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Smart Grids and Energy Markets

Phase earthing system - method for faulty phase selection with phase-to-earth faults

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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”.

The report presents the novel method developed for faulty phase selection of modern phase earthing system. 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. A reliable and sensitive method for faulty phase selection were needed which can be applied within large range of fault resistance and electrical length of the network.

Even present modern feeder terminals does not include detection of faulty phase with phase-to-earth faults which would be beneficial feature also when actual fault location is searched because in some cases any visible damage cannot be detected.



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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.

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 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 touch 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.

One cost-effective method for reducing the number of HSARS in MV networks with temporary earth faults and limiting the touch voltages is to apply modern shunt circuit-breaker (SCB) equipped with novel control logic. 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. 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 faulty phase selection method. The complete faulty phase selection was difficult to develop applying the relay technology of that time.

Demands for the protection of MV networks will be changed due to distributed generation. Originally AR functions are planned in MV system for unidirectional power transmission. If the MV feeder includes one or more DG units the feeder remains momentarily to operate islanded due to an AR maintaining the voltage in the islanded feeder in the case of phase-to-earth fault. In respect of ARs it is essential to know how DG affects the clearance time and clearance probability of the fault. The problematic influence of the DG unit is that it sustains the voltage during islanded operation lengthening the effective time of hazard voltages. Need for reducing ARs due to distributed generation clearly exists.

One possibility is to take ARs out of use. Maintaining the reliability of the electricity distribution without ARs in neutral isolated MV system requires large investments in improving the dependability (e.g. cabling, covered conductors, metal oxide surge arresters, earth fault current compensation) however if the reliability level is wanted to keep unchanged. Thus ARs cannot be removed from service with MV overhead line feeders in the short term. In order to avoid above-mentioned problems utilizing the temporary earthing of the faulty phase applying the SCB seems respectable. If an earth fault extinguishes during the PE any disturbances for DG units does not appear.

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. 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.

Major part of Finnish MV networks are overhead line networks which have isolated neutral points. The extinguishing conditions of the earth fault arcs are significantly worse than in neutral compensated systems. 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). The developed methods relate to the indication of the faulty phase during a phase-to-earth fault in neutral isolated MV (typically 20 kV) network. The starting point for the development was clear need for the reliable indication method of faulty phase with a modern PES. 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.

Indication of the faulty phase with phase-to-earth faults has also more general significance because it enables fault location in such points of the network where the phase sequence is known (e.g. secondary substations, cable terminals, disconnectors, line circuit-breakers). E.g. ocular detection of damaged metal oxide surge arrester is often impossible. Recognition of the faulty phase with phase-to-earth faults of MV system is valuable information concerning to fault statistics. Number of phase-to-earth faults in certain phase helps the evaluation the exposure of separate phases to power frequency overvoltages.

2. Description of phase earthing

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 (PE). 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. The prevailing vector group of distribution transformers is Dyn11 in Finland. 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.

The main advantage of applying the PES is that it offers nearly the same benefits with temporary earth faults as ARs but without short interruptions to the customers. This solution offers high potentiality to reduce ARs because in typical Nordic MV networks 50-80 % of the faults are earth faults.



3. Aspects of distributed generation

Demands for the protection of MV networks will be changed due to distributed generation. Originally AR functions are planned in MV system for unidirectional power transmission. If the MV feeder includes one or more DG units the feeder remains momentarily to operate islanded due to an AR maintaining the voltage in the islanded feeder in the case of phase-to-earth fault. In respect of ARs it is essential to know how DG affects the clearance time and clearance probability of the fault. In many cases applying the PES a temporary earth fault could be removed without interruption to production units. This matter is crucial in determining the unenergized time interval of HSAR, which in Finland is normally without DG set at 300 ms. In this context unenergized time interval refers to the time the circuit-breaker is open. With DG the real unenergized time of the feeder is shorter. With earth fault cases confirming the electrical safety is the most essential goal.

LOM detection is a subject attracting the greatest research interest in the area of DG protection. An increasing amount of DG together with a more efficient control system makes unintended islanding more likely. The operating time of the LOM detection of DG unit affects the unenergized time interval of HSAR needed for clearing the fault. At present 300 ms unenergized time is challenging for the LOM protection because during this time islanding detection must be capable of indicating the islanded operation and disconnect DG unit from network clearly before the closure of the MV feeder breaker in order to avoid asynchronous reconnection to the main grid. This is a challenging requirement for the LOM detection because the fault should also have time to become extinct during the unenergized time interval. One possibility is to extend the unenergized period of the HSAR, which would improve the protection co-ordination and give the fault more time to extinct. In this case the duration of the short interruption to customers will increase. In the worst case the HSAR of the MV feeder may lead to asynchronous reconnection of the DG unit to the main grid, when the generator may be damaged. This kind of situation requires the failing of the protection coordination.

In order to avoid above-mentioned problems utilizing the temporary earthing of the faulty phase applying the SCB seems respectable. If an earth fault extinguishes during the PE any disturbances for DG units does not appear.

4. Feasibility of applying shunt circuit-breakers in MV networks

4.1 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].

4.2 Implementing of 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. 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 the fault current-flow duration 500 ms 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.

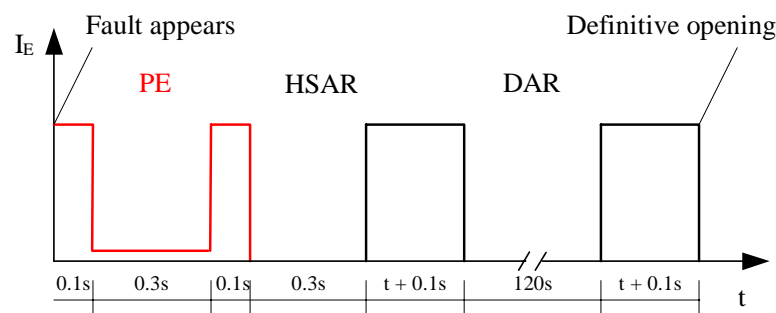


Figure 1. Operation sequence of PE and E/F protection.

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.



4.3 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.

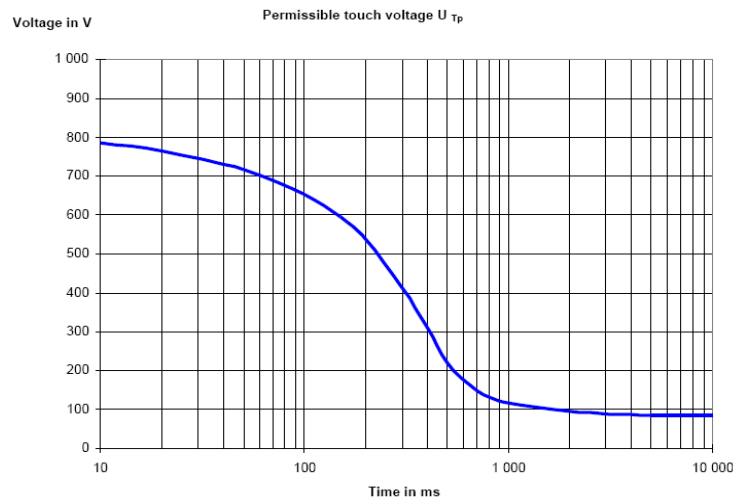


Figure 2. Permissible touch voltages U_{TP} for limited current-flow duration [1].

The highest permissible earthing voltage is double compared to 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 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. In practice the residual earth fault current is lower during PE compared to the original fault but it is difficult to prove in advance covering all possible fault 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 ($R_F = 0 \Omega$, without PE) and the highest earthing impedance.

The novel PES has been tested 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 PE (400 ms).

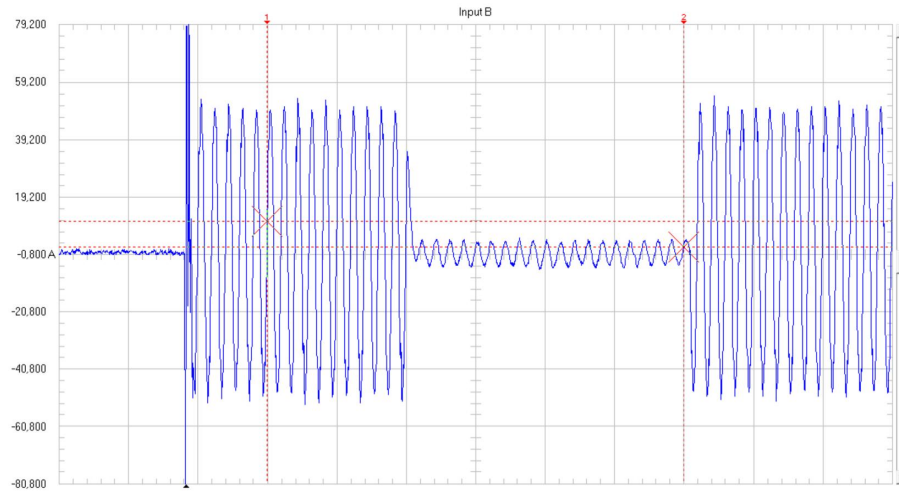


Figure 3. Fault current at the fault location with the PES.

5. Novel method for faulty phase selection in neutral isolated system

Even modern feeder terminals or other protection devices for MV network cannot detect and show the faulty phase with phase-to-earth fault of a neutral isolated or compensated MV network. In the case of low phase-to-earth fault resistances the faulty phase can be detected according to effective value of phase-to-earth voltages. In neutral isolated and compensated systems the phase-to-earth voltage of the faulty phase falls and the phase-to-earth voltages of the healthy phases rise due to a phase-to-earth fault. General detection of the existence of an earth fault is based on neutral voltage. The sensitivity of this simple method is adequate only for relatively low-resistance earth faults. The sensitivity also depends on the electric length and the natural unbalance of the MV network. The value of the fault resistance is not known and with higher fault resistances the phase-to-earth voltage of the faulty phase is not necessarily the lowest one compared to two other phase-to-earth voltages. Thus the above-mentioned method is not suitable for unambiguous detection of the faulty phase. More reliable, sensitive and unambiguous method for phase selection is needed. Sensitive and reliable method for the detection of the faulty phase is also useful when applied for the indication of high-resistance earth faults.

Indication of the faulty phase with phase-to-earth fault is also useful information for fault statistics because the stress caused by the fundamental frequency overvoltage for phase-to-earth insulations in separate phases can be evaluated.

The developed novel method for faulty phase selection is based on the measured effective value of the neutral voltage and its phase angle during a phase-to-earth fault. When an earth fault occurs e.g. in Phase A the neutral voltage rises depending mainly on fault resistance and electric length of the network. The indication of the existence of the fault can be made



according to the effective value of the neutral voltage or the change of the neutral voltage due to an earth fault. A certain threshold value for the neutral voltage can be defined. Exceeding of this threshold value starts the indication algorithm for the selection of the faulty phase. If the fault resistance is very low, near to zero the magnitude of the neutral voltage is nearly the same order of magnitude as the positive sequence voltage. Thus the voltage level of the network during an earth fault affects the neutral voltage during a fault.

The neutral voltage and phase-to-earth voltage of the faulty phase draw a semicircle as a function of fault resistance according to Figure 4. The negative sequence components of the voltages which are normally very low compared to zero sequence components during an earth fault are not taken into account here. Also the negative sequence component of the voltage increases due to an earth fault but its magnitude is very low compared to positive- and zero sequence components, however. Figure 4 presents the phase-to-earth voltages of the faulty phase and the neutral voltage when an earth fault is in phases A, B or C separately, not at the same time. The natural unbalance of the network is not taken into account here.

