IMPROVING THE QUALITY OF SUPPLY IN MV DISTRIBUTION NETWORK APPLYING MODERN SHUNT CIRCUIT-BREAKER

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ABSTRACT

This paper describes the development of the modern phase earthing system. The target was reducing the harmful short interruptions to the customers and electricity producers with phase-to-earth faults of an MV system. Neutral isolated MV systems were considered. The novel shunt circuit-breaker was tested applying RTDS (Real Time Digital Simulator) environment before field tests in the real network. Now the shunt circuit-breaker has been installed, tested with artificial earth faults and ready for service in one primary substation (110/20 kV).

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.

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) 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. 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. 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 essential requirements of the phase earthing system (PES) are the high-speed operation and reliable indication of faulty phase with an earth fault. Earlier conventional phase earthing has been applied in France [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.

FEASIBILITY OF APPLYING SCBs IN MV NETWORKS

Coordination of feeder protection and PE

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].

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 requlations [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.

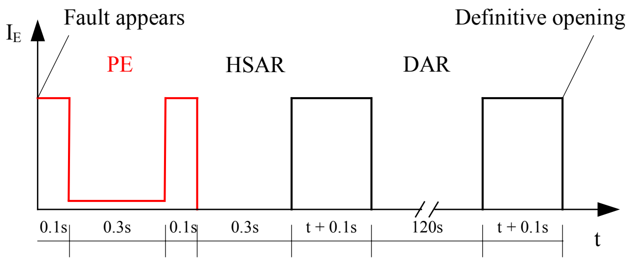

Figure 1. Operation sequence of the PE and E/F protection.

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. High impedance earth faults are not so relevant when considering the PE because they rarely have a temporary nature.

Two phase-to-earth faults

The functioning of the SCB must be reliably prevented 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 in most cases be prevented using suitable setting of the neutral voltage. The 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.

Influences of PE on touch voltgaes

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.

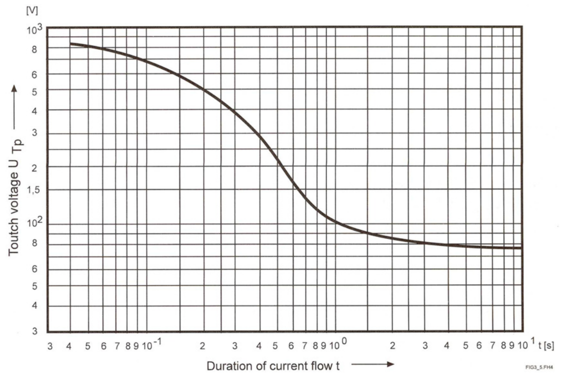

Figure 2. Permissible touch voltages U_{TP} for limited current-flow duration [1].

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.

DEVELOPMENT OF MODERN PHASE EARTHING SYSTEM

The SCB for the faulted PE tests were made by modifying Noja Power OSM27-203 pole recloser so that all three phases can be operated separately. This is possible because this recloser has different magnetic actuators in each phase.

Short open and close pulses were generated by a small Siemens PLC, which was equipped with PNP transistor output stage. PLC and fast Semikron drive modules provide the control pulses with an accuracy of 5 ms timing. Noja Power recloser does not have separate indication switches for detecting mechanically the position of the MV level main contacts so we need to pay a great deal of attention to prevent the incorrect position. It is also important to note that two phase simultaneous or sequential close control causes two-phase MV level short circuit with high current. PLC was programmed so that the earth fault is detected by the protection relay, which causes automatically the main contact to close control and then open control with fixed time delay. This ensures that the main contact under any circumstances stays in the closed position. Because the protection relay can perhaps detect in earth fault or under voltage cases simultaneous or sequential two phase earth fault signals, we equip the PLC program with 5 s blocking time that prevents after the first signal all other coming signals. Naturally, the two phase simultaneous or successive controls were also blocked.

Protection relay used in this study for detecting earth faults was Vamp 255 feeder terminal, which is very commonly used in Finland. It is capable of measuring five analog currents and three voltage measurements, and it has four output relays, and five alarm relays. The protection functions are quite versatile, but earth fault phase detection by using open delta (zero sequence) voltage phase angle measuring it doesn't have. The three phase voltage measurement is normally arranged by using two measuring channels with V-connection between the phases and the third channel is reserved for open delta voltage and sensitive directed earth fault detection outcoming feeders normally has. The relay can also be connected in such a way that all three voltage measuring channels are for measuring line voltage in star-connection and the central point is earthed. The relay is in this connection capable of detecting earth fault by comparing the phase voltage differences. In this study we had to use this connection.

TESTING THE CONTROL SYSTEM OF THE SHUNT CIRCUIT-BREAKER

The medium voltage network of Fortum Distribution fed by primary substation Kalkulla was modelled utilizing PSCAD software and RSCAD software of RTDS (Real Time Digital Simulator). The potentiality and restrictions were studied utilizing PSCAD simulations. The operation of the shunt-circuit breaker was tested in practice utilizing RTDS equipment and a network model of Kalkulla. Feeder terminal VAMP 255 was applied for controlling the logic of the SCB. The method for the indication of the faulty phase developed was implemented in the feeder terminal.

