extinguishing conditions of the earth fault arc are quite near to a neutral isolated system without phase earthing. With this type of system the extinguishing of the phase-to-earth faults is possible to improve significantly applying the phase earthing which reduces short interruptions to customers and electricity producers.

It can be observed that the touch voltage regulations (TDEF 0.6 s) cannot be fulfilled without the phase earthing or additional compensation. When the shunt circuit-breaker is closed the earthing voltage and touch voltage are clearly below the allowed limit. Also in this case the feeder E/F protection starts up again when the shunt circuit-breaker has been opened.

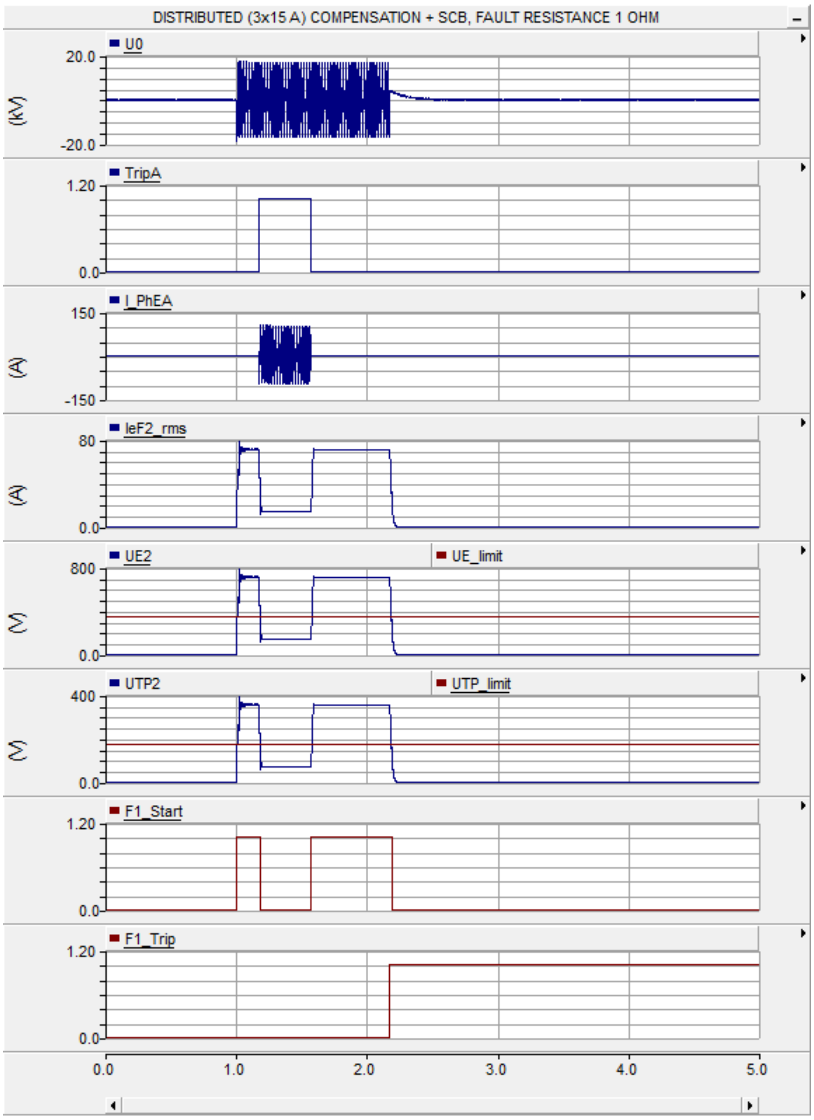

Figure 9. Applying SCB with distributed compensation 3x15A when fault resistance was 1 Ω.

Also with 500 Ω fault resistance the residual fault current and hazard voltage can be significantly reduced applying the phase earthing.

