INTERMITTENT EARTH FAULTS CHALLENGE CONVENTIONAL PROTECTION SCHEMES

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INTRODUCTION

Intermittent earth faults are a problem encountered especially in compensated underground cable networks. The deterioration of insulation manifests itself by successive breakdowns, between which the earth contact is temporarily removed. Conventional protection relays have not been designed for this fault mode and the relay of the faulty feeder may not detect the fault at all. The residual voltage will however stay high between the breakdowns and cause the unselective tripping of the station back-up protection.

1. WHAT IS AN INTERMITTENT EARTH FAULT ?

Intermittent earth fault is a fault mode encountered especially in underground cables of compensated networks, that is in networks earthed via a Petersen coil. The initial reason for the fault is a spot of damaged insulation in the cable.

There have appeared deteriorated underground cables and consequently also intermittent earth faults for a long time. The problem has however been emphasized by the increased sensitivity of various processes to interruptions of power supply. The efforts to minimize these interruptions and nonselective relay operations have led to increasing awareness of this fault mode and its significance.

When the insulation has been damaged, there are basically two possible consequences. The breakdown may lead to a permanent fault immediately or it may first lead to an intermittent earth fault. Conventional protection schemes have been designed for permanent faults and may therefore show poor performance at intermittent ones.

In compensated networks the probability of self-extinguishment of earth faults is high, since the fault current is low. If the breakdown has not given rise to a solid earth contact, there are relatively good chances that the fault will be extinguished immediately after the breakdown. But since the damaged spot in the cable has a reduced 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 successive breakdowns which is called an intermittent earth fault.

The figures 1 and 2 illustrate the current and voltage waveforms related to an intermittent earth fault. The current peaks seen in the figure 1 and the decrease of voltage in the figure 2 are related to the breakdown of insulation. As the figure 2 shows, the voltage of the faulty phase rises slowly between the breakdowns. This explains, why the damaged point in the insulation does not break down again immediately. Depending on the insulation capability of the faulty point and the rate of rise of the phase voltage, the repetition rate of breakdowns may vary much from one breakdown per several cycles up to a few breakdowns per power cycle.

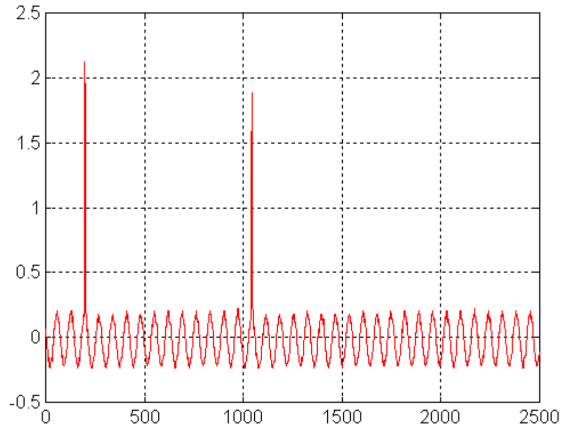

Figure 1. The current of the faulty phase related to an intermittent earth fault.

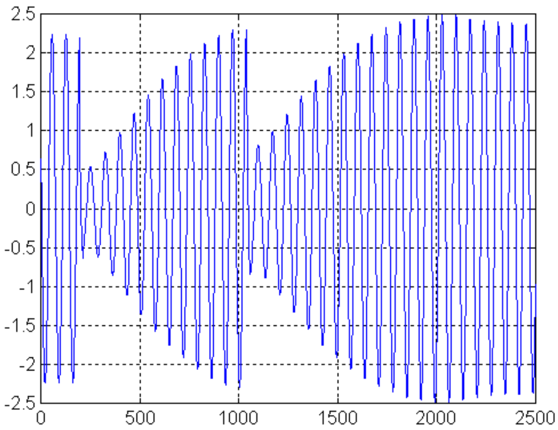

Figure 2. The voltage of the faulty phase related to an intermittent earth fault.

There are several mechanisms that lead to the deterioration of underground cables. The various physical and chemical processes related to aging of insulation are still an object of extensive research and are beyond the scope of this paper. Only one known fault mechanism is discussed in this paper.

If the fault can be characterized as an intermittent earth fault in the first place, it always involves local and temporary loss of insulation capability and consequently repetitive electrical breakdowns of insulation no matter which is the initial deteriorating mechanism. It can thus be concluded that all intermittent earth faults will lead to more or less same kind of current and voltage patterns. Only the rate of breakdowns and the magnitude of current peaks related to them vary, and this variation is only partly due to the type of the process that has led to the damages in insulation. It is thus not relevant in this context to study the actual deteriorating mechanisms in great detail.