RTDS (Real Time Digital Simulator) tests

The functioning of the developed SCB and its control system was preliminary tested utilizing the RTDS environment. The functioning of the PES was studied in the network fed by a primary substation named Kalkulla. Kalkulla substation feeds six 20 kV feeders. One feeder named Linkulla was modelled in detail. Faults with the simulations and field tests were made along Linkulla feeder whose length is 24.6 km. It consists of overhead lines and covered conductors. The SCB was located at the primary substation and was connected to 20 kV busbar. The neutral of the network is isolated and the capacitive earth fault current about 52 A. The directional E/F relay is used for the earth fault protection of the feeder Linkulla. The neutral voltage setting is 2.3 kV and the sum current setting is 0.8 A. The setting of TDEF is 0.6 s. The same IED was applied for the indication of the faulty phase for controlling of the SCB. Connections between RTDS, RSCAD, SCB and IED are presented in Figure 3.

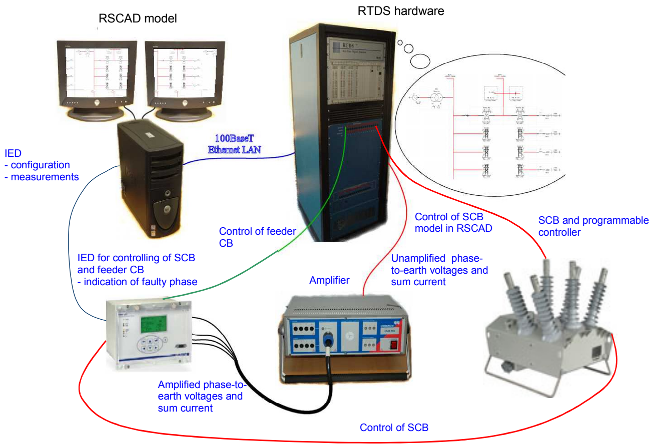

Figure 3. Connections of RTDS hardware, RSCAD model, SCB and IED.

The operation sequence of the SCB was implemented in the PLC of the SCB. The PLC get its operation command from the IED. The logic implemented in the IED detects an earth fault and indicates the faulty phase. According to this indication it sends a start command to the operational logic of the SCB and the CB of the faulty phase carries out the temporary PE. The PLC between the IED and SCB performs the operation sequence of the SCB and the CB of the faulty phase of the SCB makes an AR function. Phase-to-earth voltages and sum current of the faulty feeder are connected to the amplifier which amplifies these signals to an appropriate level for the IED. These amplified signals are connected to the IED.

The E/F relay settings of the IED were the same as the corresponding settings of the real E/F relay of feeder Linkulla. Thus the E/F relay of the IED functions as a part of RSCAD model in real time protecting the feeder Linkulla of the RSCAD model.

The operation delay of the PE with programmable logic controlling the circuit-breaker was about 200 ms. Both the IED and circuit-breaker operated predictably in RTDS environment as a part of network model of Kalkulla. Figure 4 illustrates the fault current and the current flowing via SCB, neutral voltage and sum current of the MV feeder.

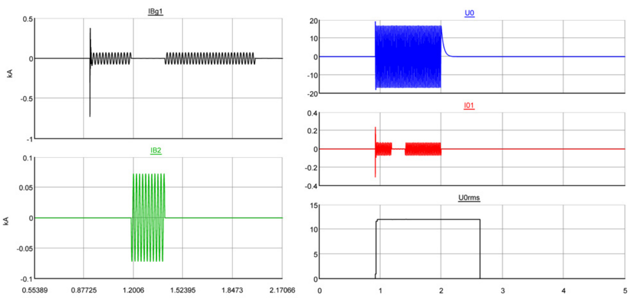

Figure 4. Fault current and current of SCB (left), neutral voltage and sum current (right).

FIELD TESTS

The novel PES was 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). Same IED including faulty phase selection method and programmable logic were applied in field tests as with RTDS demonstrations. In the field tests the operational delay of the SCB was 300 ms and the duration of the PE 400 ms. The setting of TDEF was 1.0 s. Artificial earth faults were made along the 20 kV feeder three times in every phase. The PES operated well and predictably with the field experiments. In the future it will be brought into play during continuous operation of the network. Figure 5 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).

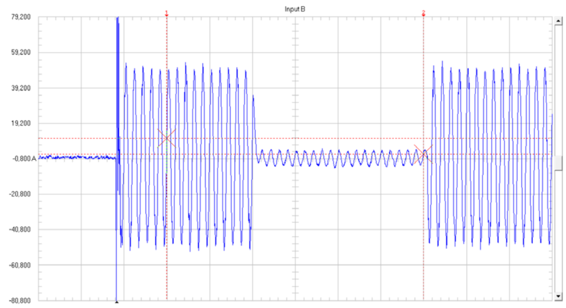

Figure 5. Fault current at the fault location with the PES.

CONCLUSIONS

The pilot implementation of the modern shunt circuit-breaker has been developed and the prototype device has been installed in the real 110/20 kV primary substation. The SCB and its control system were tested applying RTDS environment. Field experiments arranging artificial earth faults in the real network were also carried out. The detection of the faulty phase could be carried out reliably with low ohmic phase-to-earth faults. In the near future, the field installation will be brought into play during continuous operation of the network.

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