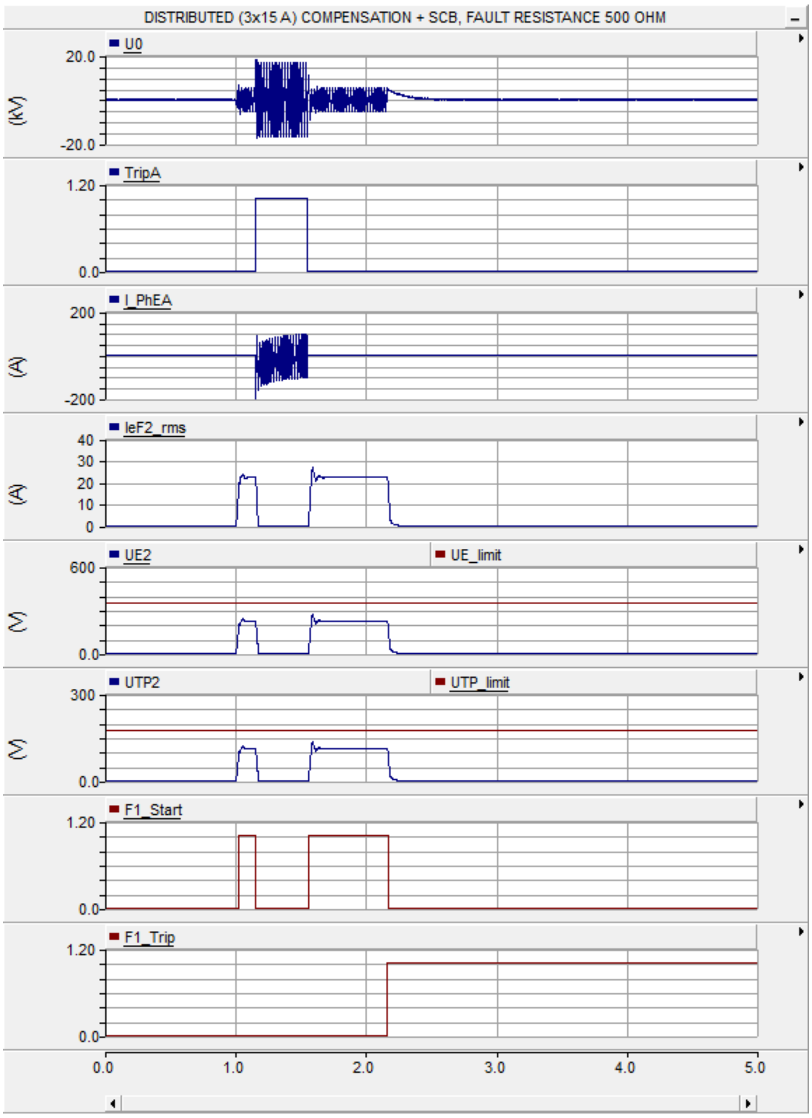

Figure 10. Applying SCB with distributed compensation 3x15 A when fault resistance was 500 Ω.

6.3 Case 3: Phase earthing with distributed compensation (3x20 A)

In this case the phase earthing was studied when only distributed compensation was connected along the appropriate feeder. The compensation degree of the whole network was approximately 52 %. This means that the extinguishing conditions of the earth fault arc are quite near to neutral isolated system without phase earthing. With this type of system the extinguishing of the phase-to-earth faults is possible to improve significantly applying the phase earthing which reduces the short interruptions to customers.

It can be observed that the touch voltage regulations cannot be fulfilled even in this case without the phase earthing or additional compensation. When the shunt circuit-breaker is closed the earthing voltage and touch voltage are clearly below the allowed limit. Also in this case the feeder E/F protection starts up again when the shunt circuit-breaker has been opened.