In the following the phase-to-earth fault in Phase A is considered. If the fault resistance is zero the effective value of the neutral voltage is equal to the positive sequence voltage of Phase A and the direction of the neutral voltage phasor is opposite compared to positive sequence voltage phasor of Phase A. When the fault resistance approaches infinity the magnitude of the neutral voltage approaches zero and the neutral voltage phasor leads almost 90° the phase-to-earth voltage A. If the basic phase angle of voltage phasor A is 30° during the normal operating conditions as is the case in Figure 4 the phase angle of the neutral voltage is in the range $120^\circ - 210^\circ$ during a phase-to-earth fault in Phase A. If the phase angle of the measured neutral voltage of the network is in the range $120^\circ - 210^\circ$ during an earth fault the fault can be indicated to be in Phase A.

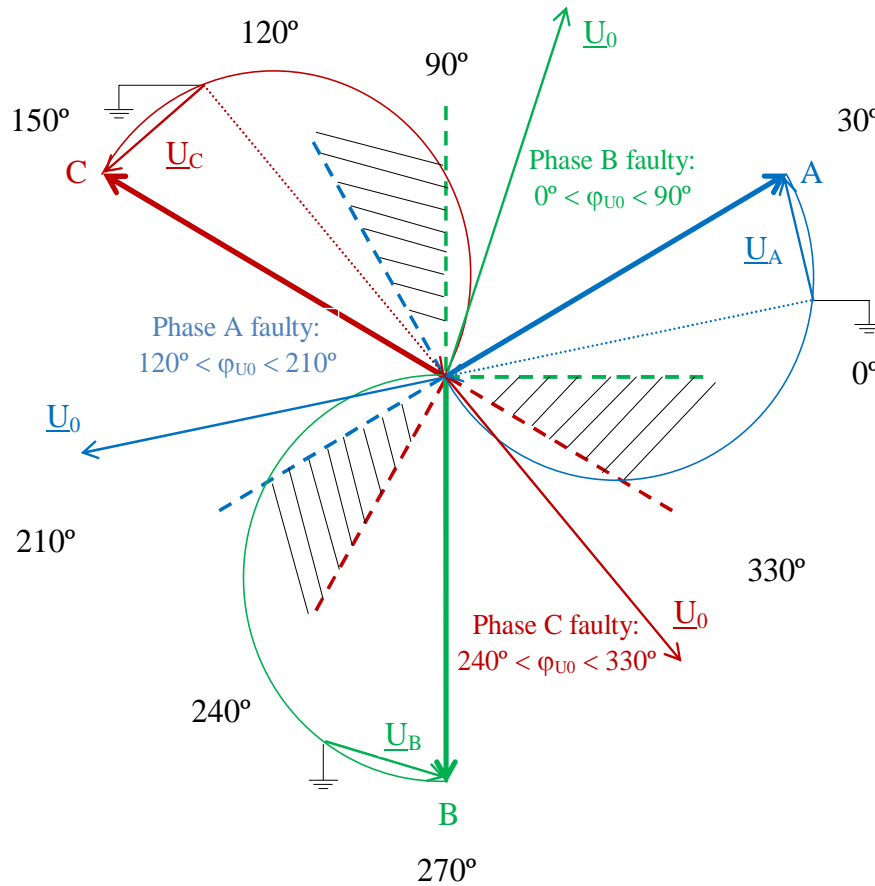


Figure 4. Forming of ranges of neutral-to-earth voltage when phase-to-earth fault is in Phase A, B or C.

Figure 5 presents the ranges of the phase angle of the neutral voltage when an earth fault is in Phase A, B or C. The phase angle of the positive sequence voltage Phasor \underline{U}_A is 30° , Phasor \underline{U}_B 270° and Phasor \underline{U}_C 150° . In the following the indication of the faulty phase according to the phase angle of the neutral voltage is presented when the fault is in Phase A, B or C.

Phase A-to-earth fault

Depending on the magnitude of the fault resistance the phase angle of the neutral voltage phasor is in the range $120^\circ - 210^\circ$ when the characteristic phase angle of the positive sequence voltage of Phase A is 30° . Thus the neutral voltage phasor leads $90^\circ - 180^\circ$ the positive sequence voltage of Phase A.

Phase B-to-earth fault

Depending on the magnitude of the fault resistance the phase angle of the neutral voltage phasor is in the range $0^\circ - 90^\circ$ when the characteristic phase angle of the positive sequence



voltage of Phase B is 270° . Thus the neutral voltage phasor leads $90^\circ - 180^\circ$ the positive sequence voltage of Phase B.

Phase C-to-earth fault

Depending on the magnitude of the fault resistance the phase angle of the neutral voltage phasor is in the range $240^\circ - 330^\circ$ when the characteristic phase angle of the positive sequence voltage of Phase C is 150° . Thus the neutral voltage phasor leads $90^\circ - 180^\circ$ the positive sequence voltage of Phase C.

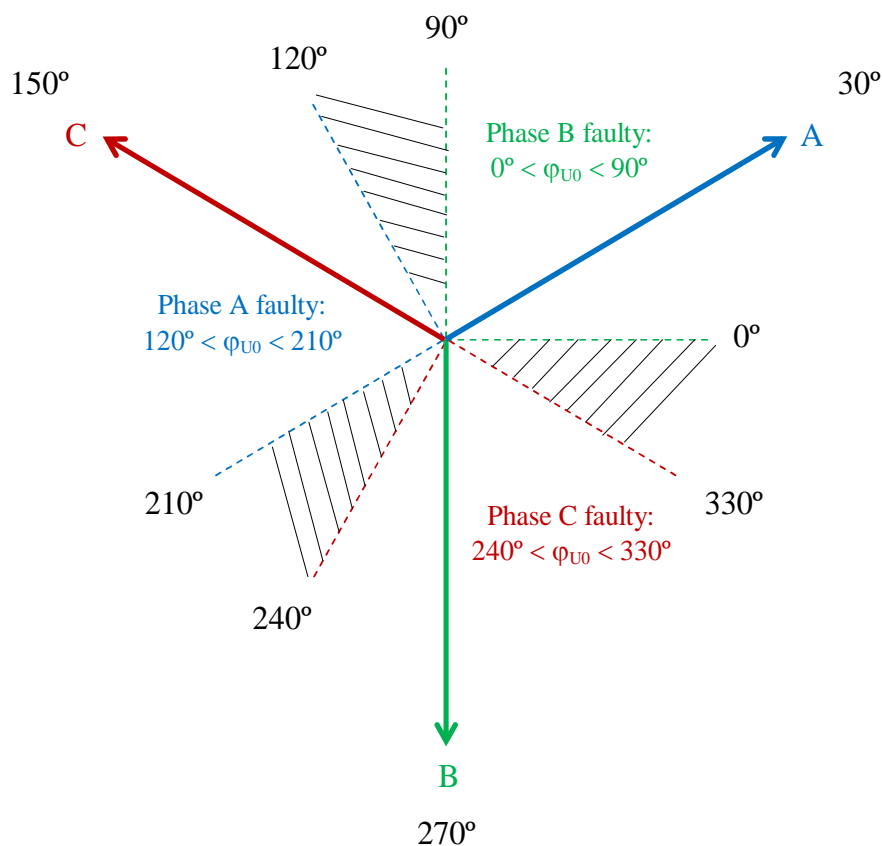


Figure 5. Ranges of neutral-to-earth voltage when phase-to-earth fault is in Phase A, B or C.

If the neutral voltage phasor leads 90° the positive sequence voltage phasor of the faulty phase in question the fault resistance is very high, in fact infinite. The indication of the faulty phase with a phase-to-earth fault starts when the neutral voltage or the change of neutral voltage exceeds a specific threshold value. This threshold value is determined according to the sensitivity requirement in respect of the fault resistance. Then the limit where the neutral voltage phasor leads 90° the positive sequence voltage phasor of the faulty phase will never be reached in an ideal case. When the neutral voltage phasor leads 180° the positive sequence voltage of the faulty phase the fault resistance is zero in the ideal case. The fault resistance value zero is theoretical because an earth fault arc also has some resistance and



the protective earthings have always some earthing resistance. It can be seen from Figure 5 that between all three faulty phase selection areas (Phases A, B and C) remains 30° margin (slash lined sectors in Figure 5). The phase angle of the neutral voltage phasor cannot be in these lined sectors during the phase-to-earth fault of any phase. In fact the fault resistance values zero and infinite are theoretical which slightly widen these 30° sectors.

The developed method for the faulty phase selection needs measured neutral voltage and phase-to-earth voltages for all three phases in phasor form including thereby both the effective value and phase angle information. The neutral voltage can be measured or it can be calculated according to phase-to-earth voltage phasors. The source data needed is normally available in modern feeder terminals. Thereby any new measuring devices are not needed.

6. Improving sensitivity of developed method for indicating high-resistance earth faults

The faulty phase can be detected reliably with a phase-to-earth fault in neutral isolated medium voltage network up to quite high values of the fault resistance applying the above-mentioned method. In the following the method for increasing the sensitivity of the faulty phase selection is presented. The method is mainly based on symmetrical component analysis and eliminating the influence of the unbalanced phase-to-earth voltages. Thereby the method can also be regarded as indication method for high-resistance earth faults. In addition to the fault indication also the faulty phase can be detected. The phasor diagram of Figure 6 presents the phase-to-earth voltages and neutral voltage in neutral isolated system with the phase-to-earth fault in Phase A. Figure 6 presents an ideal situation where the network is supposed to be fully symmetric regarding impedances and phase-to-earth voltages. Phase-to-earth voltages of Phases A, B and C are composed only of the positive sequence components during the healthy operation condition of the network. Because the system is fully balanced also regarding impedances (including phase-to-earth admittances) and loads any neutral voltage or negative sequence components cannot be detected during the healthy condition of the system. During an earth fault condition the phase-to-earth voltages are composed of the phasor sum of the positive sequence and zero sequence components. The base angle of the phase-to-earth voltage of Phase A is 30° .

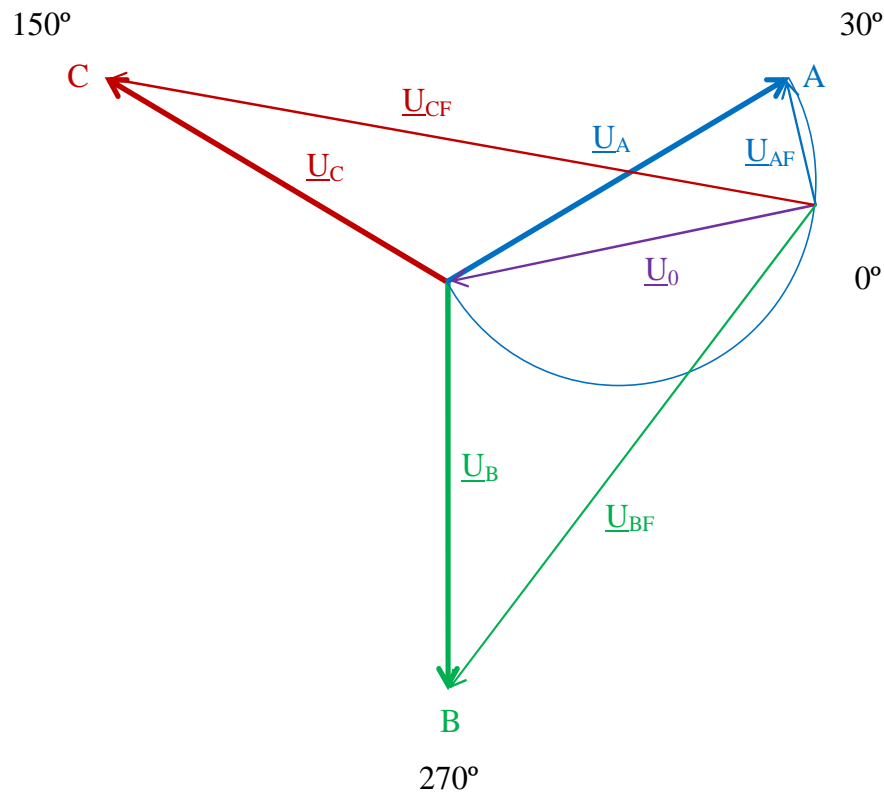


Figure 6. Phase-to-earth voltages and neutral voltage when an earth fault is in Phase A in an ideal case.