1.1. Impact of insulation material

In Norway an extensive research project has shown that old paper insulated cables have a fault rate of 1 - 2 faults / 100 km / year, whereas the fault rate for XLPE-insulated cables is 0.2 faults / 100 km / year, [1]. Statistics in other countries give approximately the same figures, [2]. This difference is explained by the difference in age : Oldest XLPE-cables have been in use from 1970's and oldest paper-insulated cables from the beginning of the century.

Because most statistics deal with permanent faults that have led to cable replacements, it is not sure that the same difference could be seen in the rates of intermittent faults, if such statistics were available. According to the experiences of the authors of this paper, XLPE-cables laid down in the beginning of 1970's cause more intermittent earth faults than paper cables.

One known mechanism that leads to intermittent earth faults in XLPE-cables is called "water treeing". There are several factors that play a role in water treeing. One are the impurities in the material, another the unevenness of the boundary surface between the dielectric and semi-conducting layers, still another is alternating electric field and the fourth one is the water that penetrates the insulation. Water acts as a catalyst in the process in which the polymer chains are broken and which leads to tree-like cavities in the insulation.

The cavity will break down, when it is filled with water. The breakdown will vaporize the water, but the ionization in the hole will lead to new repetitive breakdowns, in other words to an intermittent earth fault.

By understanding the mechanism called water treeing, it is also possible to explain, why intermittent earth faults and other earth faults of underground cables may seemingly disappear after the relay operation. After the fault has dried the cavity and the ionization has been removed by de-energizing the line, the insulation may be able to withstand the normal voltage for some time.

1.2. Impact of watertight armouring

Because water plays a central role in the deteriorating of XLPE-cables, it is clear that watertight armouring is an efficient way of slowing down the process. And when damages will appear in the insulation in the end, the watertight armouring will still be significant, since it will limit the amount of moisture entering the cavities.

Some manufacturers produce therefore exclusively water-tight cables. Also other types of armouring are however still used.

1.3. Impact of Petersen coil tuning and of parallel resistor

In compensated overhead line networks most of earth faults extinguish by themselves. The probability of self-extinguishment is highest when the fault current is lowest, that is when the Petersen coil is accurately tuned. When the probability of self-extinguishment is increased, then also the probability of intermittent earth faults increases.

It is thus possible that the occurrence rate of intermittent earth faults goes up, when the compensation method is changed from fixed Petersen coils to tuned ones. It is uncertain to which extent this conclusion is true, since no statistics are available. It is however worthwhile updating the relays to encompass also a protection function against intermittent earth faults, when tuned Petersen coils are taken into use.

The ohmic value of the parallel resistor affects the probability of intermittent earth faults in two ways. The higher the resistance is the lower is the fault current and the higher the probability of an intermittent earth fault. On the other hand the voltage of the faulty phase rises slower if the resistance is higher, which decreases the probability of a new breakdown after the previous one. It is unclear, which of these mechanisms is the dominant one, but the resistance of the parallel resistor may obviously have on impact on the occurrence of intermittent earth faults.

1.4. Special problems of mixed networks

Especially in rural areas the networks are often mixed, that is: they consist partly of overhead lines and partly of underground cables. This kind of networks are most prone to intermittent earth faults. Because the earth fault rates are relatively high due to long overhead line sections, the overvoltage stresses on the insulation caused by the risen voltages of healthy phases are more frequent than in a network consisting of underground cables only. The weak spots of cable insulation are therefore more likely to develop to faults. This problem is made worse by the fact that the longest underground cables often are located in rural areas.

2. PROTECTION ASPECTS

2.1. Problems encountered with conventional relays

The conventional earth fault relays have not been designed for intermittent earth faults which are characterised by irregular current and voltage waveforms. For this reason the relays of feeders often either fail to operate altogether or issue nonselective trippings.

The selectivity problems are made worse by the fact that the intermittent fault often causes the tripping of the station back-up protection, which leads to an interruption of the power supply for a large number of customers. The station back-up protection normally consists of a U_o -relay the operation time of which is longer than that of the directional earth fault relays of the lines. In compensated networks U_o attenuates only slowly between the break-downs of the insulation, see figure 3. U_o will thus stay at a high level and the U_o -relay will finally trip, if the relay of the faulty line fails to operate.