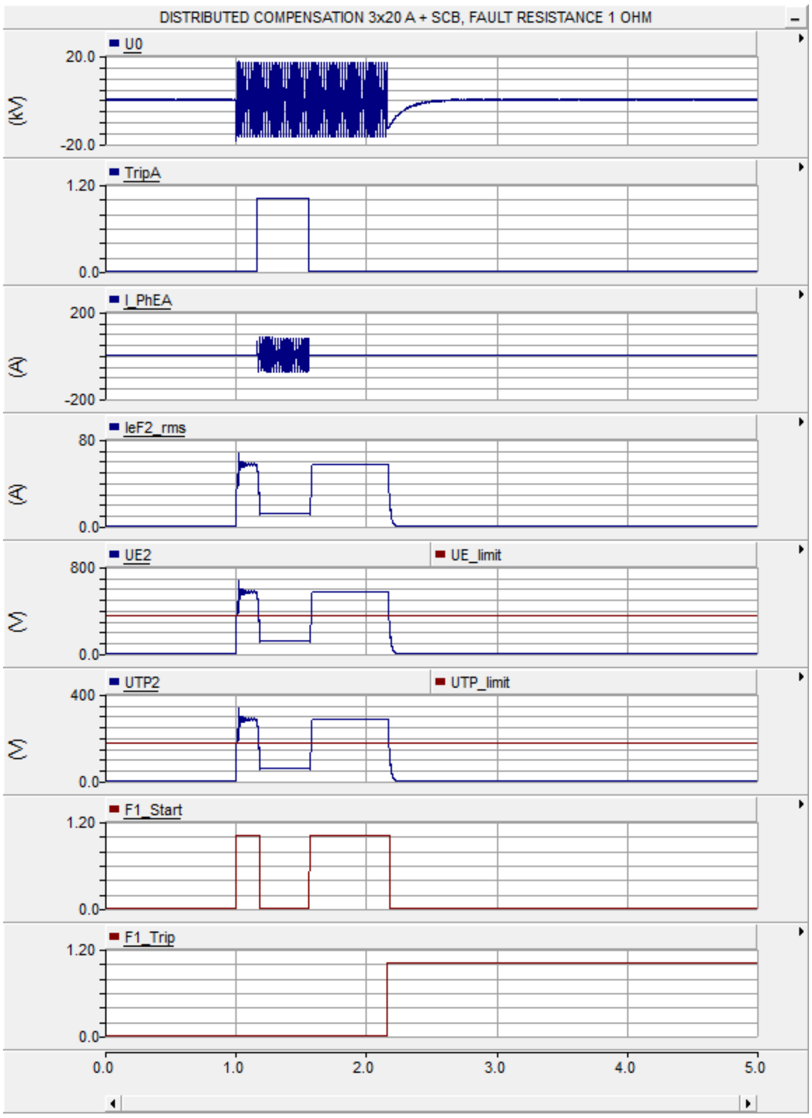

Figure 11. Applying SCB with distributed compensation 3x20 A when fault resistance was 1 Ω.