In reality the medium voltage network is never fully balanced especially if it is mainly composed of the overhead line feeders. The unbalanced healthy state of the three phase network results amongst others from the fact that the cross-arm constructions are rarely symmetric. Then the phase-to-earth capacitances and inductances of separate phases differ slightly from each others. The medium voltage feeders are normally not transposed systematic way. Then the phase conductors may be slightly of different length in separate phases. Underground cable networks are normally substantially more symmetrical than the corresponding overhead line networks. Due to above-mentioned facts low neutral voltage can normally be detected also during healthy operation condition of the network. The order of magnitude of this neutral voltage is typically 1 – 5 % of the corresponding positive sequence voltage of neutral isolated system. A slight negative sequence component can also be detected normally during healthy state of the system. This negative sequence component changes due to an earth fault. In the following is presented facts, whose effect can be mainly eliminated in order to improve the sensitivity of the method for faulty phase selection. Thereby the method is also suitable to be applied for the indication of the faulty phase with high-resistance earth faults. The method can be regarded as a sensitive indication method for high-resistance earth faults which can operate alone at the substation level or as a



complementary method with other feeder level indication methods. In the following three facts causing inaccuracy for the faulty phase selection are listed.

- Effect of the neutral voltage due to unbalance of the network during healthy state
- Effect of the negative sequence component of the phase-to-earth voltage
- Effect of unbalanced phase-to-earth voltages during healthy state of the system

In the following the unbalanced phase-to-earth voltages of the MV network with healthy state are denoted \underline{U}_A' , \underline{U}_B' and \underline{U}_C' . An earth fault is in Phase A. The corresponding unbalanced phase-to-earth voltages during an earth fault in Phase A are denoted \underline{U}_{AF} , \underline{U}_{BF} and \underline{U}_{CF} . Unbalanced phase-to-earth voltages of the network with healthy and faulty states are presented by means of symmetrical components. Every phase-to-earth voltage phasor is composed of positive, negative and zero sequence voltage components.

Due to natural unbalance of the system a low zero sequence voltage \underline{U}_0' can be detected also with the healthy state of the network. Phase-to-earth voltage phasors also include small negative sequence components \underline{U}_{A2} , \underline{U}_{B2} and \underline{U}_{C2} during healthy state of the network. Because the phase-to-earth voltages compose of the sum of positive, negative and zero sequence components the measurable phase-to-earth voltages during the healthy state of the network \underline{U}_A' , \underline{U}_B' and \underline{U}_C' are also slightly unbalanced. During healthy state of the network the following equations can be presented.

Healthy state:

$$\underline{U}_A' = \underline{U}_{A1} + \underline{U}_{A2} + \underline{U}_0' \quad (1)$$

$$\underline{U}_B' = \underline{U}_{B1} + \underline{U}_{B2} + \underline{U}_0' \quad (2)$$

$$\underline{U}_C' = \underline{U}_{C1} + \underline{U}_{C2} + \underline{U}_0' \quad (3)$$

When a phase-to-earth fault happens in Phase A the change of the neutral voltage due to an earth fault $\Delta\underline{U}_0$ draws a semicircle curve against fault resistance. According to Equation 4 the change of the neutral voltage $\Delta\underline{U}_0$ is the phasor difference between phasor \underline{U}_{0F} (measurable neutral voltage during an earth fault) and \underline{U}_0' (measurable neutral voltage during healthy state of the network). When the fault resistance is high the phasors \underline{U}_{0F} and \underline{U}_0' are of the same order of magnitude. Then the part of the measuring error will be eliminated also when the change of neutral voltage $\Delta\underline{U}_0$ is applied instead of phasor \underline{U}_{0F} .

$$\Delta\underline{U}_0 = \underline{U}_{0F} - \underline{U}_0' \quad (4)$$

The measurable unbalanced phase-to-earth voltages during an earth fault can be presented applying symmetrical components as follows. The voltage phasors \underline{U}_{A2F} , \underline{U}_{B2F} and \underline{U}_{C2F} are the negative sequence voltage phasors measurable during an earth fault. The phase-to-earth fault changes also the negative sequence voltage voltages when the fault current flows through the negative sequence impedance. In principle, also the positive sequence voltages



are slightly different during an earth fault compared to the healthy state of the system. This difference is normally very low. In Equations 5 -7 the subscript “F” is added to the positive sequence voltages meaning the positive sequence voltage during an earth fault.

Earth fault state:

$$\underline{U}_{AF} = \underline{U}_{A1F} + \underline{U}_{A2F} + \underline{U}_{0F} \quad (5)$$

$$\underline{U}_{BF} = \underline{U}_{B1F} + \underline{U}_{B2F} + \underline{U}_{0F} \quad (6)$$

$$\underline{U}_{CF} = \underline{U}_{C1F} + \underline{U}_{C2F} + \underline{U}_{0F} \quad (7)$$

According to Equations 5 – 7 every phase-to-earth voltage during an earth fault can be presented as a phasor sum of positive, negative and zero sequence voltage components during an earth fault. The phase-to-earth voltages during an earth fault can also be presented by the help of unbalanced phase-to-earth voltage of healthy state and the changes of negative and zero sequence voltage components in the following way.

Earth fault state:

$$\underline{U}_{AF} = \underline{U}_A' + \Delta\underline{U}_{A2} + \Delta\underline{U}_0 \quad (8)$$

$$\underline{U}_{BF} = \underline{U}_B' + \Delta\underline{U}_{B2} + \Delta\underline{U}_0 \quad (9)$$

$$\underline{U}_{CF} = \underline{U}_C' + \Delta\underline{U}_{C2} + \Delta\underline{U}_0 \quad (10)$$

6.1 Advanced method for faulty phase selection

In Section 5 the novel method for the faulty phase selection in a neutral isolated system was presented. This method can be improved to detect a faulty phase with high fault resistances. At the same time this advanced method can be applied for indication of high-resistance earth faults at the network level. The analysis is based on the neutral voltage and the phase angle of it. The advanced method can be applied alike the method presented in Section 5 but the influence of some sources of error is eliminated.

With low-resistance phase-to-earth faults the method described in Section 5 can be applied in the raw because the influence of the natural unbalance of the system is negligible concerning to the faulty phase selection. Thereby the phase-to-earth voltages can be supposed to be symmetrical when the ranges for the phase angle of the neutral-to-earth voltage are determined for Phases A, B and C. When the fault resistance is high the main source of error is natural unbalance of the system due to e.g. capacitive asymmetry. In some cases the neutral-to-earth voltage can be higher with healthy condition of the network than with earth fault condition. Phase-to-earth voltages are slightly unbalanced also during healthy state of the system. Due to above-mentioned unbalance the phase angle of the measured neutral-to-earth voltage may has quite wide range when the fault resistance is high. Avoiding



this problem the phase angle of the change of the neutral voltage phasor is applied instead of phasor \underline{U}_{0F} .

When the phase-to-earth voltages are unbalanced during healthy state of the network more sensitive faulty phase selection is achieved if the ranges for the phase angle of the neutral-to-earth voltage are determined using unbalanced phase-to-earth voltages \underline{U}_A' , \underline{U}_B' and \underline{U}_C' .

7. Testing the method applying PSCAD simulations

New method for reliable indication of the faulty phase was tested applying PSCAD simulations. Network model consisting of the models of feeding 110 kV network, main transformer, real 20 kV feeder and background network was generated. 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 the new indication method of the faulty phase. 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 μ F capacitance between one phase and earth at the primary substation.

Figures 7 - 16 present the indication of the faulty phase with phase-to-earth fault in neutral isolated network applying previously described PSCAD model. The fault resistance was varied between 5 Ω and 350 k Ω . The faulty phase was varied too.

The phase angles of the phase-to-earth voltages measured before a fault are used as a reference when determining the limits for the phase angle of the phasor ΔU_0 (red horizontal lines in Figures 7 - 16). The uppermost curve represents the instantaneous value of the neutral voltage. Because the phase-to-earth voltages corresponding to the healthy state are slightly unbalanced due to a capacitive asymmetry also the limits corresponding to the minimum and maximum fault resistances deviate slightly from the symmetric limits presented in Figures 4 and 5. Normally the indication of the faulty phase is started when the change of the neutral voltage exceeds a certain threshold value. Thereby the sensitivity range of the indication can be adjusted. In Figures 7 - 16 fault happens at 1.0 s. With lower fault resistances the feeder protection trips at 2.0 s. When the fault resistance is high enough the feeder protection does not trip any more. When the fault resistance is very low or very high the phase angle of the phasor ΔU_0 is very near to lower or upper phase angle limit. In these cases the value of the phase angles of the phasor ΔU_0 and angle limits can be read from the cursor values presented in the right side of the figures. In all cases the faulty phase could be indicated up to fault resistance 350 k Ω unambiguously so that the phase angle of the phasor ΔU_0 was within the defined limits in the case of the faulty phase and outside the defined limits in the case of the healthy phases. Even with higher fault resistances the faulty phase was possible to indicate but it is not evidently reasonable to read such cases as faults.

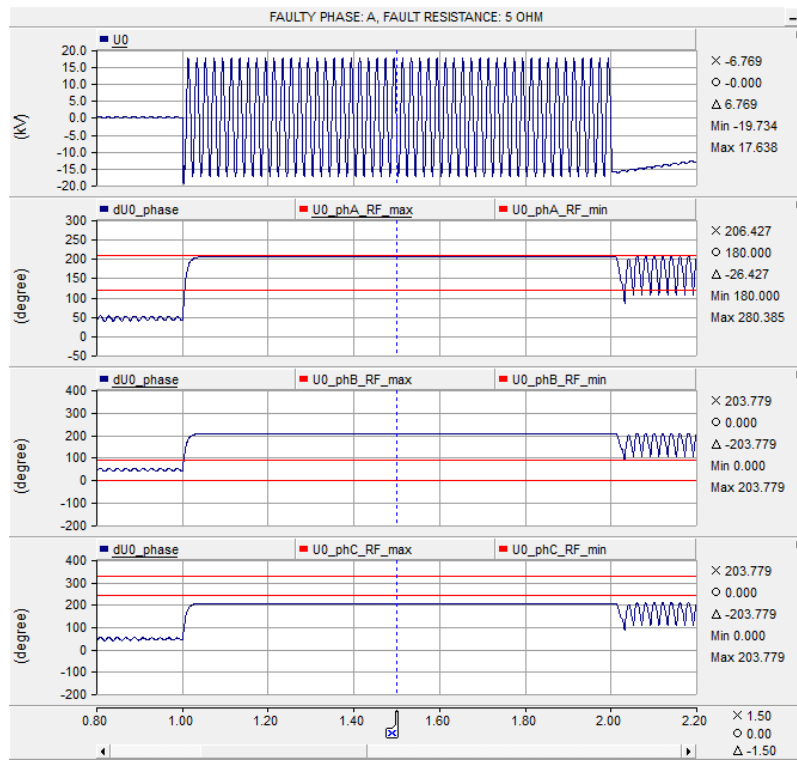


Figure 7. Indication of faulty phase (A) when fault resistance is 5 Ω .