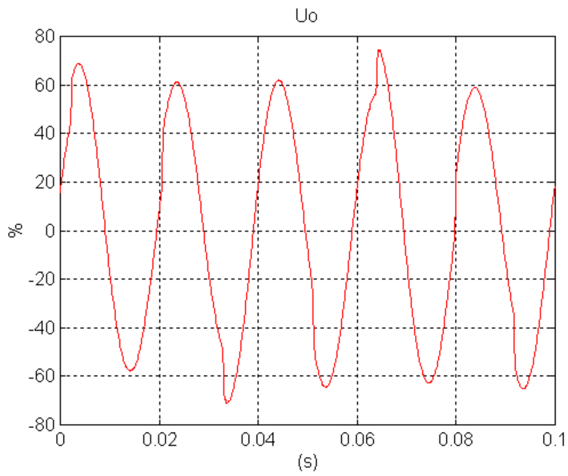

Figure 3. The residual voltage stays at a high level between the breakdowns of insulation.

2.2. Improvements of protection schemes

There are different ways of improving the performance of protection schemes at intermittent earth faults. One approach is to design the analog filters of the relay in such a way that the narrow current peaks related to the intermittent earth fault are tranformed to fundamental frequency signals. A normal directional earth fault protection algorithm can then be applied successfully even for protection against intermittent earth faults, when necessary fine-tunings are done in the algorithm and in the hardware.

A selective protection algorithm can also be based on com-paring the polarity of I_o -peaks to that of U_o (see figure 4). In the faulty lines the polarities are the same, whereas in healthy lines the polarities are opposite. This kind of algorithm is more applicable in a multi-function feeder terminal, in which the same hardware and same measure-ments are used for many different purposes. In this case it is difficult to have analog filtering in the measurement channels for intermittent earth fault protection function without losing the information needed by other functions.

One relevant feature in a selective protection scheme against intermittent earth faults is an appropriate drop-off time. Since the time period between successive breakdowns may be several cycles, the drop-off time must be at least longer than that to ensure a trip.

Both above mentioned implementations have performed satisfactorily in the field tests described in the following section. There are thus available in the market such relays that are able trip selectively at intermittent earth faults.

Fault mechanisms are never fully known, and it is possible that fault modes resembling those encountered in underground cables may frequently appear also in overhead lines. It has been discovered for instance, that a defective surge arrester or a fallen over-head line may cause similar current and voltage wave forms as a deteriorated cable. Also damaged insulators and trees touching lines are potential causes of problems.

Since repetitive current peaks with high amplitude are always related to some kind of faults, there is no risk of undue trippings even if a protection function designed for intermittent earth faults is applied in a network where they do not normally appear. It is thus recommended to always have a function for intermittent earth faults when the network is earthed via a Petersen coil.

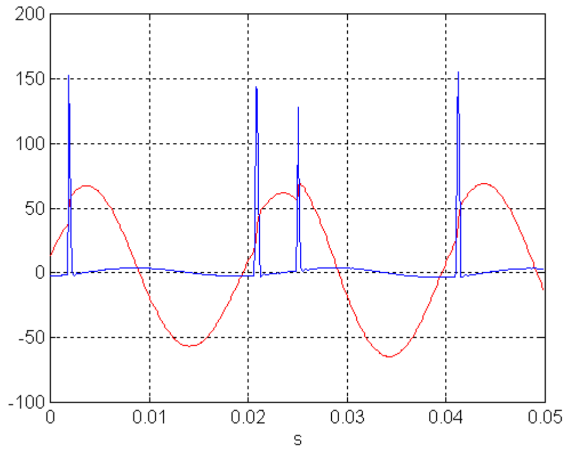

Figure 4. The I_o -peaks of the faulty line have the same polarity as U_o.

3. FIELD TESTS

To obtain more information about the characteristics of intermittent earth faults it was considered necessary to perform field tests. Same kind of tests have been done even before in the era of analog electronic relays, but now the relevant current and voltage waveforms were recorded by a digital transient recorder for off-line tests of relays designed for detecting intermittent earth faults. Some relays were even tested on-line during the primary tests. Varberg Energi AB and Jämtkraft Elnät AB are two of the companies that have co-operated with ABB in organizing the tests.