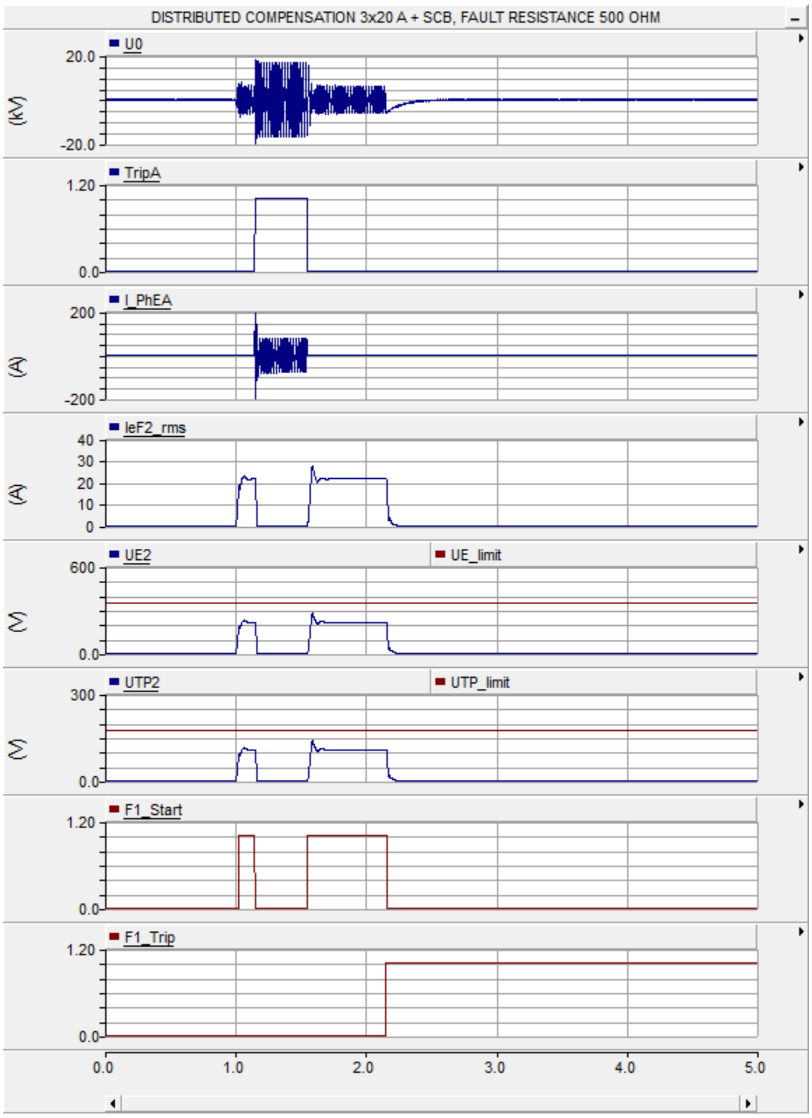

Figure 12. Applying SCB with distributed compensation 3x20 A when fault resistance was 500 Ω.

6.4 Case 4: Phase earthing with distributed (3x15 A) and centralized compensation

In this case the phase earthing was studied when both distributed and centralized compensation was connected to the network. 95 % of the capacitive earth fault current of the background network was compensated. The compensation degree of the whole network was approximately 79 %. The extinguishing conditions of the earth fault arc are already significantly better than in a neutral isolated system without phase earthing. Even with this type of system the extinguishing of the phase-to-earth faults is possible to improve applying the phase earthing.