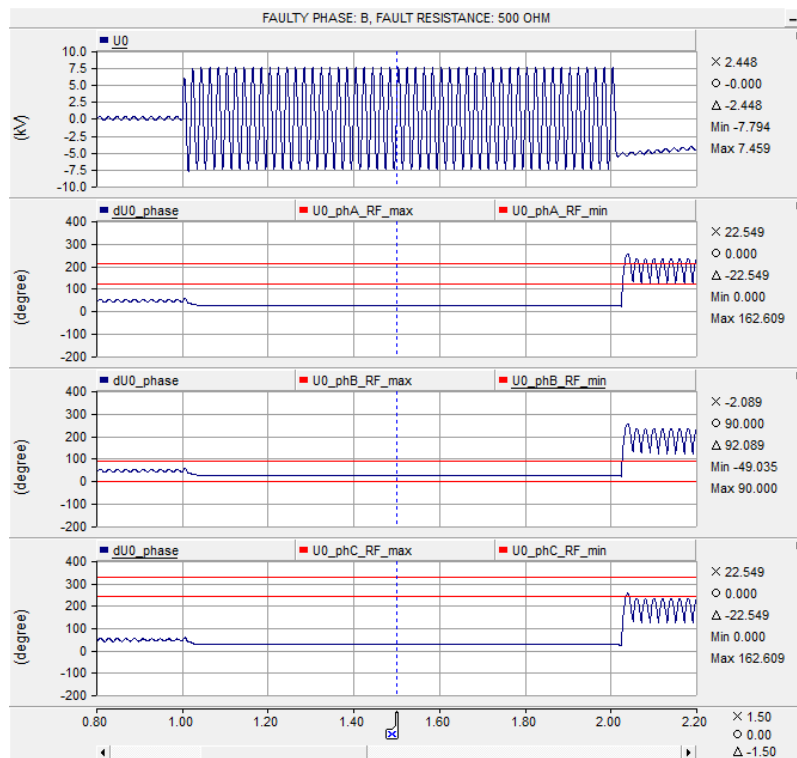


Figure 8. Indication of faulty phase (B) when fault resistance is 500 Ω .

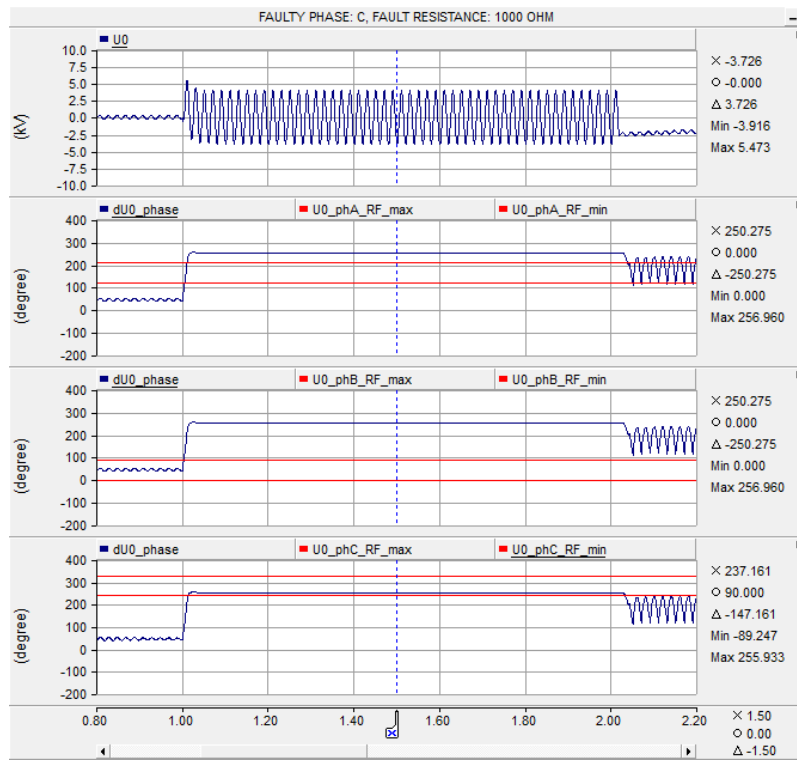


Figure 9. Indication of faulty phase (C) when fault resistance is 1 kΩ.

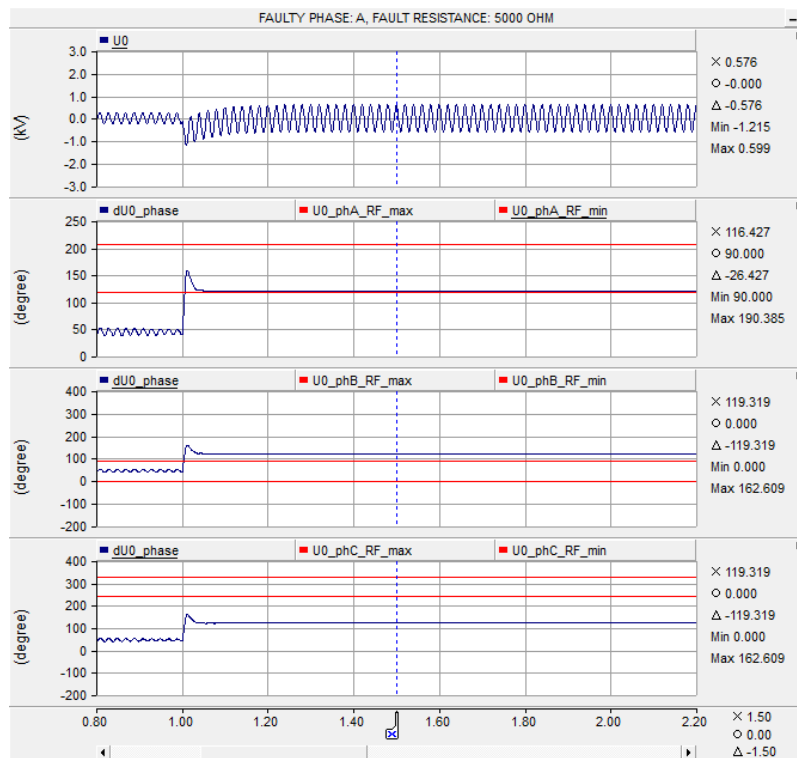


Figure 10. Indication of faulty phase (A) when fault resistance is 5 kΩ.

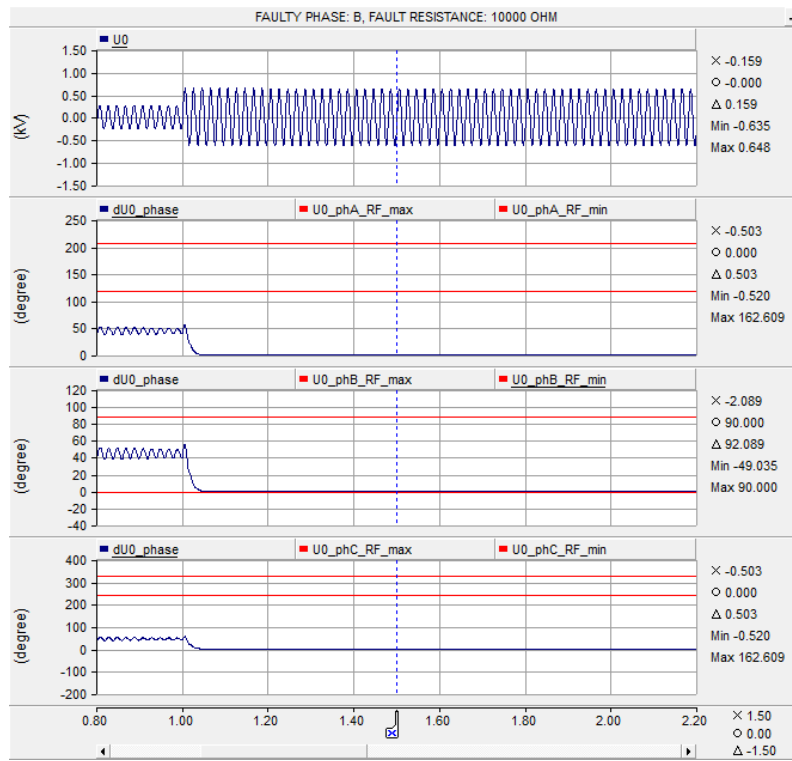


Figure 11. Indication of faulty phase (B) when fault resistance is 10 kΩ.

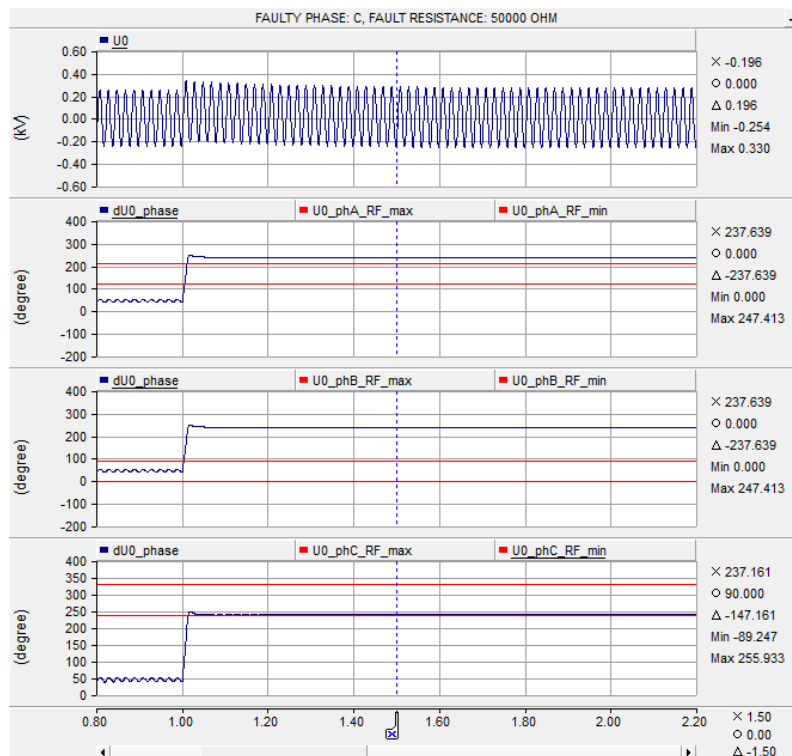


Figure 12. Indication of faulty phase (C) when fault resistance is 50 kΩ.

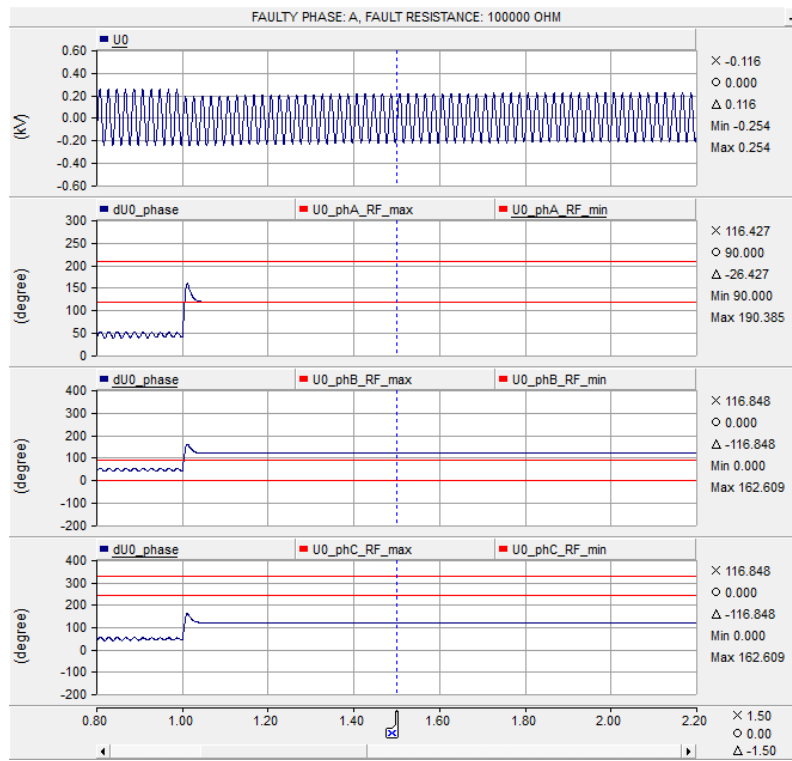


Figure 13. Indication of faulty phase (A) when fault resistance is 100 kΩ.