In the field tests the faults were created artificially by drilling a hole in the insulation layer of the cable. In the tests both paper insulated and XLPE cables were used. The hole was filled with water to make it break down. It was discovered, that the fault could disappear after water had evaporated and the line had been de-energized. To be able to continue the tests, the hole was filled with water again if necessary.

Due to practical reasons the faulty cable section was located near the HV/MV -substation. To minimize the problems caused to customers, there was no loading on the faulty line. The loads were connected to other feeders. As a consequence the faulty line was relatively short. From theoretical point of view this had no impact on the fault itself. Only the 50 Hz component of the residual current measured in faulty line was lower than it may be in practice.

The location of the intermittent fault may affect the width of the current peaks measured. Since the measurements are performed in the beginning of the line, the high frequency components of the current peak are attenuated most, when the fault is located in the end of the line. This attenuation leads to a little broader current peaks, but is not likely to have any practical consequence for the measured current and voltage waveforms since they are anyway smoothed by the analog filters of the relay.

The voltage and current wave forms obtained in the field tests resemble those shown in the figures 1-4. The actual amplitudes and widths of current peaks and their repetition rates naturally varied depending on the case, as was expected.

4. INTERMITTENT EARTH FAULTS AND RELIABILITY OF POWER SUPPLY

4.1. The role of protection relays

If the feeder protection fails to issue a selective tripping at intermittent earth faults, the back-up protection will trip nonselectively, as discussed earlier. There is even a risk, that the real cause of the tripping of back-up protection will not be found out. And because the faulty cable section is thus not located and replaced, the same damaged point in insulation will start breaking down again later.

This condition clearly has an adverse effect on the reliability of power supply and on the customer relations, since a number of users will lose their electricity from time to time without the utility being able to tell why. The more underground cables with deteriorated insulation there are in the network, the bigger is this problem.

Network companies are already often required to compensate for the damage caused by interruptions of power supply, and this trend is expected to go on. From this point of view it is clearly in the interests of utilities to minimize the supply interruptions caused by intermittent earth faults.

Replacing old feeder protection relays with new ones that are able to detect intermittent earth faults and trip the faulty line is thus economically well justified, when the network contains many old underground cables. The investment will pay off, when the intermittent earth faults become more frequent sooner or later.

When new substations or replacements of existing protection relays are being planned, it is always worthwhile making sure that the new relays have a tested algorithm for detection of intermittent earth faults. Even if there were mainly new underground cables or overhead lines in the network, the situation will change in future making it useful to be able to detect intermittent earth faults. The general trend towards using cables instead of overhead lines and the natural aging of existing cables are likely to make intermittent earth fault a potential problem in future.

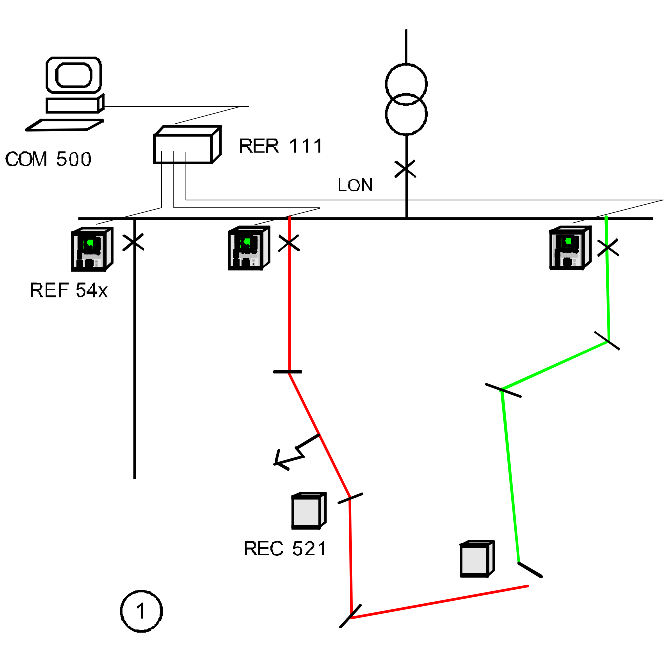

Figure 5. Minimizing the number of customers suffering from a power supply interruption by moving loads to neighbouring feeders, when the defective cable section has been located.

4.2. Replacing old cables

When there are feeder protection relays able to issue a selective trip at an intermittent earth fault, the reliability of electricity supply is greatly improved, because nonselective operations of back-up relays are avoided. The trips of feeder relays are however still a power quality problem. Replacing deteriorated cables is a necessary measure when reliable service to customers is pursued.