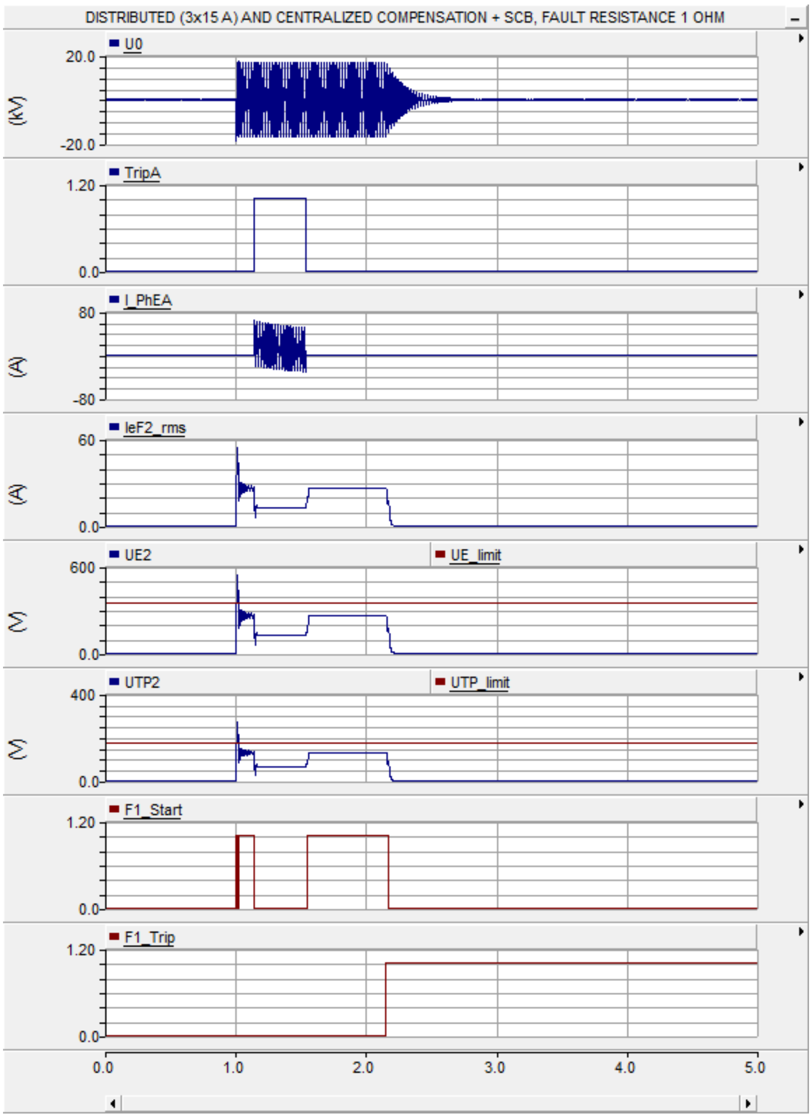

Figure 13. Applying SCB with distributed (3x15A) and centralized compensation when fault resistance was 1 Ω.

It can be observed that the touch voltage regulations can be fulfilled in this case without phase earthing or additional compensation. The earthing voltage and touch voltage are below the allowed limit without phase earthing. Also in this case the feeder E/F protection starts up again when the shunt circuit-breaker has been opened.