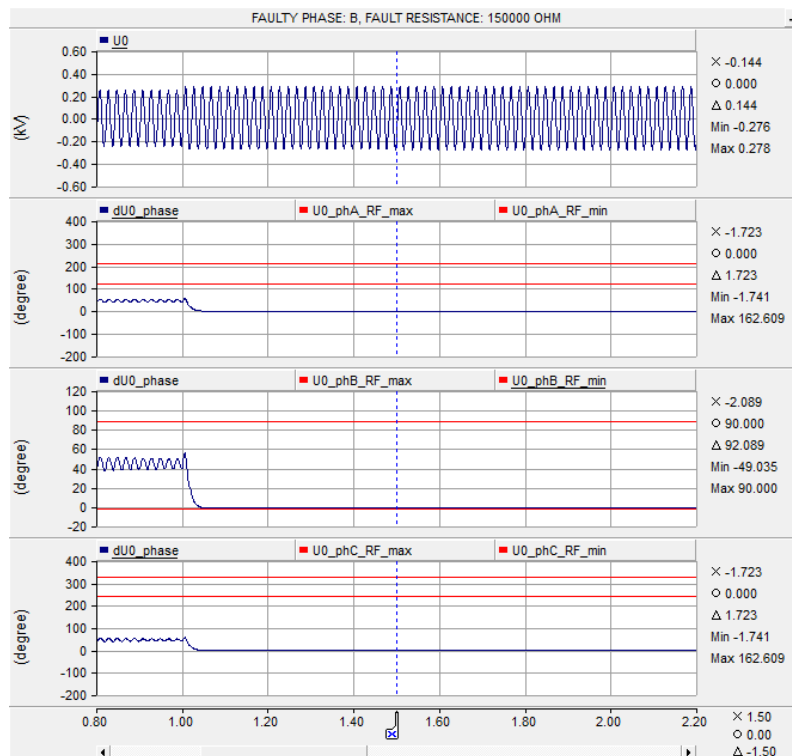


Figure 14. Indication of faulty phase (B) when fault resistance is 150 kΩ.

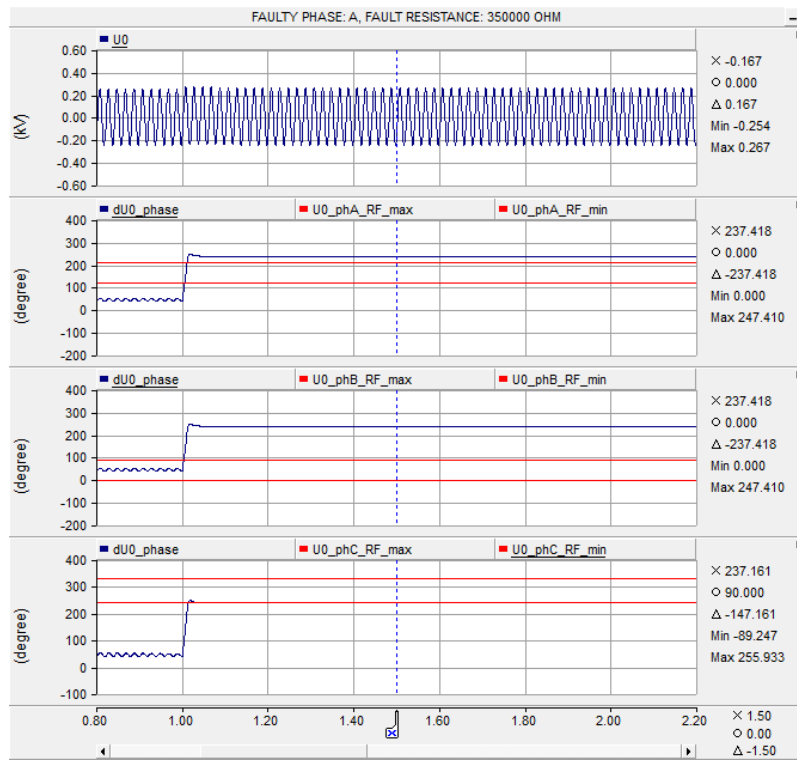


Figure 15. Indication of faulty phase (C) when fault resistance is 250 kΩ.

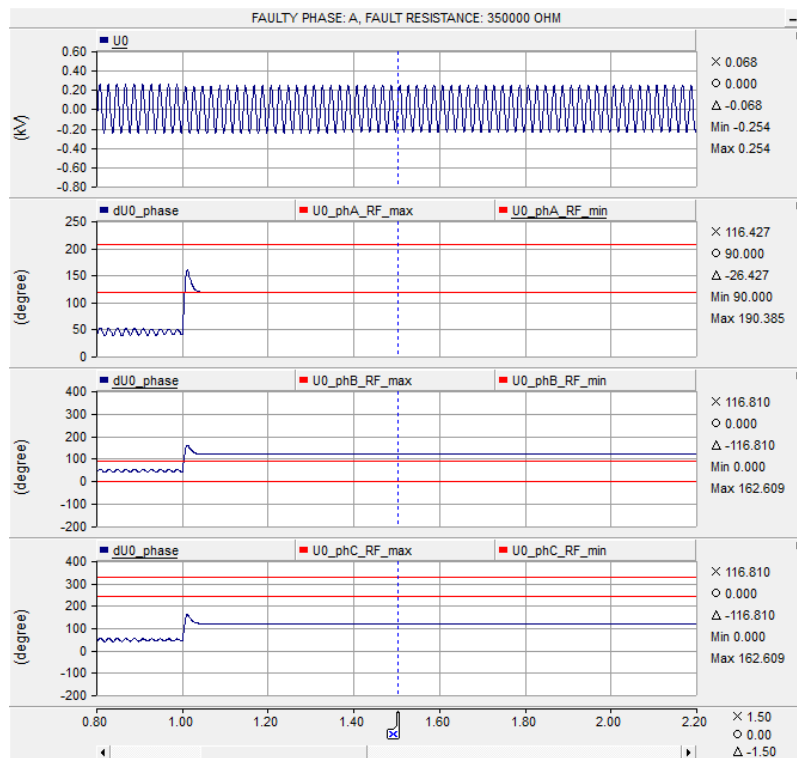


Figure 16. Indication of faulty phase (A) when fault resistance is 350 kΩ.



7.1 Controlling a shunt circuit-breaker applying the novel faulty phase selection method

The novel indication method for reliable faulty phase selection was applied for controlling the shunt circuit-breaker. Same network model as with previous section was applied. The indication of the faulty phase is started when the effective value of the change of neutral voltage ΔU_0 exceeds a certain threshold value. The sensitivity of the phase earthing can thereby be adjusted by choosing a suitable threshold value for the change of the neutral voltage. The capacitive unbalance in the 20 kV network was taken into consideration in the model connecting one 0.2 μF capacitance between one phase and earth at the primary substation correspondingly as with testing indication of the faulty phase without phase earthing. Thereby a low neutral voltage can be detected also during healthy state of the system.

The faulty phase is selected according to same principles as with the earth fault indication. When the phase angle of the phasor ΔU_0 was within the defined limits in the case of one phase and outside the defined limits in the case of two other phases the faulty phase could be concluded unambiguously. Previously described logic was modelled in PSCAD and it functioned automatically when an earth fault was simulated.

Figures 17 – 22 present the functioning of the faulty phase selection and logic controlling the shunt circuit-breaker when the fault resistance was varied between 5 Ω and 100k Ω . The possible sensitivity range is in practice the same as with an earth fault indication but normally phase earthing is not reasonable to use with very high-resistance earth faults. The uppermost signal is the instantaneous value of the neutral voltage. In the case of low-resistance earth faults the neutral voltage changes very slightly when a phase earthing occurs. In the case of high-resistance earth fault the change of the neutral voltage due to fault itself is hardly observable. Start and trip signals for every phases are also presented same as the fault current of the faulty phase of the shunt circuit-breaker (I_{PhE}).

When the faulty phase was detected the faulty phase was earthed during 400 ms. After starting 100 ms delay was applied for the tripping signal. The lowest signal represents the blocking signal. It prevents the two other (healthy) phases of the shunt circuit-breaker to close simultaneously as the faulty phase. Thereby a double earth fault or cross-country fault cannot occur. With real life application this blocking would be reasonable to last longer after the phase earthing, perhaps some seconds, preventing the repetitive phase earthings.

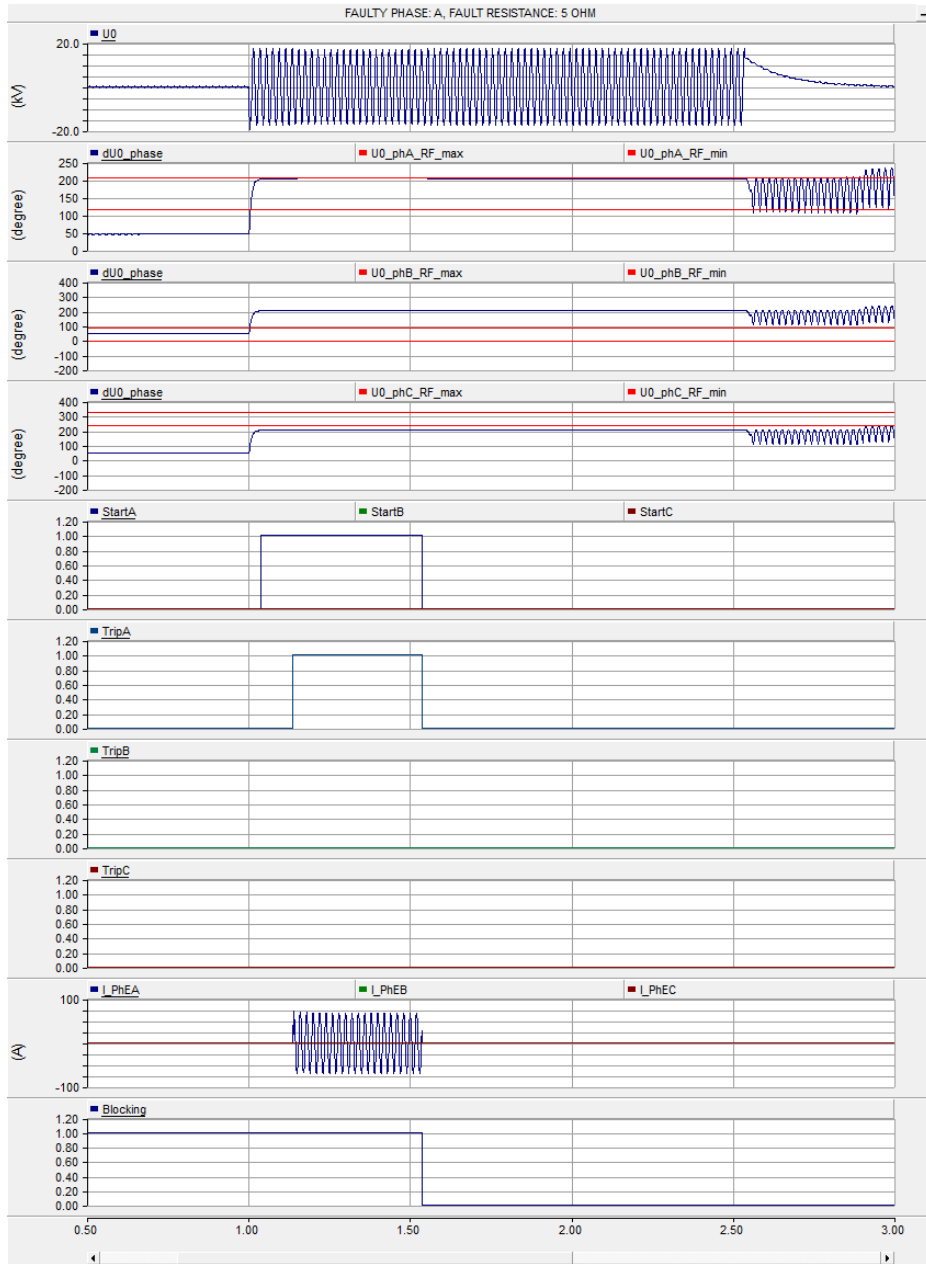


Figure 17. Functioning of the SCB when faulty phase is A and fault resistance 5 Ω.