It is not necessarily economically justifiable to replace all underground cables at a certain age, because there is a large variation in their life times. Paper insulated cables, that have been laid down in the beginning of century, are still in service in many places without high fault rates. On the other hand XLPE cables, that have been in service since 1970's, may already show signs of deteriorated insulation.

When the relays are able to trip selectively at intermittent earth faults, it is possible to follow such a strategy that the cables are replaced only when they get permanently faulty. Because the intermittent earth fault may seemingly disappear by de-energizing the line, it is worthwhile trying to simply close the circuit breaker and continue the service.

There is another reason, why it is practical to postpone the cable replacement until the intermittent fault has developed to a permanent one. The commonly used cable fault location methods are based on a stable earth contact at the faulty spot. Such a permanent contact does not exists for an intermittent fault. It is thus not possible to locate it accurately with any known method.

Deteriorated spots of insulation can in some cases be located by partial discharge measurements performed when the cable has first been de-energized, [3]. The inaccuracy of this method is of the order of tens of meters. It is however uncertain, whether spots causing intermittent faults always give rise to measurable partial discharges. Signal attenuation and various sources of noise make it also impossible to detect partial discharges located more than a few kilometers away from the measurement point.

Another approach is to try to find approximately the fault location by trial-and-error -method and run the network in such a configuration that there is a minimum loading on the defective line. In this way the number of customers suffering from an interruption will be minimized, when a permanent earth fault will occur in the end. See figure 5.

If the intermittent earth fault seemingly disappears after the relay operation, it is uncertain, if the defective cable section is moved to another feeder or not when the configuration of the network is changed. And when an intermittent fault appears next time it is not necessarily the same fault. It would therefore be better if the trial-and-error -method were applied during the fault.

There are however risks in running the network at intermittent earth faults. There may appear high touch voltage peaks e.g. on the cases of ring main units. The intermittent earth faults have so far been relatively rare and there are consequently no safety regulations concerning them, which naturally does not make it safe to neglect the risks.

If the probability of intermittent earth fault is known to be higher in one line section as compared to others, this knowledge can be made use of when trying to find such a network configuration that a minimum number of customers will suffer from power interruptions.

4.3. Making use of disturbance recorders

No generally available statistics concerning intermittent earth faults are available. It is thus difficult for persons responsible for protection to assess the importance of this phenomenon in their networks. Using disturbance recorders is therefore a good starting point when a utility is willing to investigate the occurrence of this fault mode.

In many modern protection relays there are built-in disturbance recorders available. If current and voltage waveforms resembling those in figures 1 and 2 are frequently encountered among the recordings and there appear nonselective trippings in this context, then it can be concluded that intermittent earth faults are a problem that needs to be addressed. For instance the approach outlined in previous section could then be considered.

5. CONCLUSIONS

Intermittent earth faults has been discussed as a phenomenon in this paper. It has been shown, why this fault mode manifests itself especially in compensated underground cable networks and why conventional earth fault relays often fail to operate selectively at these faults.

Ways of improving protection algorithm was also discussed and the feasibility of selective feeder protection against intermittent earth faults was proved by referring to the field tests performed. Interruptions in power supply are minimized by having relays with such functionality, since nonselective tippings of back-up relays are then avoided.

Replacement of old cables was touched briefly. Some possible courses of action were outlined.

All details of intermittent earth faults are not yet satisfactorily known. It is therefore difficult to give generally applicable statements as to the course of action that should be taken to minimize power supply interruptions, when this type of faults start to cause relay operations. In addition to having relays that are able to trip selectively at intermittent earth faults the use of disturbance recorders was recommended as a means of obtaining a better understanding of the role of this fault mode in various networks.

REFERENCES

[1] A.C. Gjaerde, L. Lundgaard, H. Faremo, “Feilstatistikk for massekabel, endeavslutningar og skjoter 1991-1995”, June 1997, EFI TR A4550, In Norwegian.

[2] Cable fault statistics 1990 (9th Inquiry), UNIPEDE DISCAB, 50.02 DISCAB Secretariat, 12th October, 1992.

[3] E. Pultrum, O.J.G.M Groen, E.F. Steennis,”Cost effective maintenance for MV cable circuits : VLF partial discharge mapping”, 12th CEPSI, 2.-6. November, 1998, Pattaya, Thailand.