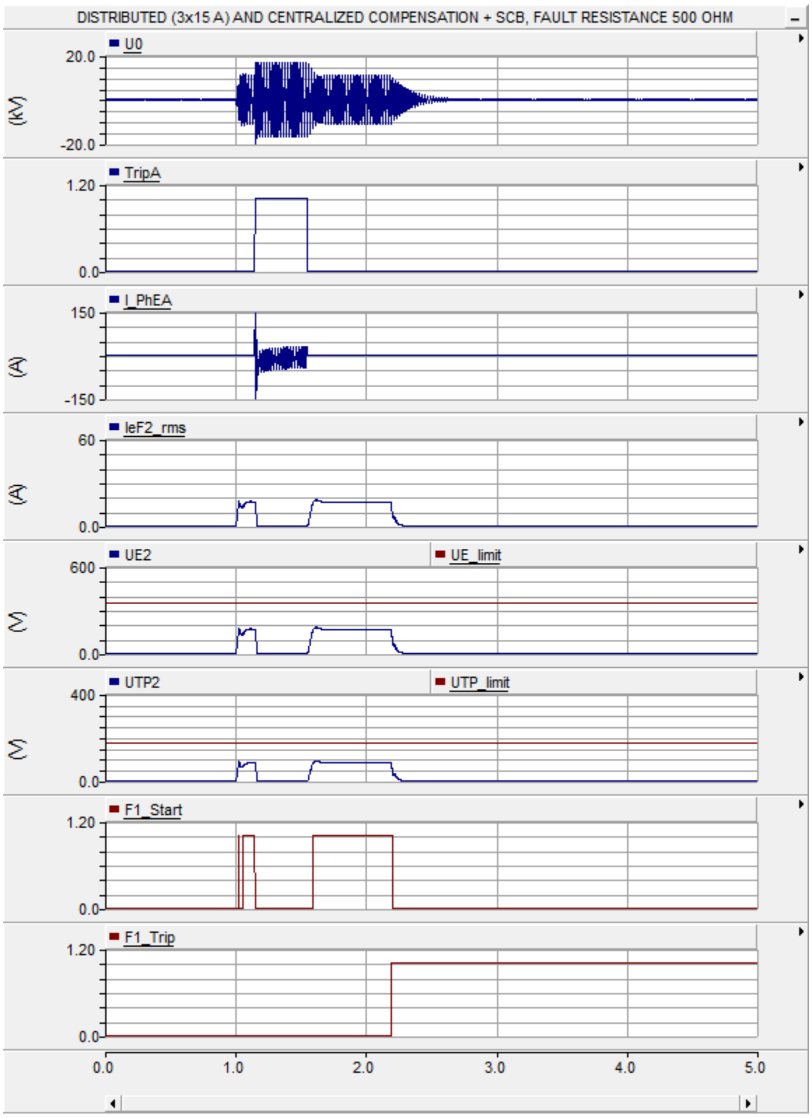

Figure 14. Applying SCB with distributed (3x15 A) and centralized compensation when fault resistance was 500 Ω.

7. Summary

The earth fault arc can be extinguished by connecting the faulty phase temporarily to earth at a feeding primary substation. Then the major part of the fault current is transferred away from the fault location. The recovery voltage at the fault location after the arc current has been interrupted is very advantageous for the extinction of the arc when the fault disappears during the phase earthing. The residual fault current is also low. Both facts improve the probability that the temporary earth fault will be cleared without the operation of the feeder circuit-breaker. The method does not cause any interruption or voltage dip for the customers or generators of the electricity producers. The phase earthing can be applied as a complementary function as part of the normal earth fault protection. Then the temporary phase earthing should be made during the tripping delay of the earth fault protection if the settings of the E/F protection are not wanted or allowed to change due to touch voltage regulations [1]. If the fault does not disappear during the phase earthing the normal feeder E/F protection operates the same way as without phase earthing.

The modern phase earthing system provides some benefits also in neutral compensated systems. When the distributed compensation is applied the compensation degree of the whole network remains often relatively low because the overcompensation of the feeders must be prevented in all cases. Otherwise the earth fault protection of the overcompensated feeder will trip with external faults. In the consequence of the low compensation degree the probability for the self-extinguishing of the earth fault arc is smaller than with fully compensated systems. Applying the phase earthing the self-extinguishing probability can be increased and thereby the number of short interruptions to customers can be reduced.

The earth fault current compensation reduces the fault current and thereby hazard voltages. This makes it possible to lengthen the tipping delay of the feeder E/F protection. Thereby the faulty feeder can be kept earthed longer which improves the probability of self-extinguishing of the fault. Even with the high compensation degree the fault current and hazard voltages at the fault location can be reduced applying the phase earthing.

In many cases the starting signal of the feeder E/F relay goes down when the shunt circuit-breaker is closed due to small fault current or changes in the phase angle between the sum current and the neutral voltage. This means that the total tripping delay increases including also the time the shunt circuit-breaker is closed. Although the residual fault current is normally very low during a phase earthing this time must be included to the total tripping time based on the hazard voltage regulations if the reliable method for proving the residual current at the fault location does not exist. One possibility for managing the total tripping time is that state information of the shunt circuit-breaker would be connected to the feeder terminals. This would prevent the starting signal of the feeder E/F relay going down when the shunt circuit-breaker is closed. Thereby the total tripping time would be always the same including the time the shunt circuit-breaker is closed. The total tripping time of the feeder E/F protection could be near to the time the shunt circuit-breaker is closed. If the phase earthing does not extinguish an earth fault the self-extinguishing is quite improbable after the phase earthing.

Intermittent earth faults can be a problem especially in compensated underground cable networks or mixed networks including underground cables when the fault current is compensated to a low level. The rising speed of the recovery voltage at the fault location after the fault current has been interrupted at the zero crossing has an essential significance in this fault mechanism. Applying the phase earthing the phase-to-earth voltage of the faulty phase is very low when the shunt circuit-breaker is closed. In many cases this would prevent the forming of intermittent fault which can lead a more severe secondary fault.

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