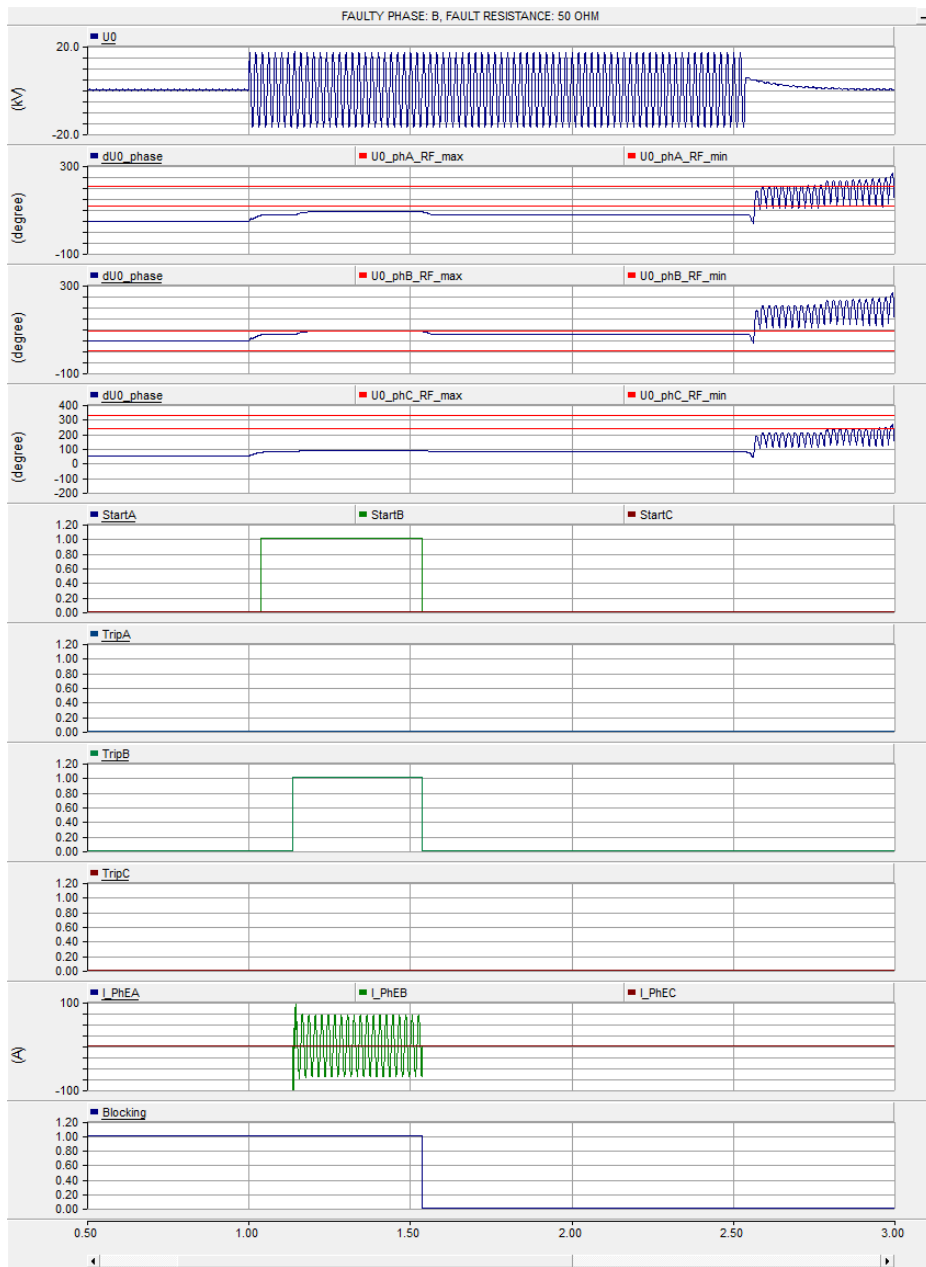


Figure 18. Functioning of the SCB when faulty phase is B and fault resistance 50 Ω.

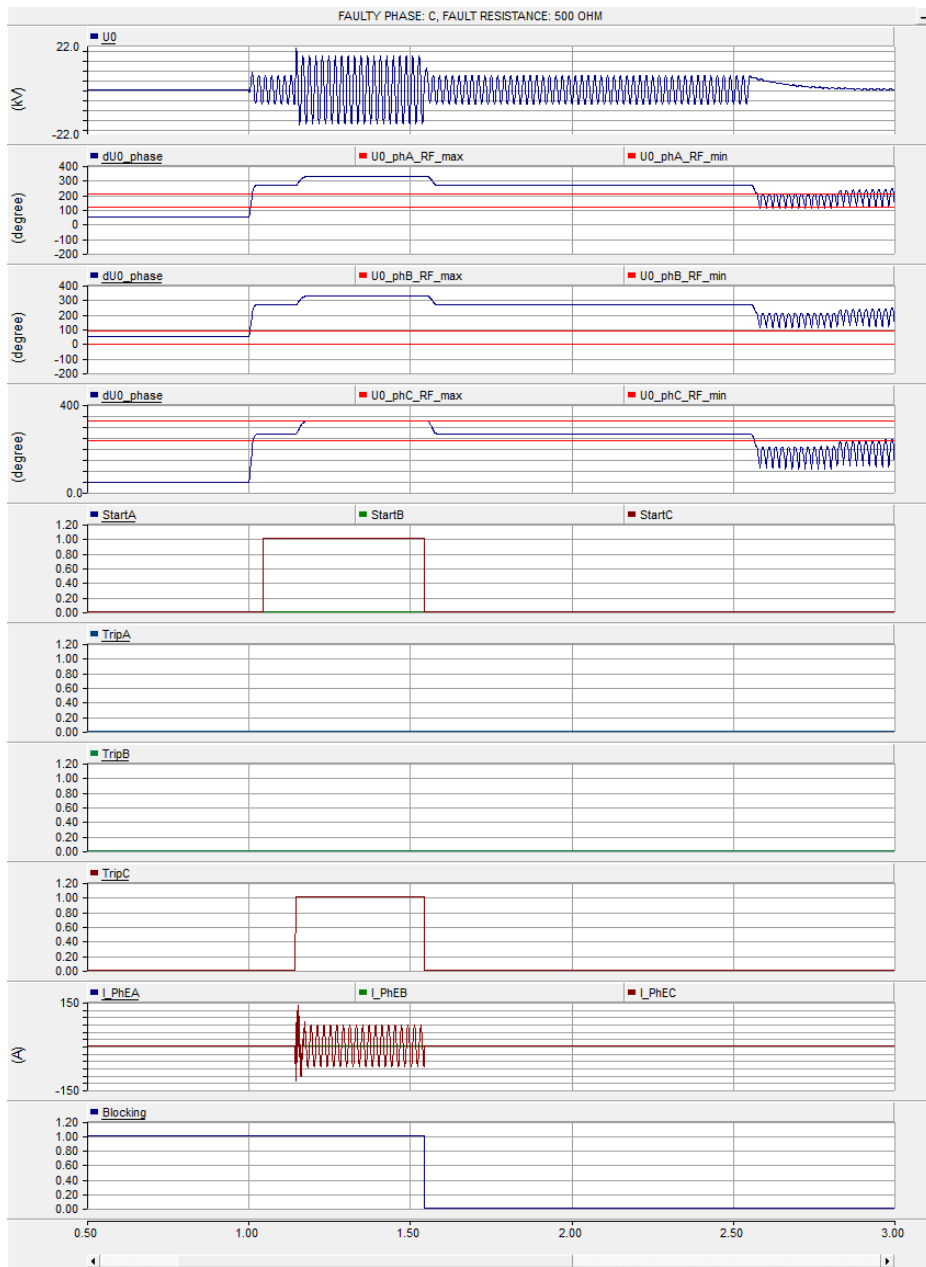


Figure 19. Functioning of the SCB when faulty phase is C and fault resistance 500 Ω.

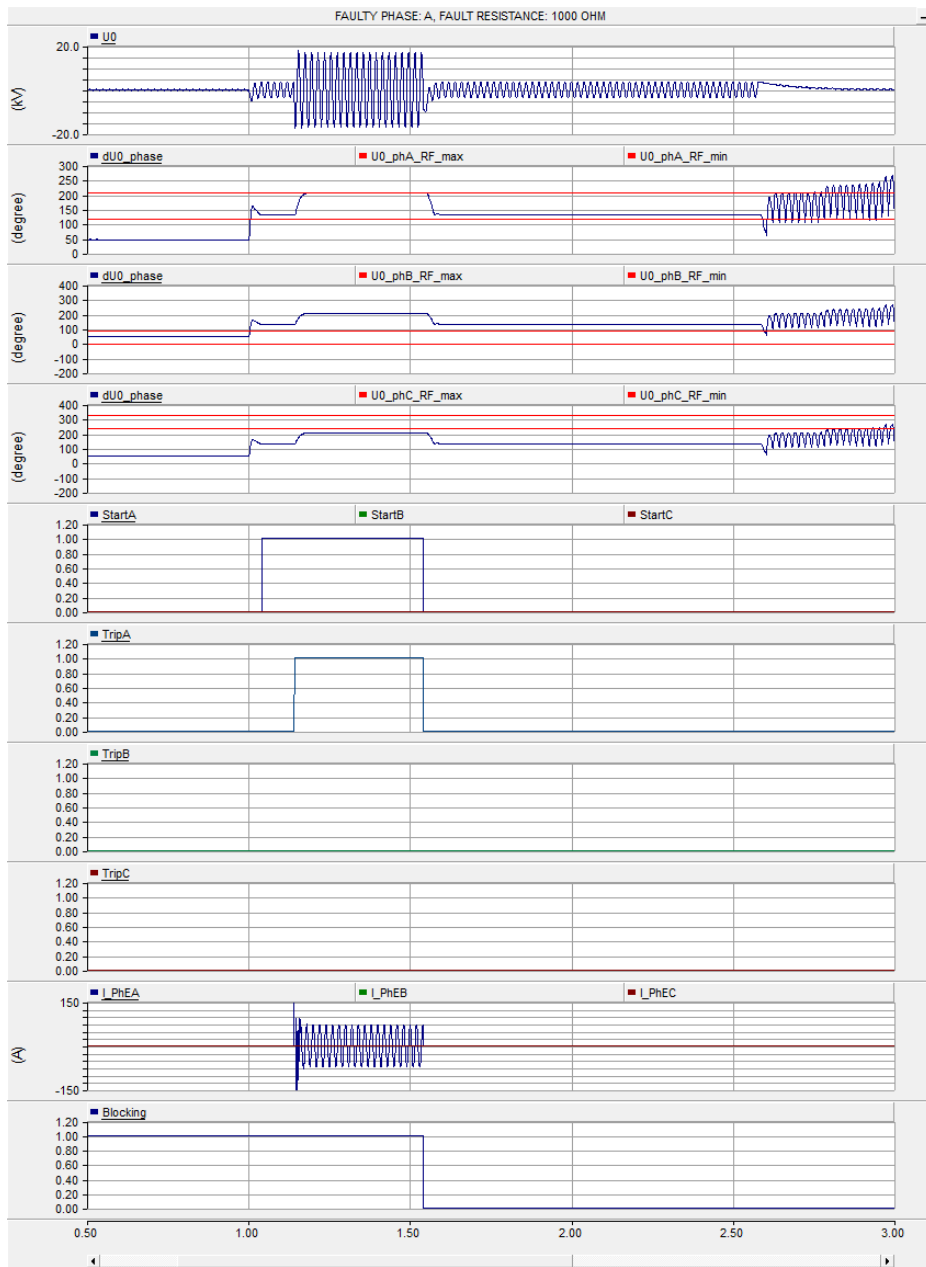


Figure 20. Functioning of the SCB when faulty phase is A and fault resistance 1 kΩ.

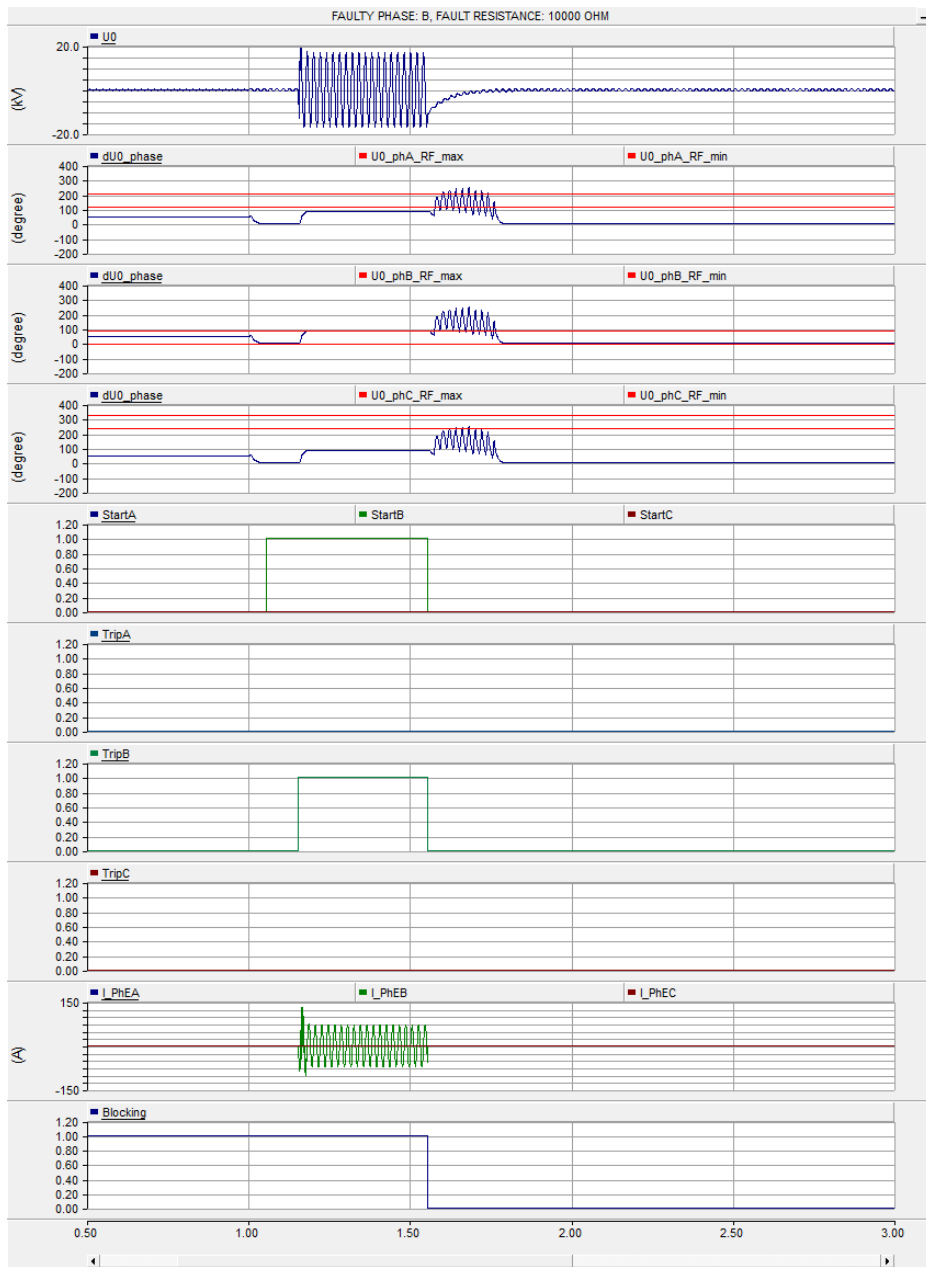


Figure 21. Functioning of the SCB when faulty phase is B and fault resistance 10 kΩ.

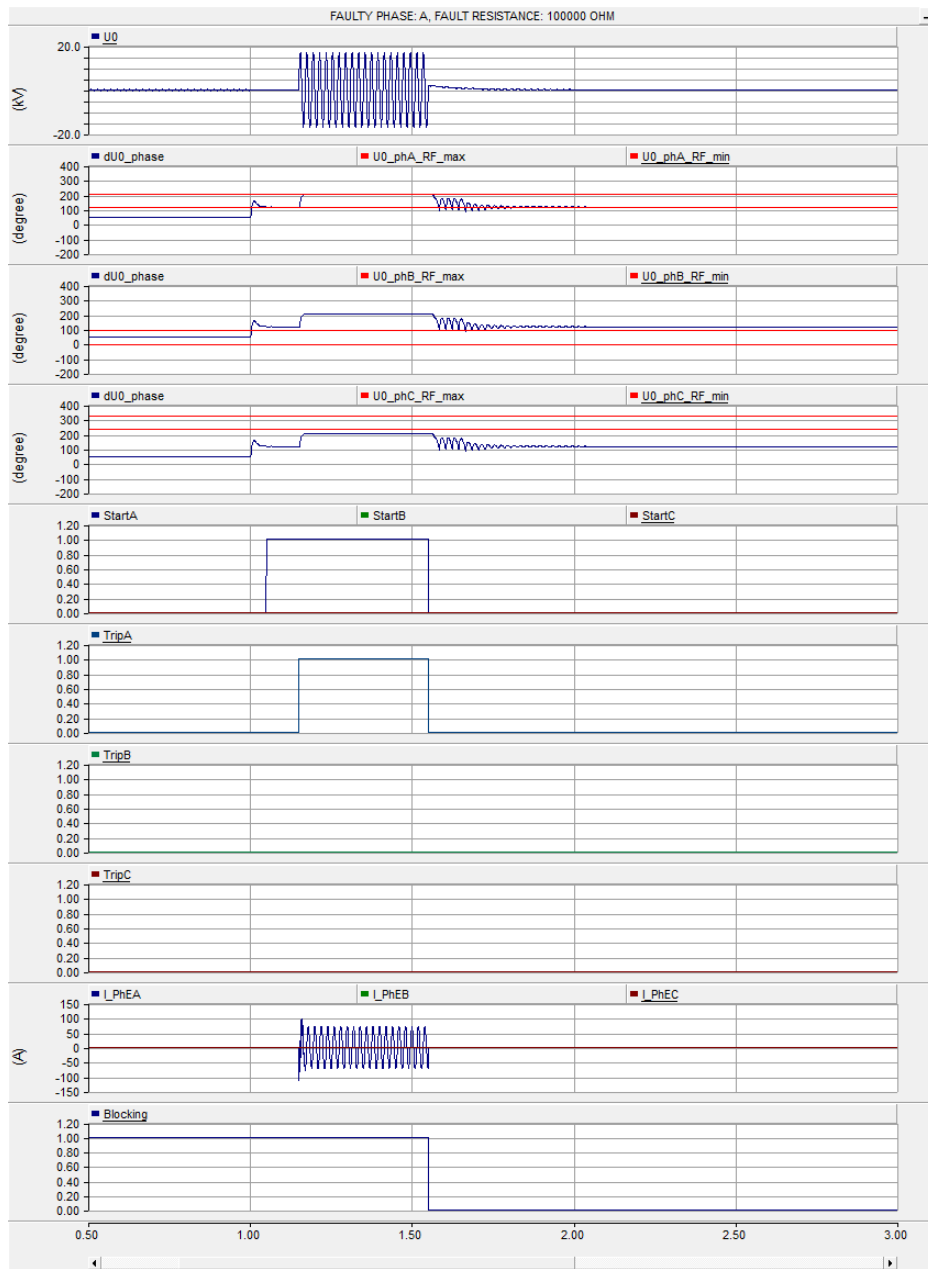


Figure 22. Functioning of the SCB when faulty phase is A and fault resistance 100 kΩ.



8. Effect of phase earthing system on operation of DG units connected to an MV network

In the following the effect of applying the phase earthing system on the operation of the distributed generation unit is presented. A distributed generation unit e.g. wind power plant is normally connected to the 20 kV distribution network via block transformer. Normally the vector group of the transformer is Dyn11. Distribution transformers feeding low voltage customers have the same vector group. Thereby similar analysis is valid also for the voltages of the low voltage customers. In this study 1.65 MVA Dyn11 block transformer whose rated voltages was 21/0.69 kV was applied. This is quite typical transformer used for connecting the wind power plant to the 20 kV network.

With these simulations a phase-to-earth fault happens at 1.0 s. The duration of the phase earthing was 1.0 s in these simulations. The fault disappears by itself at 1.9 s. The uppermost curve represents the neutral voltage of the network. Trip signals and fault current of separate phases of the shunt-circuit (I_PhE) breaker are also presented. Signal IeF1 represents the earth fault current at the fault location. Two lowest graphs represent phase-to-earth and phase-to-phase voltages at 690 V voltage level of the block transformer.

It can be observed that the fault clearing applying the shunt circuit-breaker does not cause any significant changes to the phase-to-earth or phase-to-phase voltages at the generator voltage level. Regardless of the type of the distributed generator it is difficult to see that applying of the phase earthing system would cause disturbances for the operation of the DG unit when the phase-to-earth fault disappears during the faulty phase is earthed. If the fault does not disappear during a phase earthing the feeder protection trips which cause an interruption for a generation unit.

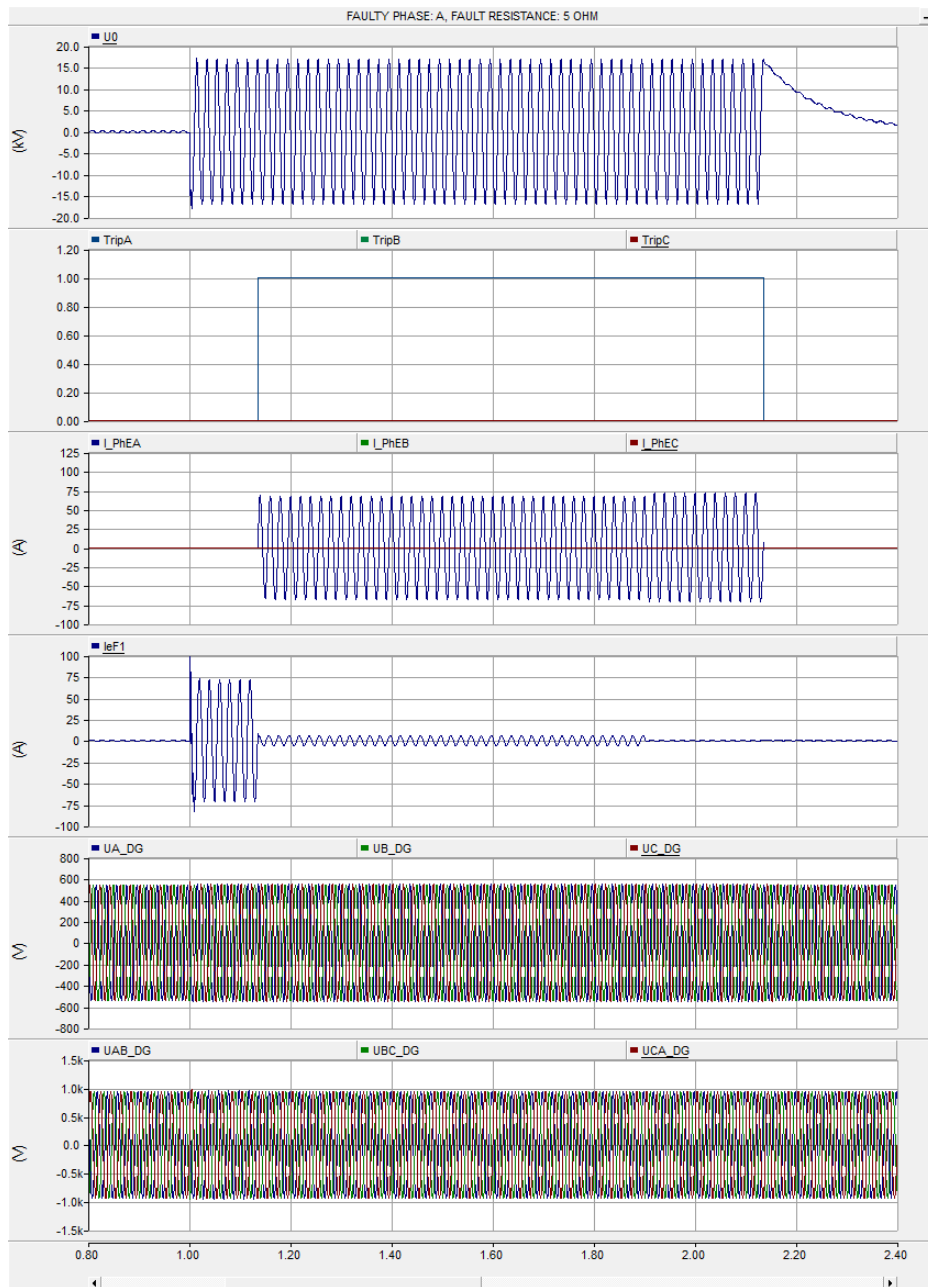


Figure 23. Phase-to-earth and phase-to-phase voltages of DG unit during functioning period of SCB when faulty phase is A and fault resistance 5 Ω. Fault disappears at 1.9 s.

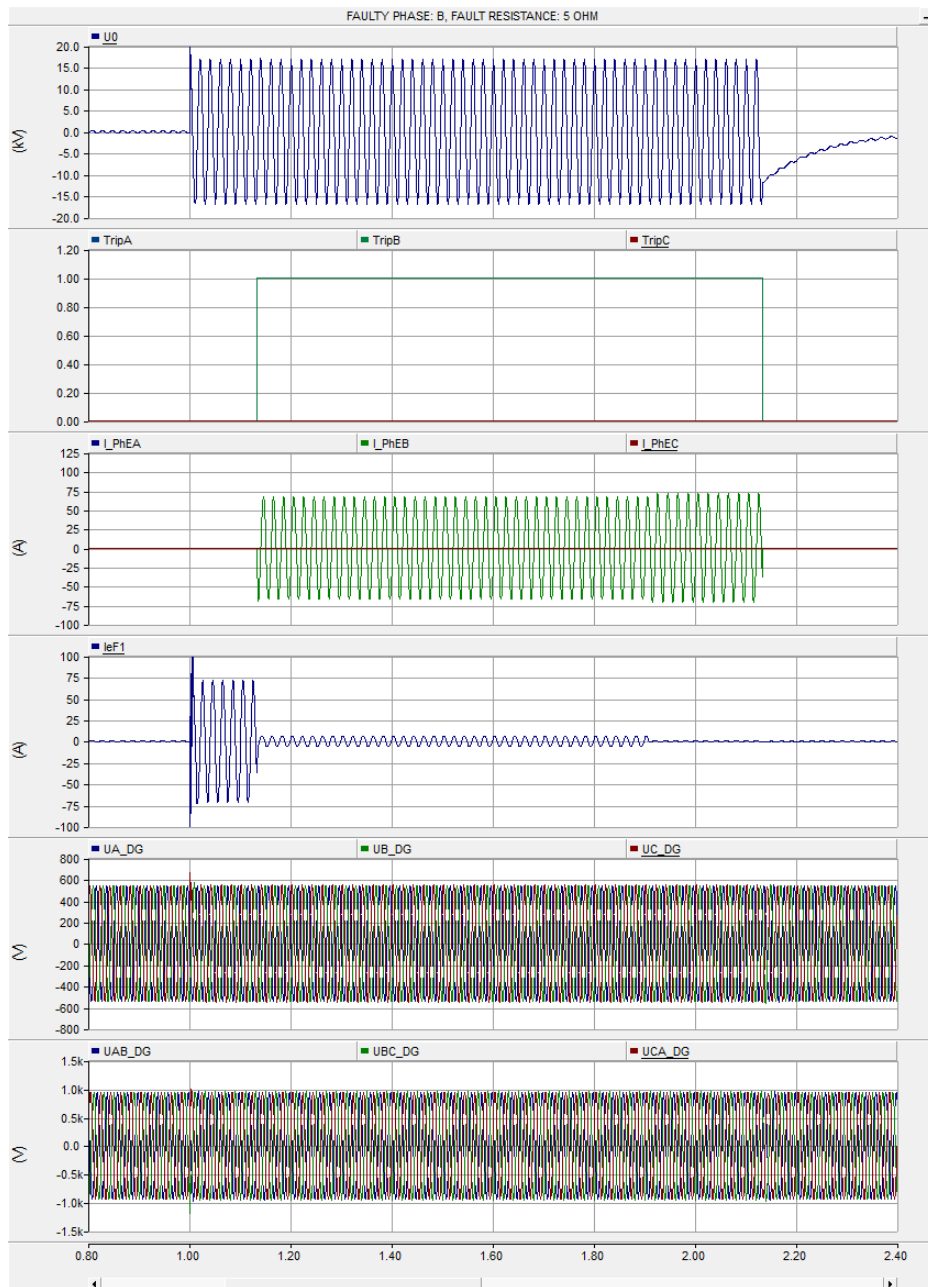


Figure 24. Phase-to-earth and phase-to-phase voltages of DG unit during functioning period of SCB when faulty phase is B and fault resistance 5 Ω . Fault disappears at 1.9 s.

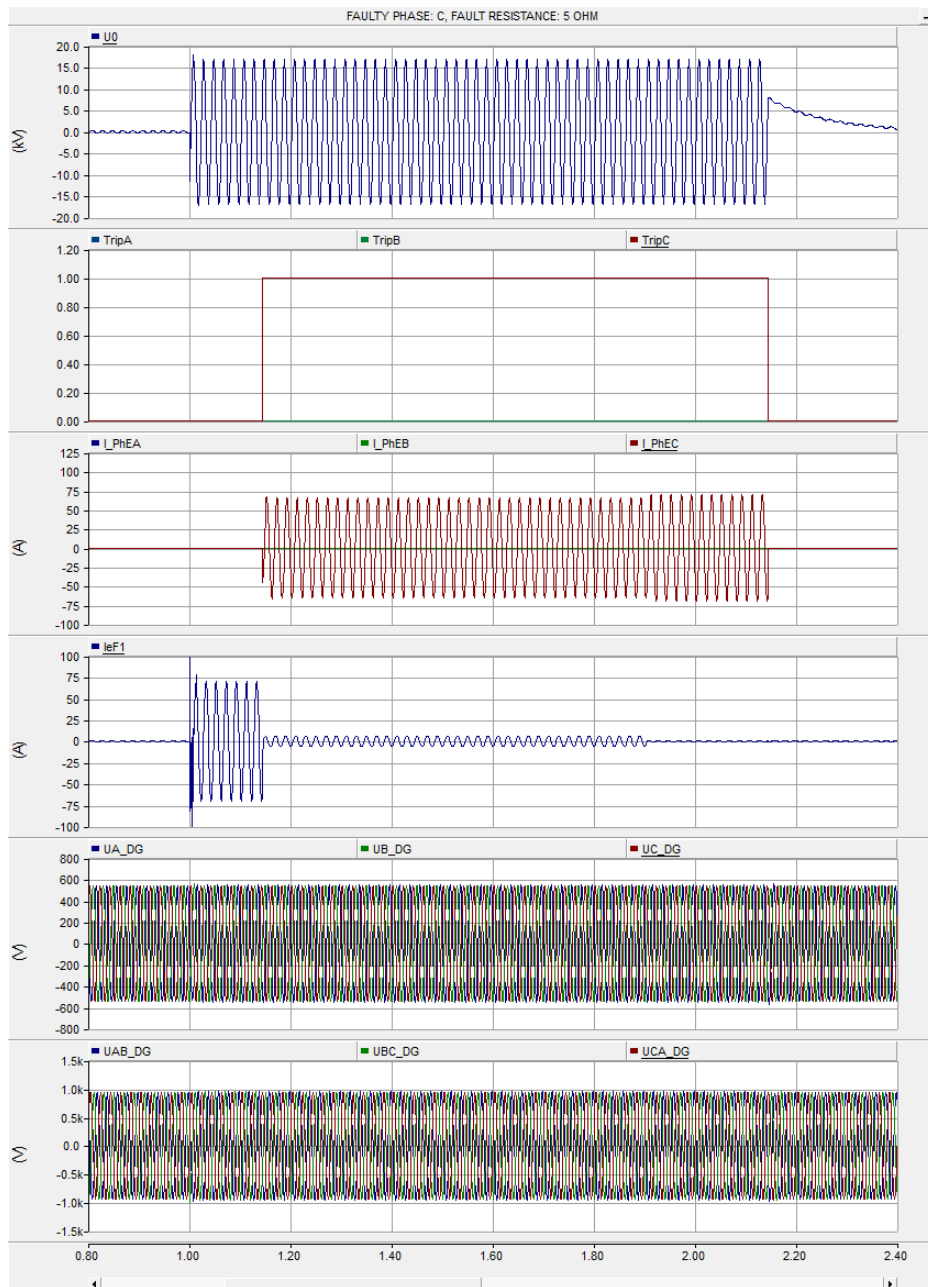


Figure 25. Phase-to-earth and phase-to-phase voltages of DG unit during functioning period of SCB when faulty phase is C and fault resistance 5 Ω . Fault disappears at 1.9 s.



9. 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 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. When the phase earthing is applied as a complementary function as part of the normal E/F protection, the temporary phase earthing 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 phase earthing the normal feeder E/F protection operates the same way as without phase earthing.

Modern phase earthing system needs a reliable and sensitive method for the faulty phase selection. The reliable faulty phase selection can be realized also with high fault resistances applying the analysis based on the phase angle of the neutral-to-earth voltage. Certain ranges for the phase angle of the neutral voltage phasor can be defined indicating the existence of the phase-to-earth fault in the appropriate phase. Usually this method is adequate for the phase selection when applying modern shunt circuit-breaker because the need for the phase earthing system concerns mainly relatively low-resistance earth faults.

The real medium voltage network consisting of either partly or only overhead lines has some natural asymmetry. This unbalance causes some inaccuracy for faulty phase selection when the fault resistances are very high. This inaccuracy can be reduced when the change of the neutral-to-earth voltage phasor instead of the measurable neutral voltage during an earth fault is used for the faulty phase selection analysis. In this case unbalanced prefault phase-to-earth voltage phasors are used as a reference when the ranges for the phase-angle of the neutral to earth voltage are determined. This advanced method is suitable for the reliable faulty phase selection also with high-resistance earth faults. This method can also be applied in the raw for the indication of the high-resistance earth faults on the primary substation level or as a complementary method with some other indication method on the feeder level. In the latter case the faulty feeder can be indicated applying some other algorithm and the faulty phase is indicated applying the method in question.

Testing the appropriate method using PSCAD simulation software shows that the faulty phase could be detected reliably up to fault resistance 350 k Ω . Even higher fault resistances were possible to detect with the simulation model but these cases are not so relevant because they cannot be concluded faults. The control logic of the SCB was tested up to fault resistance 100 k Ω . In all cases the indication of the faulty phase and control logic of the SCB operated perfectly.

The fault clearing applying the shunt circuit-breaker does not cause any significant changes to the phase-to-earth or phase-to-phase voltages at the generator voltage level when the DG



unit is connected via block transformer to the network. Thereby applying the phase earthing system does not cause disturbances for the operation of the DG units when the phase-to-earth fault disappears during the faulty phase is earthed.

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- [2] P. Bornard, C. J. Leconte, F. Pourbaix, J. P. Tete, 1987, "Improving the service quality of rural networks: Reduction of short interruptions", Proceedings of the 9th International Conference on Electricity Distribution, AIM, pp. c.05.1 - c05.7
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